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RESEARCH ARTICLE

Integrating human-centred design approach into Sustainable-Oriented 3D Printing Systems

Emilio Rossi[1] · **Massimo Di Nicolantonio**[2]

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Abstract

Modern 3D printing systems have become pervasive and widely used both in professional and in informal contexts, including sustainable-oriented ones. However, the risk to create very effective but non-sustainable solutions is very high since 3D printing systems could potentially increase the environmental emergencies and the unsustainable growth. In the transition process toward sustainable ways of production and consumption, the so-called human factor still plays an important role in the achievement of sustainable-oriented actions; it drives the adoption of proper lifestyles that directly and indirectly influence the ways through which such technologies are used. Therefore, future Sustainable 3D Printing Systems should integrate the humans in the systems' development. This study presents two important results: (a) it presents a set of interdisciplinary 'Sustainable 3D Printing Systems', which compose a promising sustainable-oriented scenario useful to support the transition processes toward sustainable designs and productions, and (b) it proposes a new strategy for the integration of human-centred aspects into Sustainable 3D Printing Systems, by combining insights from human-centred design approach.

Keywords Human-centred design · Sustainable scenario · Design driven research · 3D printing systems · Human systems integration

1 Introduction

According to the 'Brundtland Report'—formally entitled 'Our Common Future'—presented by the World Commission on Environment and Development in 1987, the concept of Sustainable Development is defined as 'a development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED 1987). The Sustainable Development is therefore a societal multidimensional long-term goal where both environmental protection policies and socio-technical innovations are equally relevant and used to mitigate the anthropic impacts on ecosystems at all scales.

Even though the main goal of the Sustainable Development has been maintained over years, the boundary conditions have radically evolved; for instance, the new market demands from emerging and developing countries, the demographic growths, the democratization of technologies (i.e. affordable access to services) and the rising of new fast-emerging economies have significantly reshaped the current approaches on sustainability-related issues.

This aspect is today crucial for industrial productions and for the design discipline, which intrinsically links end-users' needs (marker demand), production technologies and capabilities (human and systems performances) and entrepreneurial competitiveness (market offer). By integrating products' generation, development and distribution, the design discipline contributed in the evolution of the concept of sustainability over the years, for instance, the design of eco-friendly products (environmental mono-disciplinary approach) (Vezzoli and Manzini 2008); the design of sustainable services (dematerialization-based approach) (Prendeville and Bocken 2017); the development of context-based forms and scenarios for sustainable wellbeing (distributed networked approach)

✉ Emilio Rossi
erossi@lincoln.ac.uk

Massimo Di Nicolantonio
m.dinicolantonio@unich.it

[1] Lincoln School of Design, University of Lincoln, Brayford Pool, Lincoln LN6 7TS, UK

[2] Department of Architecture, University of Chieti-Pescara, Viale Pindaro 42, 65127 Pescara, Pescara, Italy

(Manzini 2002; Manzini and Vezzoli 1998); the design of mixed solutions composed by products and services—Sustainable Product-Service Systems (Ceschin 2014); and, recently, the design of socio-technical systems meeting transition studies and social innovations (systemic business approach) (Ceschin and Gaziulusoy 2016).

In design discipline, extensive studies and experimentations conducted in last three decades have produced and increasing awareness on sustainability-related issues and on the impact of the discipline toward the design of 'sustainable solutions'. These explorations have clearly demonstrated that Sustainability in design is today intrinsically related to the design of sustainable forms of wellbeing, which are also able to generate new forms of consumption, lifestyles, social education and collective behaviours—the so-called culture on Sustainability (Manzini 2003). Then, the socio-technical impacts of people's behaviours influence the design of effective sustainable solutions (Manzini 2014; Willis and Manzini 2005) both on the quantitative point of view (i.e. the number of solutions designed and produced) and on the qualitative one (i.e. market, societal and cultural effectiveness of sustainable solutions).

In terms of impacts of sustainable designed solutions, there is a clear interdependency between market demands (end-users' needs of functions and results) and industrial productions (market capability to provide effective offers). The more end-users' behaviours become aligned with sustainability-oriented issues, the more the industrial productions have to vary their offers in a double strategy: (a) by introducing more rational forms of production, because out-dated productions techniques have to be abandoned, and (b) by linking the human domain into production processes to maximize the effectiveness and the cultural impacts of solutions into behavioural changes.

On the Industry 4.0 point of view, recent 3D printing technologies are rapidly changing the way companies and the fast-rising class of 'makers' design and produce their products (Martinez and Stager 2013; Bruner 2017). As explained by ISO (ISO/ASTM International 2015), 3D printing is an umbrella term used to describe all processes in which material (plastics, glass, concrete, metals, food, sand) is joined or solidified under computer control to create three-dimensional objects. Compared with other industrial processes for mass production, in recent years the democratization of services and the low prices of 3D printers have encouraged the application in many informal and non-industrial applications (i.e. Fab Labs, makers movement, etc.). Thus, people got a higher awareness on their capability to create customized objects, and, consequently, new printing-oriented services have been developed to support this socio-technical transition (Benkler 2006), which also aims to support the waste reduction of production materials. The shift here described is significant since it produces a sort of evolution of the role of customers within the products' value chain: From passive buyers they can now become active producers of objects. As described by Scheeren et al. (2018), 3D printing started a contemporary renaissance of the 'homo faber' meaning, making people able to create perfect—tangible—solutions for the tasks they have to perform.

In some ways, informal 3D printing processes could be intended as new distributed sustainable forms of low-tech productions, since they work both on the socio-technical impacts of the creations (i.e. personal gratification through own productions) and on their techno-economic implications (i.e. generation of rough business models); however, the risk to produce unsustainable impacts on the ecosystems remains very high. Here, the main problem linked to this issue is that sustainable-oriented advances on 3D printing technologies principally concern vertical innovations—mono-disciplinary research—like eco-efficient materials (i.e. recycled biomaterials) (van Wijk and van Wijk 2015), first forms of production services (i.e. print-to-delivery services, cloud manufacturing) (Zhou et al. 2018), economically efficient services (i.e. 3D printing for education) (Canessa et al. 2013), solutions for housing emergency and large-scale applications (Hager et al. 2016) and low-tech applications (i.e. DIY 3D printers) (de Jong and de Bruijn 2013).

There is a clear divergence between what should be done and what is currently happening in terms of sustainable-oriented actions in 3D printing domain. A systemic approach is therefore necessary to maximize the efficacy of actual sustainable-oriented 3D Printing' actions with the human need to have a balanced economic, environmental and social conditions – horizontal approach and multidisciplinary research on sustainable wellbeing.

As the need to have only—mostly—sustainable solutions is a prerogative for customers, entrepreneurs, policymakers and, in general, the current society, it is believed that an expansion of current technology-centred 3D printing approaches toward multidisciplinary perspectives can extend their intrinsic potentials in the reaching of new sustainable scenarios. By meeting the societal transition process toward the so-called Sustainable Society, 3D printing can play a strategic role on the development of new production processes and ways of thinking, which can produce radical and large-scale human and social innovations.

