Technological Forecasting & Social Change

Social Impacts of Additive Manufacturing : A Stakeholder-driven Framework

--Manuscript Draft--

Manuscript Number:	TFS_2020_70R2
Article Type:	Research Paper
Keywords:	Additive manufacturing, Social, Impacts, Stakeholders, Critical review
Corresponding Author:	helena carvalho Universidade Nova de Lisboa Faculdade de Ciencias e Tecnologia Caparica, Portugal
First Author:	Bardia Naghshineh
Order of Authors:	Bardia Naghshineh
	André Ribeiro
	Celeste Jacinto
	helena carvalho
Abstract:	Additive manufacturing (AM), also known as 3D Printing, is believed to be a disruptive technology, and therefore the assessment of its ensuing sustainability impacts is necessary. The insufficient evidence in extant literature addressing the social impacts of AM suggests that, to date, the social sustainability aspect of this technology has received scant attention. The current study addresses this knowledge gap through a critical literature review that leads to the identification of 42 social impacts of AM and associates them with relevant stakeholders shaping a social life cycle typology that indicates to what extent each stakeholder is affected by AM. Additionally, a set of indicators for measuring some of the identified AM social impacts are proposed. Finally, the findings are summarized in the form of a framework that can help future research to holistically investigate the social sustainability implications of AM technology.
Response to Reviewers:	

Social Impacts of Additive Manufacturing: A Stakeholder-driven Framework

Abstract

Additive manufacturing (AM), also known as 3D Printing, is believed to be a disruptive technology, and therefore the assessment of its ensuing sustainability impacts is necessary. The insufficient evidence in extant literature addressing the social impacts of AM suggests that the social sustainability aspect of this technology has received scant attention. The current study addresses this knowledge gap through a critical literature review that leads to the identification of 42 social impacts of AM and associates them with relevant stakeholders shaping a social life cycle typology that indicates to what extent each stakeholder is affected by AM. Additionally, a set of indicators for measuring some of the identified AM social impacts are proposed. Finally, the findings are summarized in the form of a framework that can help future research to holistically investigate the social sustainability implications of AM technology.

Keywords: Additive manufacturing, Social, Impacts, Stakeholders, Critical review

1. Introduction

AM technology creates the final part/product by depositing materials layer-by-layer to create an object (Khajavi, Partanen, and Holmström 2014). It is different from traditional manufacturing technologies such as machining that mainly use subtractive methods on raw materials. The relevance of AM technology among organizations has raised significantly in the past years since its applications are vast, and it offers an innovative set of opportunities to generate and capture value (Piller, Weller, and Kleer 2015). Furthermore, the technology can be applied in different life cycle stages of a product enabling its life extension and supporting sustainable manufacturing processes (Despeisse et al. 2017a).

Extant literature shows that the economic and environmental sustainability aspects of AM have been addressed in several research streams. However, the social sustainability aspect of AM has remained underdeveloped (Ford and Despeisse 2016). Normally, emerging technologies affect the stakeholders involved in the life cycle of a product/service (Chen et al. 2015), and AM is no exception (Gebler, Schoot Uiterkamp and Visser, 2014) since significant social impacts caused by this technology are forthcoming (Huang et al. 2013). Despite the fact that many organizations are already using AM technology worldwide, knowledge regarding the social impacts of this technology is limited (Matos et al. 2019), which leaves a considerable gap in the body of literature (Matos and Jacinto 2019). The scarcity of studies addressing this knowledge gap (Ribeiro et al. 2020; Jiang, Kleer, and Piller 2017) calls for a critical analysis of AM's social sustainability aspect (Vijayavenkataraman, Lu, and Fuh 2016) in order to identify the social impacts of this technology and understand how they may change the societies (Olla 2015) and industrial systems, especially from a life cycle perspective (Villamil et al. 2018; Despeisse et al. 2017b). The assessment of a product/service and its surrounding system from a social life cycle perspective, i.e., Social Life Cycle Assessment (S-LCA), can help organizations improve their performance and consequently, the well-being of the involved stakeholders (UNEP/SETAC, 2009).