Whilst both sustainable-oriented actions in 3D printing and in design recognize the strategic role of 'human factor' in the achievement of effective sustainable-oriented actions at the level of systems (i.e. development of new sustainable-oriented business models, transition studies, proper lifestyles, aware market demands, etc.), this study works on the hypothesis that an important improvement of the 'sustainable quality' of existing 3D printing services can be realizable by combining the HCD approach (human-centred design) (Goodwin 2009) with current advances in Design for Sustainability theories (i.e. PSSs (Product-Service Systems) (Ceschin and Gaziulusoy 2016) and SLOC (Small-Local-Open-Connected) Scenarios (Manzini 2003)).

According to current advances produced in 3D printing and Design for Sustainability domains, this paper aims to identify new research topics for human-centred Sustainable-Oriented 3D Printing. Specifically, this paper aims to:

- Produce evidences linking 3D printing technologies and sustainable design-oriented theories.
- Demonstrate the positive impacts of Design for Sustainability's theories in the advancement of 3D printing technologies—i.e. definition of 'Sustainable 3D Printing Scenarios'.
- Present a set of interdisciplinary 'Sustainable 3D Printing Systems' composing a promising sustainable-oriented scenario useful to support the transition toward sustainable ways of design, production and consumption.
- Develop a new strategy for the integration of humans into Sustainable 3D Printing System—behavioural transition toward sustainable consumption models—obtained by combining the main insights described by the HCD approach.

2 Methodology

Two main research methods have been combined in order to define the methodology used in this study: 'systematic analyses' (Denyer and Tranfield 2009) and 'exploratory designs' (Streb 2010). Systematic analyses, mainly operated via Literature Reviews and data systematizations, have been used to explore the theoretical frameworks of Design for Sustainability theories and Sustainable-Oriented 3D Printing advances. Later, exploratory designs have been produced to generate new groups of experimental data that have been subsequently used to set up promising sustainable design-oriented scenarios.

The use of a combined methodology is due to the intrinsic nature of this study: working on the development of proactive design-related multidisciplinary scenarios (inductive process) using the factual data mono-disciplinary studies (deductive process). As reported by Denyer and Tranfield (2009), the use of systematic review differs from other review methods because of its distinct and exacting principles; in this study, the systematic review was used in the first stage—deductive process—to develop an in-depth exploration of disciplinary relations within subjects and, later, to understand potential areas for cross-sectorial relations. The use of this method, rather than traditional Literature Review, is consistent with the will to develop comparable data from two very different disciplinary domains. Later, the use of exploratory designs was used to investigate situations or interventions which, a priori, have no clear or single sets of outcomes (Streb 2010; Seaton and Schwier 2014); the use of this method was also legitimated if compared with what discussed by Yin (2014): Exploratory designs are used to explain links that are too complex for surveys or experimentation.

As shown in Fig. 1, this study used an own quali-quantitative three-phase approach synthetically described below.

Phase 1 (Paragraphs 3): *Systematic review on Design for Sustainability and Sustainable-Oriented 3D Printing literature*. Data obtained in this phase have been used to define an overall picture of emerging sustainable-oriented theories and cutting edge production models based on 3D printing advances.

Phase 2 (Paragraph 4): *Development of a design scenario for Sustainable-Oriented 3D Printing Systems.* Data obtained in Phase 1 have been used to develop an interdisciplinary design-oriented scenario for 'Sustainable-oriented 3D Printing', where promising insights have been combined and later implemented in twenty 'Sustainable-Oriented 3D Printing Systems' and a number of 'Relevant Research Topics and Promising Design Opportunities'.

Phase 3 (Paragraph 5): *Methodological integration of human-centred design approach into Sustainable-Oriented 3D Printing Systems*. From data achieved in Phase 2, a later methodology has been developed in order to investigate the integration of HCD approach into Sustainable-Oriented 3D Printing Systems, which has identified holistic design topics combining human-centric sphere (i.e. human factors and tasks) with systemic one (i.e. solutions' semiotics, interactivities and meanings).

3 Literature Review

As part of the systematic analyses, the two synthetic Literature Reviews presented here investigate 3D printing's emerging sustainable-oriented studies and cutting edge Design for Sustainability theories. Data obtained have been used later to develop the design scenario for Sustainable 3D Printing, where insights have been combined into new theories.

3.1 Literature Review of sustainable-oriented studies on 3D printing

Sustainability-oriented 3D printing studies follow a quasi-vertical approach (i.e. mono-disciplinary explorations), which is the result of the 'traditional' technology-push industrial culture (Kamran and Saxena 2016) driving the innovation in the sector. Current state of the art of studies and industrial developments (i.e. Verganti 2009; Rifkin 2012; Canessa et al. 2013; de Jong and de Bruijn 2013; Gebler et al. 2014; van Wijk and

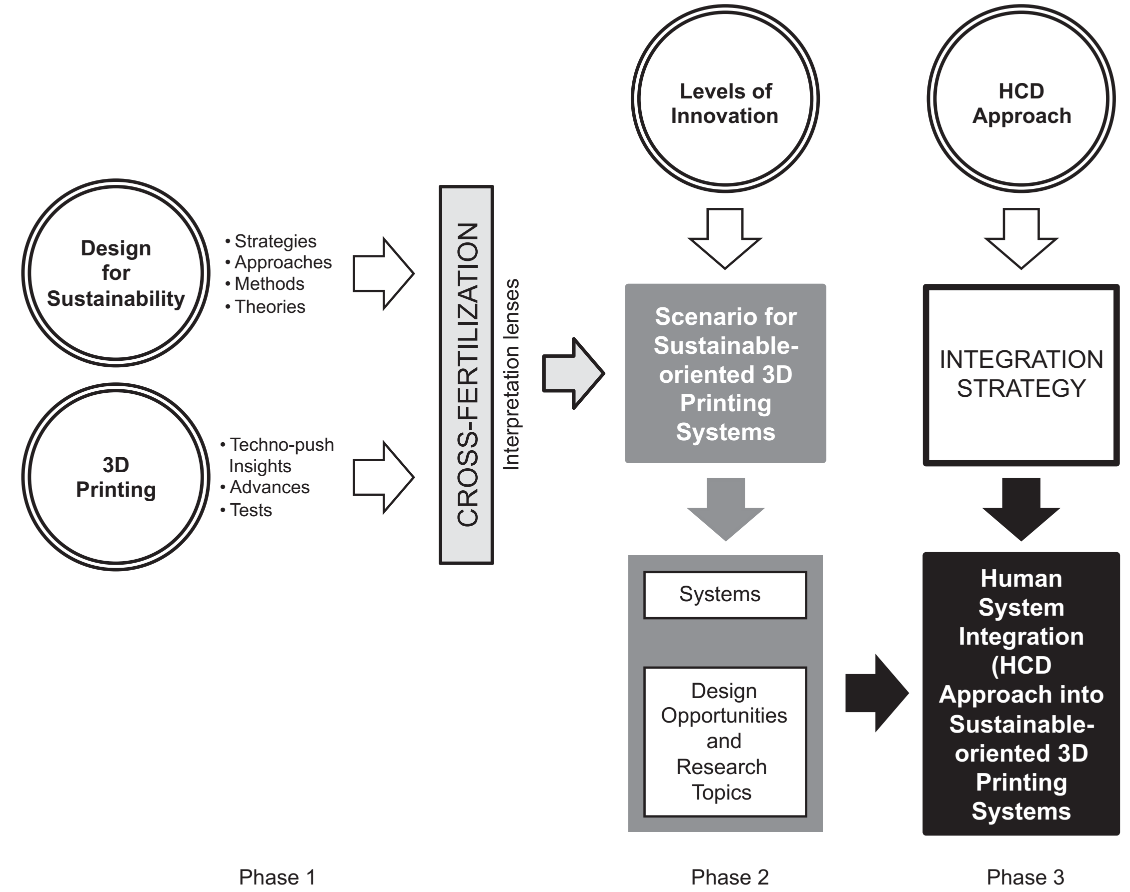

Fig. 1 Research structure

van Wijk 2015; Hager et al. 2016; Liu et al. 2016; Cerdas et al. 2017; Sakin and Kiroglu 2017; Jammalamadaka and Tappa 2018; Zhou et al. 2018; Rossi and Barcarolo 2019) show that the main innovations are focused[1] on the following:

- Innovation in engineering and engineering-related domains
- New technological components, including construction industry
- Low-cost and open-source 3D printing technology services
- Development of printable (bio)materials
- Technological improvements of production processes
- Circular economy's scenarios (i.e. recycling, low energy grids, etc.)
- Interdisciplinary applications (i.e. Inclusive Design)

In 3D printing domain, the main aspects related to Sustainable Development concerns the environmental protection (i.e. reduction/mitigation of production wastes), which are both directly and indirectly linked to the qualitative improvement of production processes (i.e. affordability and optimization), the (eco)compatibility of materials and the mitigation of the productions impacts on ecosystems. Only limited experimentations consider, simultaneously, the environmental, economic and social aspects of Sustainable Development—'three-legged stool' model. This analysis demonstrates that the environmental aspects are very easy to be taken into account in 3D printing industry and, then, systemic approaches covering all aspects of Sustainable Development are not always affordable for industrial production, if compared with the Returns of Investments (ROIs).

At large, the analysis of sustainability-oriented 3D printing studies have proven that a holistic approach could be useful to evolve the simplistic 'eco-qualities' — eco-characteristics— of 3D printing productions toward systemic and integrated approaches that consider all products' life cycle elements, including, but not limited to, (a) material supply, (b) design of solutions (i.e. solutions linking ecological aspects and socio-economic customers' needs), (c) process simplification, (d) respect of workers and (e) strategic design approaches helping the transition toward sustainable printable solutions connecting economic, environmental and social domains of Sustainable Development.

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

3.2 Literature Review of theories on Design for Sustainability

In last three decades, Design for Sustainability discipline increased its impact in the development of application at all scales: from the design of eco-friendly productions (early studies in late 1980s) to the design of complex solutions for system innovation. Many studies have been developed both by researchers and by research communities.[2] Whilst the environmental impact of products and production processes is still a key factor (i.e. cleaner productions, minimisation of wastes, recycling approaches, etc.), today it is no longer considered as sufficient to pursue the goals of sustainable productions; systemic approaches are more considered as effective and then preferred.

The analysis of studies in design helps to understand main sustainable-oriented approaches for creating sustainable solutions (i.e. products, services, research tools, strategies and design-oriented competitive business models). The synthetic Literature Reviews are therefore focused on seven theories that are considered significant for current disciplinary studies and for the purpose of this study:

- Eco-Design (for new products)
- Design for Sustainable Behaviours
- Biomimicry Design
- Product-Service Systems
- Small-Local-Open-Connected Scenarios
- System Design for Sustainability
- Design for Systems Innovations and Transitions

Eco-Design is a design approach focused on the whole life cycle of products (from the extraction of materials used to produce goods to the disposal of their parts and components) using, for example, LCD (Life Cycle Design) and LCA (Life Cycle Assessment) (Pigosso et al. 2015). Eco-Design aims to mitigate the environmental impact of products, as well as to minimize the consumption of natural resources by investigating, through LCA methodologies, the phases that generate the most 'critical' environmental impacts and, then, by providing strategic insights to design in a mitigation perspective.

As reported by Ceschin and Gaziulusoy (2016), which quote Brezet and van Hemel (1997) and Binswanger (2001), in Eco-Design the environment has the same status as more traditional industrial values such as profit, functionality, aesthetics, ergonomic performance and overall quality. On the methodological point of view, the Eco-Design implementation is often operated using sets of principles, guidelines, criteria and research tools (i.e. Manzini and Vezzoli 1998; Vezzoli and Manzini 2008).

[2] See, for example, the Learning Network on Sustainability International (LeNS) (https://www.lens-international.org).

Design tools and approaches supporting the development of sustainable behaviours on customers—behaviour change—to support the ecological effects generated by ecological design strategies (i.e. LCD) compose *Design for Sustainable Behaviours* (Lockton 2013).

Biomimicry Design (often known as Bio-inspired Design) uses natural models as a resource to develop solutions solving human problems through ecological standards. Nature-inspired elements are used to judge the 'correctness' of innovations. There is a clear analogy between this design approach and the ecological evolution of biological models; the hypothesis subtended Biomimicry Design is that nature has learnt what works and what is appropriate and, therefore, the use of nature-inspired analogies can become an effective way to develop eco-efficient solutions. In these terms, Biomimicry Design is closer to the design of emulative biology-based solutions—natural and/or evolutionary innovations.

Referring to the studies developed by Janine Benyus (1997), Biomimicry Design uses three different levels to produce the innovation: (a) formal mimicking (solutions' shapes and proportions have a clear analogy with the natural domain), (b) process mimicking (solutions uses functional analogies with biological systems) and (c) (eco)systemic mimicking.

Design of Product-Service System (PSS) concept aims to minimize environmental impacts of both productions and end-users' consumptions using marketable sets of products and services able of jointly fulfilling end-users' needs (Goedkoop et al. 1999). According to Mont (2002), 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.

As discussed by Mont (2002) and Ceschin (2012, 2014), there are different benefits to developing PSSs for manufacturing companies; for example, PSSs are able to: (a) increase the product's value, (b) base growth strategies on innovation in mature industries, (c) improve relationships with consumers, (d) improve the value for customers (increased servicing and service components extend its function) and (e) anticipate the implications of future take-back legislation.

Proposed by Ezio Manzini (2010, 2015), *SLOC (Small-Local-Open-Connected) Scenario* is a sustainable-oriented design model where emerging global phenomena are intersected with three main innovations: (a) the green revolution (and the environmentally friendly systems it makes available), (b) the spread of networks (and the distributed, open, peer-to-peer organizations it generates) and (c) the diffusion of creativity (and the original answers to daily problems that a variety of social actors are conceiving and implementing).

SLOC Scenario leads toward sustainable solutions indicating 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. On this matter, Manzini (2010) often refers to the 'GLocal'—acronym of Global-Local—which is a complex design-oriented sustainable scenario connecting local values/issues and global conditions/opportunities. Accordingly, SLOC Scenario promotes context-based forms of sustainable wellbeing where local values are interconnected with global market and systemic actions generate clear and positive effects on local economies.

As described by Vezzoli (2010), *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 product services that are sustainable from the environmental, social and economic point of view.