In view of the foregoing, the main objective of this paper is to address this knowledge gap by identifying the AM social impacts that affect stakeholders involved in different life cycle stages, and therefore, we put forward the following research question:

RQ: What are the relevant social life cycle impacts of Additive Manufacturing on different stakeholders?

In general, the social sustainability aspect receives less attention due to its complicated nature and rigorous methods of quantification (Ma, Kremer, and Ray 2018). This knowledge gap is even more pronounced for AM as an emerging technology. The present research addresses this knowledge gap by a critical review of the existing literature to identify AM social impacts and makes use of the S-LCA methodology to explain how these impacts can affect different stakeholders. This study brings together dispersed yet important pieces of information regarding AM technology and its ensuing social impacts. Since developing the means to measure AM social impacts is not fully explored within extant literature (Matos and Jacinto 2019), this research proposes illustrative indicators for some of these impacts. This knowledge shortfall is even more evident when considering that the existing research on social impacts and their indicators is quite fragmented throughout different areas of knowledge (Kühnen and Hahn 2017). Lastly, this research contributes to the body of knowledge by proposing a framework for the identified AM social impacts together with proposed indicators merging this fragmented research theme into a coherent illustration for future research.

The rest of this paper is structured in the following manner. The second section explains the methodological approach used for this research. Section three focuses on explaining the critical review findings. In section four, the typology and framework are presented, and the results are discussed. Lastly, in the fifth section, the contributions, along with limitations and suggestions for future research are highlighted.

2. Methodological approach

Life Cycle Assessment (LCA) has proved to be a widely accepted methodology to assess the impacts on environmental, economic, and social sustainability aspects. LCA uses a holistic perspective and encompasses various activities, from raw material extraction to product disposal (Rejeski, Zhao, and Huang 2018). Considering LCA's comprehensiveness, this study makes use of the S-LCA methodology that emphasizes a social approach to fulfill the research objective. The selection of S-LCA is not only due to its relevance to the research gap but also its wide range of applicability. S-LCA has been used many times in the recent past to measure the social impacts of various new technologies and has also been applied at different scales from products to their surrounding systems (Di Cesare et al. 2018). At the same time, the growing sustainability requirements have encouraged the organizations utilizing AM technology and their customers to assess products through a life cycle sustainability perspective (Ma et al. 2018), and S-LCA is the only social assessment methodology that examines social impacts from a life cycle perspective (Wang, Hsu, and Hu 2016). S-LCA gathers existing data to report upon social impacts in the product life cycle from creation to disposal (Benoît et al. 2010). Meanwhile, among the many methodological frameworks for S-LCA, the methodological sheets for subcategories in S-LCA (UNEP/SETAC, 2013) is the most commonly used framework (Sutherland et al. 2016) with a core focus on stakeholders that qualifies for the purpose of the current study. Hence, it was selected as a central reference to help this study propose a stakeholder-driven framework. It is worth noting that UNEP/SETAC (2013) is widely accepted among the research community and is generally used as a basis for developing social sustainability frameworks (Ma et al. 2018).

Before advancing any further, defining the terms "social impacts" and “stakeholders” is necessary. The Interorganizational Committee on Guidelines and Principles for Social Impact Assessment (1994) defines social impacts as “the consequences on human populations of any public or private actions that alter the ways in which people live, work, play, relate to one another, organize themselves so as to meet their needs and generally cope as members of society". Furthermore, UNEP/SETAC (2009) defines the social impacts of a product as consequences of social interactions formed between the product's surrounding system, e.g., the technology being utilized to manufacture the product, and the stakeholders engaged in the life cycle of the product. Additionally, a stakeholder “is any group or individual who is affected by, or can affect, the achievement of an organization’s objectives” (Freeman and McVea 2001, p. 5). UNEP/SETAC (2013), divides stakeholders into five categories, namely “Worker”, “Consumer”, “Local Community”, “Society”, and “Value Chain Actors”, which are in turn divided into different subcategories.

In order to accomplish the research objective, a research process based on a critical review of the literature was done. Figure 1 summarizes all the mentioned steps taken to identify the AM social impacts.