SDS can be developed using, for example, the specific 'Method for System Design Sustainability' (MSDS) (Vezzoli et al. 2009, 2014; Ceschin and Gaziulusoy 2019), and its key elements are as follows: (a) customer satisfaction (satisfaction unit) intended as a 'reference', (b) interaction between stakeholders as a 'subject' and (c) the sustainability as a 'goal'.

Finally, *Design for Systems Innovations and Transitions* embodies PSSs Design and Design for Social Innovation to transform socio-technical systems using technological, social, organizational innovations (Gaziulusoy and Brezet 2015).

4 Development of a design scenario for Sustainable-Oriented 3D Printing Systems

The development of the *design scenario for Sustainable 3D Printing Systems* ($DS_{(S3DPS)}$) has been created using 'cross-fertilization processes' (Celaschi and Deserti 2007) and 'exploratory designs' (Streb 2010), by combining Design for Sustainability research approaches (DfS) with Sustainable-Oriented 3D Printing technological advances (3DP) (Rossi et al. 2020) (Formula 1).

$$DS_{(S3DPS)} = DfS \cap 3DP$$

On the methodological point of view, the cross-fertilization process used to define the design scenario aimed to generate both vertical and horizontal meaningful innovations, as also recommended by Verganti (2009). The interpolation process followed two main phases, which are synthetically described below:

- Individuation of 'Levels for Sustainable Innovation' describing the macro-areas and the interdisciplinary connections between domains of socio-technical innovation, useful to set sustainable-oriented transitions
- Development of 'Design Opportunities for Sustainable-Oriented 3D Printing Systems', which compose the sustainable scenario for promising applications and developments (multilevel topics)

4.1 Individuation of Levels for Sustainable Innovation

Six 'Levels for Sustainable Innovation' (Fig. 2) have been defined with the aim to explore and understand the disciplinary and the interdisciplinary dimensions of possible sustainable-oriented design interventions. These levels explore the sustainable design-oriented actions in two manners: (a) vertical explorations and (b) interdisciplinary explorations. For all six levels, some 'strategic factors' address the exploration of focused topics (Table 1).

Vertical exploration mainly refers to the disciplinary exploration of technological, economic and organizational factors. Vertical explorations are fundamental to understand the relations between disciplinary insights and thematic-push factors driving the potential sustainable innovation in each level. Levels obtained from vertical explorations are as follows:

1. Technological Level, which is useful to promote technology-driven vertical and semi-vertical actions
2. Economic Level, which is useful to encourage the adoption of aware business models and multi-scalar development actions
3. Organizational Level, which is useful to explore and scale the effect of bottom-up community-centred actions

Interdisciplinary exploration refers to the cross-sectorial combinations of technological, economic and organizational factors; interdisciplinary explorations are useful to explore the multidimensional relations between emerging multidisciplinary insights driving the sustainable innovation in each level. Levels obtained from interdisciplinary explorations are as follows:

1. Techno-economic Level, which is useful to explore technology-centred business models
2. Socio-economic Level, which is useful to include and explore sets of value-based interactions and participative business models into design actions
3. Techno-organizational Level, which is useful to explore the impact of technology-supported systemic interactions of networks and assets

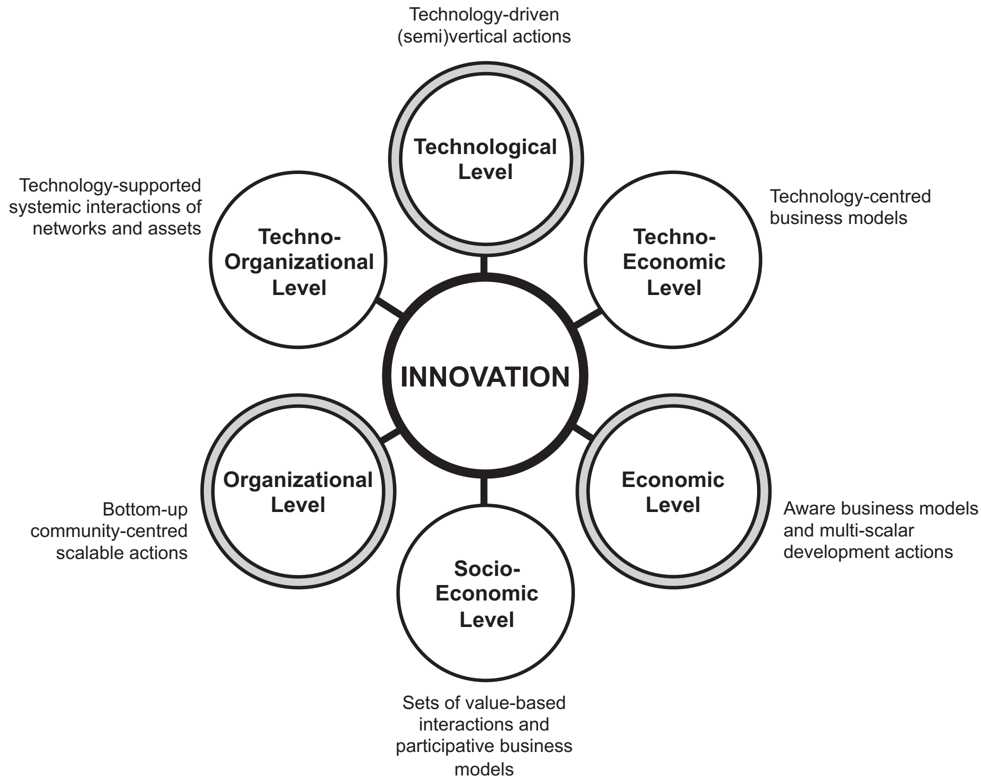

Fig. 2 Six Levels for Sustainable Innovation

In the later stage of the data development, the collected Driving Factors have been used to generate focused insights for the development of 'Relevant Research Topics and Promising Design Opportunities' in scenario where Sustainable-Oriented 3D Printing Systems can operate (see 4.2.).

4.2 Development of the scenario for Sustainable 3D Printing: definition of design opportunities for Sustainable-Oriented 3D Printing Systems

As shown in Table 2, twenty different 'Sustainable-Oriented 3D Printing Systems' and a number of related 'Relevant Research Topics and Promising Design Opportunities' compose the scenario for promising applications of Sustainable 3D Printing—which is a scenario valid if and only if conditions of Sustainable Development will be reached using competitive business models.

The multidisciplinary sustainable scenario for Sustainable-Oriented 3D Printing Systems presented here—a scenario where the idea of Sustainable Development generates social innovations, wellbeing-oriented economic models and new forms of production systems—aims to create a multidimensional operative context to act both at the strategic level of production systems (i.e. macro-productions) and at the micro level of design (micro-making); the idea is to create a set of data usable by designers[3] and researchers to the advancement of current state of the art in the industrial and non-industrial studies.

Both systems and related topics/opportunities have been therefore intended as open design and research themes to be taken into account in order to support the transition processes toward sustainable-oriented multilevel production systems for promising 3D printing-based applications and designs.

5 Methodological integration of human-centred design approach into Sustainable-Oriented 3D Printing Systems

As briefly introduced before, the integration of the so-called human factor into the scenario for Sustainable-Oriented 3D Printing Systems is strategic for the achievement of effective sustainable-oriented actions at the level of systems, since it supports both the development of new sustainable-oriented business models and the exploration of promising transition studies, wellbeing-based sustainable lifestyles, aware market demands, etc.