>insert Figure 1 here<

A critical review is more than simply describing the literature, and requires a degree of analysis that normally results in a model or hypothesis representing the most important elements of the subject under study (Grant and Booth 2009). At the same time, for the results to be comprehensive, an extensive literature review was carried out, comprising two stages, i.e., stage 1) a structured literature review; and stage 2) an unstructured literature review. In a first step to carry out the structured literature review, we selected an exhaustive search string comprised of relevant keywords, i.e. "additive manufacturing", "additive process*", "layer manufacturing", "3D print*", "3-D print*", "3D-print*" ,"direct digital manufacturing", "solid freeform fabrication", "digital fabrication", "rapid manufacturing", "rapid prototyping", "rapid tooling", "social", "societal", "impact", "implication", "life cycle", "life cycle assessment", "LCA", "social life cycle assessment", "SLCA", "S-LCA". We used the “Advanced Search” feature to apply the search string to all databases available in “Scopus” and “Web of Science”. The search was focused on the title, abstract, and keywords of the papers. The results returned papers until early May 2020. After applying the search string, 391 papers were found (275 in Scopus, and 116 in Web of Science). After removing 89 duplicate papers between the two databases, the abstracts of the remaining 302 papers were screened to collect evidence leading to the identification of AM social impacts. In cases where no explicit information was available within the abstract of papers, the full text was screened to find adequate evidence. In total, information from 46 papers was found relevant and used at this stage. In the second stage, an unstructured literature review was carried out by consulting the references of the papers found in the structured literature review, which resulted in the selection of 34 relevant papers. Through these papers, more evidence was gathered.

Appendix A presents the results of the extensive literature review. The majority of the sample is comprised of papers published in peer-reviewed journals. Most of these papers are published in the following journals: Journal of Cleaner Production (7), Technological Forecasting and Social Change (7), International Journal of Production Economics (4), Journal of Manufacturing Technology Management (4), and Rapid Prototyping Journal (4) totaling to 26 published journal papers. As shown in Appendix A, the rest of the papers are dispersed in a wide range of journals. Only 15 of the research articles are published as conference papers and book chapters. The summary statistics of the sample in Table 1 indicate that most of the publications took place between the years 2014 and 2018 that account for 75% (65/80) of the whole sample.

>insert Table 1 here<

Through the critical review of the gathered evidence, 42 AM social impacts were identified. Appendix B presents the identified impacts with their references accompanied by examples of supporting evidence. Next, the identified AM social impacts were classified according to the stakeholder subcategories by UNEP/SETAC (2013). The classification of these impacts was based on considering the formal definitions provided by UNEP/SETAC (2013) for each stakeholder subcategory. Subsequently, a typology (Figure 2) was shaped that represents the extent of AM social life cycle impacts on stakeholder categories and subcategories.

Moreover, illustrative indicators were provided for some of the identified AM social impacts by mainly using the available indicators in UNEP/SETAC (2013). The criterion for indicator selection from UNEP/SETAC (2013) was based on how well the indicator definition represented the identified AM social impact. In cases where there were no relevant indicators available, a few were suggested by the authors since there is a need to develop relevant indicators when conducting S-LCA (Di Cesare et al. 2018). The proposed indicators are mainly quantitative or qualitative (Searcy, Dixon, and Patrick Neumann 2016). In a few cases, semi-quantitative were also considered. Semi-quantitative indicators are used when the collected data is, for example, questionnaires with "yes" or "no" responses or rating scale responses (UNEP/SETAC, 2013). In a final step, the outcomes of this study were summarized in the form of a framework, as shown in section 4.

3. Critical review

Drawing on a critical review of the gathered evidence through an extensive literature review and considering the formal definitions provided by UNEP/SETAC (2013), 42 AM social impacts were identified (Appendix B). As explained in the subsections that follow, these impacts are associated with relevant stakeholder subcategories based on sound reasoning that explains how each stakeholder subcategory can be impacted by AM.

3.1. Local Community

According to UNEP/SETAC (2013), the “Cultural Heritage” subcategory represents the elements that define a community, such as a language, knowledge and traditional craftsmanship, cultural spaces, and objects (i.e., burial grounds), as well as social and religious practices. The deterioration of cultural heritage can occur during globalization with the advancement of technologies, which makes the preservation of historical and cultural traditions crucial. AM can improve socio-cultural sustainability by supporting prosumption, i.e., production by consumers. Individuals within their communities can use AM, as a means of “Digital Prosumption”, to preserve their cultural heritage since they can produce the parts/products they need by themselves, which means there will be less external interference in their local cultures. Also, "Social Inclusion” is a relevant AM impact as the use of this technology allows individuals with impaired abilities to participate in social activities. For instance, AM makes the concept of 3D-museums possible by reproducing replicas from museums to engage with people with visual impairment. Another example is the use of AM technology by educators and teachers dealing with visually impaired pupils to produce a variety of adapted and interactive educational material at a low cost. “Social Acceptance” of AM technology is another impact that entails cultural and religious implications. For example, in some religions, the use of 3D-printed organs is deemed inappropriate and forbidden.

The “Local Employment” subcategory mainly addresses the direct or indirect impacts on training, income, and job opportunities for the community members. “Education and Training” is facilitated by AM in many ways. One instance is the emergence of digital fabrication laboratories, e.g., Fab Labs, which are equipped with 3D-printers that help learners be innovative using co-created models and prototypes. These innovative approaches will lead to better active learning experiences that enable individuals to practically approach problem-solving techniques. AM technology promotes “Local Manufacturing”, also known as distributed/decentralized manufacturing, as the proximity between supply chain members, e.g., suppliers, manufacturers, and customers, can be reduced. This change will have consequences for local employment. Moreover, due to a high degree of “Automation” in AM technology, demand for labor will be affected, regardless of whether the production is foreign or domestic. Along these lines, changes in “Employment Structure” is another AM social impact attributable to this subcategory.

UNEP/SETAC (2013) defines immaterial resources as access to information, freedom of expression, community services (e.g., healthcare and education), and intellectual property rights. “Access to Immaterial Resources” is impacted by AM “Technology Transfer” to the community, facilitating access to information and sharing knowledge among the active members. AM encourages a participatory culture among community members through “Open Innovation” to freely express their ideas. Moreover, both “Digital Prosumption” and “Open Innovation” empowered by AM can encourage the community members to perform voluntary acts of service. However, AM can also trigger legal disputes among communities as the ubiquity of 3D-printers in unregulated settings, e.g., homes, can create complications for intellectual property rights, e.g., "Intellectual Property Infringement”. Additionally, “Medical Additive Manufacturing” impacts the community’s healthcare system, e.g., making it possible to offer personalized healthcare to meet the specific needs of the community members.

“Safe and Healthy Living Conditions” subcategory relates to how AM technology impacts the health and safety of a community. Therefore, “Environmental Impacts” fits in this subcategory, since the use of AM leads to reduced production waste (through design and process optimization) and CO2/GHG emissions resulting in a reduced carbon footprint. AM has the potential to enhance “Disaster Mitigation” responses and develop operations through the rapid production of equipment, items, and replacements needed in disaster areas. When compared to conventional infrastructures, AM allows the creation of advanced and "Modern Infrastructure" at low cost and in accordance with the needs of the community.

“Access to Material Resources” expresses the fact that communities share material resources (natural or human-made) and tend to protect and increase the quality and quantity of local resources and infrastructure. Hence, sustainable methods of production are of importance to communities in order to avoid conflicts, especially in developing countries. This calls for sustainable use of natural resources and waste recycling, especially in production. The minimized “Environmental Impacts” of AM through reduced waste generation implies its relevance to this subcategory. In general, AM provides opportunities for "Sustainable Production" by reducing raw material usage and energy consumption in production processes. AM contributes to more efficient and sustainable use of resources, e.g., redesigning products with fewer components, i.e., component consolidation. As an enabler of “Circular Economy”, AM supports a culture of material reuse/recycling and promotes the development of urban waste processing techniques. At the same time, AM corroborates the concept of “Degrowth” that aims at reducing energy and material throughput in production and questions the necessity of further economic growth. Moreover, the possibility of creating “Modern Infrastructure” via AM is of great use to communities to enhance the quality of their infrastructures.