[3] The term 'designer' is here used in its broader meaning as 'someone able to ideate and realize a new solution, or a solution significantly better than existing ones'.

Table 1 Levels for Sustainable Innovation

Technological Level (technology-driven semi-vertical actions)	Techno-economic Level (technology-centred business models)	Economic Level (aware business models and multi-scalar development actions)	Socio-economic Level (sets of value-based interactions and participative business models)	Organizational Level (bottom-up community-centred scalable actions)	Techno-organizational Level (technology-supported systemic interactions of networks and assets)
Strategic factors • Bio- and eco-driven emphasis • Technological pushes • Systems' performances and effectiveness • Technology-led iterations and/or incremental processes • Purely vertical and/or vertical aligned innovations • Radical technological advances and epiphanies • Product-service smart integrations • Cyber-physical systems' integrations • Responsive solutions • Technology-led investments • R&D on systems	Strategic factors • Technology-led aware business models • Industrial transitions toward sustainable productions • Productions' effectiveness and efficiency • Technology-driven competitiveness • Design- and technology-driven innovations • Efficiency of processes' life cycles • Optimization of resources (based on techno-processes) • R&D for eco-innovations • Networked manufacturing • Redundancy reduction • Technological dematerialization	Strategic factors • Sustainable economic wellbeing • Community growth • Development of new skills • Sharing economy • Explicit and tacit knowledge sharing and management • Systemic resiliency (capability) to transition actions • Human development (as an asset) • Networked development • Quality-oriented contextual business models • Systemic self-recovery capability • Shift from 'personal possession' to 'public access/use' • Investment in local resources and growth	Strategic factors • Community building • Open source solutions and 'copyleft' behaviours • Reuse of existing local values (revitalization of traditions and heritages) • Co-generation of business models • Collective intelligence • Participative business models • Community development • Autopoietic capability of systems • Interdisciplinary and holistic actions • Variability and diversification (support of)	Strategic factors • Human wellbeing and increasing of the quality of life • Social justice • Community strength and social cohesion • People's rights and collective participation • Human direct involvement • Community's dignity • Participative welfare • Democracy-oriented actions • Collection of best practices • Scalable social models (replication of likely conditions) • Access to information • Fair management • Investment in social activities and human development • Qualitative development and social innovation • Updating and replacement	Strategic factors • Technology-supported community-oriented actions • Social networking • Co-development of technical assets • Social computing • Technology-mediated collective interactions • Collective intelligence to supporting social actions • Sharing of contextual assets (solutions for) • Service- and network-based communities • Techno-tools for wellbeing-oriented interventions •Democratization of advanced technologies • Complexity reduction • Technological transparency

As stated in the introductory part of this paper, and according to what has been discussed by Jasiulewicz-Kaczmarek and Saniuk (2015), Tatcher (2017), Thatcher and Yeow (2016, 2018), Tatcher et al. (2017), Cheah et al. (2018) and ISO (2019a), the so-called human factor plays an important role on systems, and it can—by deduction—strategically improve the 'sustainable quality' of 3D printing systems. Thus, the integration process followed two main phases:

- Development of the 'Strategy for the integration of HCD approach into Sustainable-Oriented 3D Printing Systems'
- Methodological experimentation on 'Design Opportunities for Sustainable-Oriented 3D Printing Systems'

5.1 Strategy for the integration of HCD approach into Sustainable-Oriented 3D Printing Systems

The integration of the 'human dimension' into Sustainable-Oriented 3D Printing Systems has been operated combining the HCD approach with Systems' Relevant Research Topics and Promising Design Opportunities, which are directly and indirectly linked to current advances in Design for Sustainability theories and the Manzini's SLOC Scenarios (Manzini 2003). Accordingly, this methodological integration will link to the following: Design for Sustainability, 3D Printing and HCD.

As reported by the introductory section of ISO 9241-210 (2019b), HCD is:

Table 2 Sustainable 3D Printing Scenario: Design Opportunities for Sustainable-Oriented 3D Printing Systems—based on Rossi et al. (2020)

Sustainable-Oriented 3D Printing Systems	Relevant Research Topics and Promising Design Opportunities (not limited to)
1. Eco-inspired and/or biomimetic 3D printing systems	• Research, design and development for bio-/eco-inspired products, services and product-service systems (using/supporting 3D-printed systems) • Research and development for bio-/eco-inspired production processes (using 3D-printed systems) • Research, design and development for bio-/eco-inspired life cycles (using 3D-printed systems)
2. Dematerialization-based and function-oriented 3D printing systems	• Reduction- and dematerialization-based design strategies (i.e. light-weight approach) • Combination of service-based solutions to improve the systems' effectiveness • Mitigate the production of tangible goods and switch toward service-oriented solutions • Introduction of goal-oriented approaches (innovation driven by the achievement of goals instead by the production of objects) • Development of Sustainable Product-Service Systems (SPSSs)
3. Integrated 3D printing systems for sustainable productions	• Integrated 3D printing systems (and/or sets of solutions) improving the eco-efficiency of industrial products/production • Integrated 3D printing systems (and/or sets of solutions) to boost the socio-technical factors related to industrial products/productions • Multilevel 3D printing systems (and/or sets of solutions) to optimize the design and the engineering of products/productions • New business models supported by integrated 3D printing systems • Robotic autonomous 3D printing production processes (i.e. cyber-physical systems)
4. Sustainable industrial development through 3D printing.	• Industrial processes' sustainable innovation through 3D printing systems • Use of 3D printing-based manufacturing processes for the upgrading of industrial productions • Introduction of transition-oriented competitive business models for the innovation of industrial productions • Use of LCD/LCA for the development of 3D printing-based new industrial processes • 3D printing for distributed manufacturing in regional/local productions • Development of regional/local industrial clusters
5. Sustainable innovations on essential networks	• Use of 3D printing in energy productions • Development of power grids' eco-efficiency and effectiveness • Improvement of hydric infrastructures' eco-efficiency and effectiveness • Boosting the innovation in sustainable-oriented networks • Innovative healthcare systems for human sustainable wellbeing • Mitigation in the consumption of new lands (and intelligent reuse of existing spaces/resources) • Optimization of transportation, supply and distribution systems
6. 3D printing systems supporting the sharing of local values in GLocal business scenarios	• GLocal-oriented co-design for the economic emancipation • GLocal growth supported by the co-development (co-design) of strategic actions • Empowerment of economically sustainable GLocal forms of entrepreneurship through human capital development • GLocal rediscover and promotion of context-based productions • Codification and sharing of autochthonous production techniques and skills (projection of local elements to global scenarios) • Context-based solutions to empower the GLocal businesses
7. Sustainable 3D Printing Systems using local resources to support Circular economies	• Eco-compatible and/or biomaterials (zero impact strategy) • Autopoietic GLocal production networks based on local collective intelligence • Co-creation and sharing of tangible resources and intangible assets • B2B services for SMBs and SMEs • Resilient business models mixing Social Inclusion and Social Innovation
8. Sustainable systems generating open 3D-printed innovations	• Boosting local heritage through the creation of context-based innovations • HCD-based business solutions promoting inclusive and sustainable socio-techno-economic forms of sustainable wellbeing • Introduction of sustainable open ideas in 4.0 scenarios • GLocal forms of business to support the identity of stakeholders • Services for converting and the sharing know-how/best practices
9. (Systems of) Learning platforms for sharing knowledge	• Accessible platforms for sharing best practices, case studies, practical experiences and pedagogical tools • Design and development of solutions for stimulating autonomous self-learning (even using modern IoT-/AI-based solutions) • Autopoietic learning systems and platforms for sharing open know-how

Table 2 (continued)

Sustainable-Oriented 3D Printing Systems	Relevant Research Topics and Promising Design Opportunities (not limited to)
	• Learning platforms for gathering, converting and sharing tacit knowledge • Accessible databases to gather open knowledge on goal-oriented topics • Collaborative learning platforms (based on stakeholders' collective intelligence)
10. Accessible 3D printing systems	• Accessible and usable 3D printing systems (and their sub-parts: products, services, distribution networks, supply chains, etc.) • Research and design of low-cost 3D printing systems • Research and design of DIY 3D printing systems • 3D printing systems based on collective intelligence and values sharing • 3D printing supporting the launch on new entrepreneurships • Development of economically affordable new business models (transitions from unsustainable/semi-sustainable business models into promising sustainable ones)
11. 3D printing systems supporting GLocalism's empowerment	• Systems of solutions supporting the development of skills and work-related abilities (for 3D printing-based GLocal business) • GLocal-oriented sharing of local resources • Resilient systems for the revitalization of rural areas through competitive Sustainable 3D Printing-based business models • GLocal platforms to boost context-based economies (based on 3D printing production processes) • Sustainable business models for the right pricing of local resources/products (fair 3D printing-based market competitiveness)
12. 3D printing systems for the Sustainable Development of rural areas	• 3D printing-based systems for the sustainable and strategic promotion of local heritage • 3D printing-based systems for the development of 'slow'—context-based—forms of economies • Learning solutions for the development of new skills • Resilient systems for the reconversion of skills (i.e. post-crisis economic scenarios) • 3D printing-based systems for emerging and developing countries.
13. 3D printing-based distributed economies and/or large-scale strategic systems supporting GLocalisms	• GLocal smart platforms linking top-down actions and bottom-up needs • GLocal technologies (technological democratization 'for all') • Resilient collaborative infrastructures to support scalable and flexible forms of entrepreneurships • Development of distributed forms of open intellectual capitals (i.e. copyleft)
14. Community-oriented 3D printing systems	• 3D printing systems for Communities of Practice (CoP) • 3D printing systems for Communities of Interest (CoI) • Community-oriented 3D printing solutions for the production of goods and mixed solutions (i.e. PSSs) • Community-oriented new business models based on the use of 3D printing solutions
15. Distributed 3D printing systems for basic necessities	• Distributed 3D printing systems for the production of primary goods • Distributed 3D printing systems to contrast poverty and low-income conditions • Distributed 3D printing systems to mitigate emergency scenarios (i.e. post-earthquakes scenarios) • Distributed 3D printing systems to develop affordable solutions for basic needs • Distributed food manufacturing systems • Health-oriented and/or biological production systems
16. Inclusive 3D printing systems	• Diversity-inspired 3D printing systems operating on GLocal scenarios/markets (using diversity as a resource) • Community-centred 3D printing systems based on context-based scenario and bottom-up needs • Need-based economies supported by 3D printing systems • Socially inclusive 3D printing systems • 3D printing systems 'for all' • Affordable 3D printing systems to prevent child labour
17. Networked 3D printing systems for personal and collective health	• Development of platforms supporting human healthcare systems • Application of networked 3D printing systems to support housing-related issues in emerging and developing countries • Autopoietic networks for fair collaborations and sharing of know-how (i.e. CoP, Wikis, etc.) • Networked 3D printing systems for sanitary purposes • Networked innovations in emerging and developing countries
18. Eco-intelligent 3D printing systems	

Table 2 (continued)

Sustainable-Oriented 3D Printing Systems	Relevant Research Topics and Promising Design Opportunities (not limited to)
	• Smart solutions supporting eco-efficient 3D printing systems (i.e. IoT-/AI-based solutions) • Human-centred solutions to improve the impact of 3D printing systems at micro scales • Product-Service Systems for 3D printing-based distributed manufacturing • Integration of 3D printing systems in operative formal and informal environments/products
19. Humanized systems for 3D printing	• Human-centred 3D printing systems • Sustainable and usable 3D printing systems (i.e. solutions making users and sustainable processes closer) • Ergonomically performing 3D printing systems • Humanized eco-friendly 3D printing systems (i.e. AI-based) • Bio-3D printing • Adaptive 3D printing systems
20. Trans-disciplinary issues for 3D printing advances	• Trans-disciplinary studies and applications on the role of 3D printing (i.e. goal-oriented issues concerning recent advances of 3D printing and inter-, multi-, intra-sectorial disciplines)

> […] an approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques. This approach enhances effectiveness and efficiency, improves human wellbeing, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects of use on human health, safety and performance.

On the methodological point of view, Giacomin (2014) describes the HCD approach using a hierarchical pyramid scheme, the 'human-centred design pyramid' (Fig. 3), containing a set of questions regarding the relationships between end-users and artefacts:

> […] the classical rhetorical questions of antiquity of Quis (who), Quid (what), Quando (when), Quem ad Modum (in what way) and Cur (why) have been associated with current design semantics to structure the growing layers of complexity. This new interpretation of human centred design is based on a hierarchy which has at its base the scientific facts about human physical, perceptual, cognitive and emotional characteristics, followed by progressively more complex, interactive and sociological considerations.

This interpretation is important because it introduces new insights for the further integrations with complex systems.

Therefore, the strategy here proposed for the integration of HCD approach into Sustainable-Oriented 3D Printing Systems will combine the five HCD questions—Who, What, When, How, Why—with the insights contained in the Design Opportunities for Sustainable-Oriented 3D Printing Systems, as described in the Fig. 4. The idea is to qualitatively

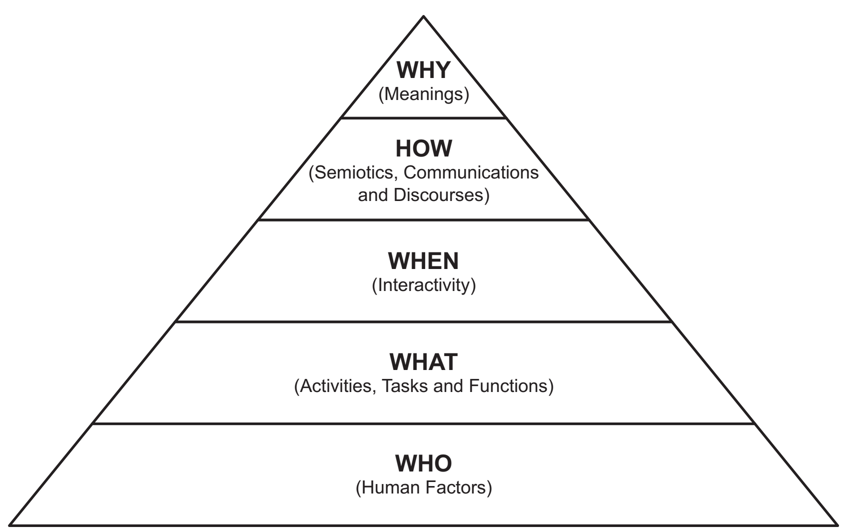

Fig. 3 HCD pyramid (redesigned from Giacomin 2014)

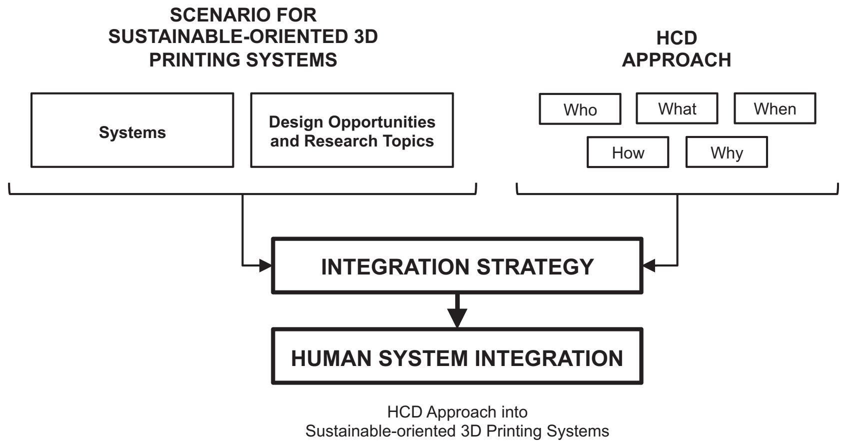

Fig. 4 Strategy for the integration of HCD approach into Sustainable-Oriented 3D Printing Systems

increase the human aspects of Sustainable-Oriented 3D Printing Systems, supporting the theories on transitions studies and context-based sustainable wellbeing contained into the Design for Sustainability literature (i.e. Manzini 2010, 2011), as well as to propose a clear and flexible strategy for any further integration of HCD into complex production systems.

5.2 HCD integration into Sustainable-Oriented 3D Printing Systems: results

The methodological experimentation of the Strategy for the integration of HCD approach into Sustainable-Oriented 3D Printing Systems has been conducted on all twenty Sustainable-Oriented 3D Printing Systems described in Table 2, in order to explore potential theoretical-methodological conflicts and to validate the consistency of the proposed insights into the framework set-up before.

To provide a synthetic overview of the extensive outcomes achieved in this study, Table 3 shows the results obtained for the Sustainable-Oriented 3D Printing System No.1: 'eco-inspired and/or biomimetic 3D printing systems'. As can be seen, for each HCD question, a number of 'topics for integrating HCD approach into Sustainable-Oriented 3D Printing Systems' provide a clear strategy to integrate the 'human dimension' and the 'human factor' into such productive sustainable systems. In particular, the insights contained in the right part of the table have been presented as open questions and/or exploratory design actions, with the aim to generate the right grade of flexibility within improvement actions (Human System Integration—HSI).

6 Conclusions and discussions

This study achieved two groups of significant research results. The first important research result concerns the development of a design scenario for Sustainable-Oriented 3D Printing, which is composed by a number of promising Sustainable-Oriented 3D Printing Systems and a set of focused Relevant Research Topics and Promising Design Opportunities for subsequent sustainable experimentations. The second important research result concerns the integration of the so-called human factor into Sustainable-Oriented 3D Printing Systems, obtained through the development of a Strategy for the integration of HCD approach into Sustainable-Oriented 3D Printing Systems, which links Design for Sustainability, 3D Printing and HCD. In particular, this last result integrates and extends the meaning of HSI by bridging the contribution of design discipline into the design research on complex production systems.

The analysis of the first group of research results shows that the concept of Sustainable-Oriented 3D Printing—and related systems as here described—can produce significant innovations and impacts both in industry and in informal sustainable-oriented contexts (i.e. SMBs, GLocal interventions and productions, etc.), if properly implemented using aware business models, context-based resources, systemic intelligence and smart technologies; this indeed is in line with current Design for Sustainability strategic approaches (i.e. Manzini and Jégou 2003; Vezzoli 2010; Ceschin 2014). As the need of sustainable solutions will continue to increase, the new Sustainable-Oriented 3D Printing Systems will play a strategic role by increasing the quality of networked, hybrid and SLOC-oriented scenarios.

By presenting 'Relevant Research Topics and Promising Design Opportunities for Sustainable-Oriented 3D Printing Systems', this study defined a complex and extensive design scenario where, in the next years, new cross-sectorial studies on design, economics, engineering, chemistry and materials science will and could converge. In addition, the results achieved in the first part of the study have proven that if conditions of Sustainable Development will be reached using competitive business models linking current 3D printing advances with novel and holistic Design for Sustainability's research insights, the

Table 3 Human integration into 'eco-inspired and/or biomimetic 3D printing systems'

HCD framework (key questions)	Topics for integrating HCD approach into Sustainable-Oriented 3D Printing Systems
'Who' (human factors)	•End-users' role -Understanding end-users' choosing factors (will and need to use) -Understanding end-users' purchasing and consuming factors -Understanding how to generate empathy and emotions with/through systems -Understanding how to actively involve end-users within systems' processes •Bio-driven human factors -Understanding how nature and biological factors can improve the systems' affordance -Understanding how to improve the affection with systems -Understanding how to improve the systems' usability -Understanding how bio-inspired factors can mitigate the human errors and the cognitive workloads -Understanding how natural cycles can support the development of bio-organizational factors •Human's needs and desires -Understanding how nature and the ecological instances influence humans' needs -Understanding how to boost socio-cultural aspects of systems -Understanding how to improve human identity in the interactions with the systems •Symbioses between humans and natural elements -Understanding how to interpret natural cycles to develop consistent symbioses between humans and systems -Understanding how to interpret natural times to improve the awareness and the consistency of systems -Understanding how to generate coherent meanings to improve human factors
'What' (activities, tasks and functions)	•Ecology-driven functions, tasks and activities -Exploring ecologically compatible activities, tasks and functions -Exploring ecologically efficient activities, tasks and functions -Exploring ecologically aware activities, tasks and functions -Exploring bio-inspired activities, tasks and functions -Exploring mimetic activities, tasks and functions -Exploring organic activities, tasks and functions •Systems' integration with environment(s) -Exploring the integration of systems' activities, tasks and functions -Exploring the combinability of systems' activities, tasks and functions -Exploring the co-existence of systems' activities, tasks and functions -Exploring the simplification of systems' activities, tasks and functions -Exploring the optimization of systems' activities, tasks and functions •Mimetic/analogical approach -Exploring mimetic activities, tasks and functions -Exploring goal-oriented activities, tasks and functions using natural analogies -Exploring cyclical activities, tasks and functions
'When' (interactivities)	•Natural relations and bio-interactions -Understanding natural relations and bio-interactions with systems and their parts -Understanding end-users' interactions with bioactivities -Understanding nature-oriented behavioural patterns to support bio-interactions -Understanding how to strengthen and enrich nature-driven feedbacks from systems -Understanding systems' natural usability (effectiveness, efficiency and satisfactions) -Understanding how to develop bio-inspired interactions using local natural elements -Understanding how to give consistency and affordance to natural relations and bio-interactions -Understanding hot to generate meaningful natural relations and bio-interactions -Understanding interactivity of natural realm for their conversion within systems -Understanding how to reduce the psychophysical distance with interactive stimuli -Understanding interactivities' comfort and pleasantness •Bio-emulations (for next system(s) development) -Understanding the biology of the ecosystem where the activities will be developed -Understanding natural mechanisms, cycles and patterns -Understanding natural patterns to develop consistent interactivities -Understanding bio-languages and bio-communication -Understanding evolution patterns -Understanding (self-)learning mechanisms •Nature supporting new products and systems' functioning -Understanding natural stimuli and communication (i.e. feedbacks, warnings, affordances, synesthetic combinations, etc.) -Understanding interactivities of natural patterns into bio-systems -Understanding systemic bio-relations within ecological systems

Table 3 (continued)

HCD framework (key questions)	Topics for integrating HCD approach into Sustainable-Oriented 3D Printing Systems
'How' (semiotics, communications, discourses)	•Incorporation of natural cycles into systems -Understanding how to incorporate natural key elements into visible communicative elements -Understanding natural cycles for the development of new semiotics •Semantic analogies with natural cycles -Understanding natural patterns and cycles to produce consistent communications -Understanding natural stimuli and communication (i.e. feedbacks, warnings, affordances, synesthetic combinations, etc.) -Understanding natural behaviours to generate straight communications (fully understandable) -Understanding natural patterns and stimuli to produce coherent affordances and environmental stimuli -Understanding natural semantics to produce inclusive operating environments •Ecology-driven aesthetics -Understanding natural proportions and aesthetic relations -Understanding ecological schemes and links among systems' parts (overall aesthetics) -Understanding how to convert natural ecological canons into systems' semiotics •Use of coherent multisensory feedbacks -Understanding how to improve systems' quality using natural stimuli and responses -Understanding pros and limits of multisensory communication -Exploring the comprehensibility of vertical communications (mono-sensory) and horizontal (multi--sensory) -Understanding the effects of time on multisensory stimuli -Understanding the pleasantness of multisensory feedbacks (strategies for combination) •Eco-semiotics -Understanding how to incorporate natural stimuli into systems' semiotics -Understanding hot to generate consistent communications within systems' elements -Understanding natural semiotic patterns (conversion into systems' components)
'Why' (meanings)	•Functional and procedural meaningfulness -Understanding how to development systems' consistent functions and tasks -Understanding how to support the development consistent system-related meanings -Understanding how to add value to systems' functions and tasks •Nature-inspired awareness and belonging -Understanding how to generate belonging and empathy on systems using meaning-driven natural elements -Understanding nature as element to generate socio-technical awareness and belonging -Understanding how to generate eco-driven identities •Normalization of natural cycles into human activities -Understanding how to convert natural cycles into meaningful systems' elements -Understanding human-natural symbioses (to be included into systems) -Understanding how natural patterns can qualitative improve human activities and habits •Eco-branding of bio-systems -Understanding how to improve bio-systems using ecological branding strategies -Understanding ecologically inspired promotion strategies -Understanding how to develop ecologically compatible branding strategies

proposed scenario can produce significant impact in the way designers and researchers could operate together to generate sustainable solutions.

On the other hand, the analysis of the second group of research results has proven that even in some very complex systems, like the one described in by Sustainable-Oriented 3D Printing Systems, the 'human factor' can increase the overall quality systems; this can be obtained, for example, by operating a methodological integration with the HCD approach, which is one of the most used design approaches used in design discipline, able to produce effective and usable solutions—i.e. ergonomically correct (Cooley 1989; ISO 2019b; LUMA Institute 2012).

Moreover, the use of the HCD approach in the integration strategy with Sustainable-Oriented 3D Printing Systems proves that it is possible to create focused interdisciplinary connections between sustainable-oriented production systems and the HCD discipline itself, bringing more the attention even on the 'humans factors' of design interventions. As it has been shown in the 'topics for integrating HCD approach into Sustainable-Oriented 3D Printing Systems' of Table 3, the above-mentioned integration strategy has allowed to cover both techno-centric aspects of Sustainable 3D Printing-based productions (i.e. sustainable supply of eco-compatible printable materials, eco-efficient delivery systems, etc.) and the human-centred ones, which explore the implications of such systems and productions with human-related issues (i.e. sustainable-driven end-users' purchasing and consuming factors). Accordingly, the integration of the HCD approach into Sustainable-Oriented 3D Printing Systems is fully in line with the new sustainable idea of HSI.

In terms of overall quality of the results for HSI domain, this methodological study can be considered relevant since it opens new research paths and interdisciplinary links between engineering and design disciplines. Whilst this study also provided an initial outline of the achievable results, extensive explorations with real case studies could be very useful to understand, for example:

- The coherence of the research framework here presented and discussed only for Sustainable-Oriented 3D Printing Systems—extension in other production HSI-related domains, beyond 3D Printing, Rapid Prototyping and Additive Manufacturing.
- The correctness of information developed for the domain of Sustainable-Oriented 3D Printing Systems in relation to the 'human factor'—beyond the general quality and the correctness of the results in techno-centric domains, an important element would also concern the correctness of data even on the human side of productive systems.
- The routes needed to operate research-driven standardizations of Sustainable-Oriented 3D Printing processes within industrial domains.
- The sets of actions needed by industrial stakeholders to vary their actual production layouts and processes in the way of sustainability.

In terms of further applications, research improvements and methodological opportunities for transitions studies, it is important to point out that this study could allow the development of remarkable results and the investigation of unexplored research issues, for instance:

- Development of metrics and quali-quantitative tools to evolve the methodological insights introduced in this study into comparable data; this would make qualitatively and quantitatively verifiable the insights and the results developable within the Scenario for Sustainable 3D Printing. For example, understanding if 3D printing systems for Communities of Practice can produce effective improvements and sustainable transitions in the way through which people develop items, use personal products and share information with other communities' members; this will help to understand whether, how and when to stimulate the collective intelligence and the adoption of sustainable behaviours.
- Development of standards and key performance indicators (KPIs) combining insights from Sustainable 3D Printing Scenarios and HCD; this would reinforce the above-discussed elements whilst producing the first set of references—i.e. industrial standards, design criteria, etc.—useful to totally control the new HCD-based Sustainable 3D Printing processes. For example, the development of a set of KPIs for inclusive 3D printing systems—see Table 2—would allow to verify the grade of 'inclusiveness' of printable solutions (i.e. respect of human dimension, prevention of social stigmas, valorisation of human conditions, meeting of real/special needs, grade of stakeholders participation, etc.).
- Refinement of knowledge and useful information with and through case studies—generalization of the knowledge framework. For example, this could be very useful if aimed to understand:

- The impact in emerging and developing countries (i.e. how Sustainable 3D Printing can boost the industrial transition toward sustainable business models)
- The impacts on COPs and COIs (i.e. how new 3D printing-oriented sustainable business models can be personalized according to new HCD-based insights)
- The impact on services and services design, including hybrid solutions like PSSs and sustainable PSSs
- The use of cross-sectorial pedagogical processes and validation paths to understand how to improve current educational programs revolving around 3D Printing, Rapid Prototyping and Additive Manufacturing

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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