“Delocalization and Migration” refers to the large-scale migration and resettlement of individuals who seek employment due to economic developments in different regions. Since the growing use of AM has implications for the global economy, “Involuntary Resettlement” can occur. However, the possibility to do “Remote Work” via AM enables some individuals to work closer to their place of origin. Also, “Local Manufacturing” and “Automation” will shift production closer to consumer countries due to the decreased labor costs, and consequently, many individuals will have to relocate to these countries.

“Community Engagement” subcategory assesses the extent to which community stakeholders are included in the decision-making processes. AM characteristics avail the opportunity to implement “Consumer-Centric Production” that directly involves consumers in the production processes. AM also promotes the concept of “Social Manufacturing”, which allows communities to be actively engaged in the manufacturing of products, and thus allows them to be part of the decision-making processes. Moreover, AM enables manufacturers to co-create/co-design their products ("Co-Creation/Co-Design”) with communities, and therefore more effectively engage with communities and their needs.

“Secure Living Conditions” refers to an organization’s duty to safeguard communities from weak security oversight attributable to their activities. It also implies the potential to improve regional living conditions for the community where the activities take place. Hence, “New Policies and Regulations” should be introduced by authorities since the use of AM as an emerging technology can have unprecedented consequences for the communities. Failure to introduce new policies and regulations by authorities can cause legal disputes to arise within communities. For instance, “Production of Weapons” is consequential misconduct of AM technology that can pose severe risks to the security of regions and communities where AM technology is being used, which calls for the introduction of “New Policies and Regulations”.

3.2. Value Chain Actors

“Fair Competition” assesses whether organizations conduct their business in a fair way by conforming to the legislations that intercept anti-trust, anti-competitive behavior or monopoly practices, e.g., erecting barriers to market entry; imposing geographic quotas; abusing market position; colluding to prevent competition. Meanwhile, AM enables “Democratized Production” by allowing an increasing number of producers the possibility to manufacture and distribute their products beyond the centralized manufacturing model. “New Business Models” are emerging through the use of AM. For instance, digital product designs can be generated globally, and products can be manufactured locally. Also, “Small-Run Production” enabled by AM technology will affect market competition. It would allow small and medium-sized enterprises (SMEs) with less capital to take part in different industry sectors, especially the AM sector. These are all instances that facilitate “Market Entry”.

“Respect of Intellectual Property Rights” refers to the assignment of property rights via patents, copyrights, and trademarks to their lawful owners. It is important to have legal systems prepared for defending the best interests of the stakeholders in a value chain. “Intellectual Property Infringement” is an AM impact that indicates the need to have legal systems available for this technology as the protection of intellectual property rights will probably be a great challenge. This is likely as product designs can be widely disseminated, and identical products will be manufactured by compatible 3D printers. Also, “Digital Prosumption”, enabled by AM, allows users to prolong the average life of a product, i.e., "Product Life Extension", by repairing or changing dysfunctional product parts, which can have intellectual property rights repercussions. Therefore, “New Policies and Regulations” are expected to be introduced by authorities.

“Supplier Relationships” refers to the mutual activities, co-operations, and agreements that regulate the exchange, trade, and relation between organizations. An organization is expected to consider the potential impacts or unintended consequences of its business activities on other organizations and prevent or minimize any potential negative impact. The innovative processes empowered by AM and the merging of different phases of production leads to “Supply Chain Reconfiguration”, e.g., elimination of many supply chain stages and suppliers or on-demand manufacturing, which will affect “Supplier Relationships”.

“Promoting Social Responsibility” states that organizations need to integrate social responsibility into their core business processes and consider stakeholders' interests, who are affected by their activities, to achieve both corporate value and social value. AM helps organizations to approach this goal through “Environmental Impacts”, “Modern Infrastructure”, “Sustainable Production”, “Circular Economy”, and “Degrowth”, all of which are social impacts related to organizational activities that can help promote social responsibility.

3.3. Consumer

The “Health and Safety” subcategory aims to understand if products perform their intended functions without posing risks to consumers. AM products, especially those intended for nutrition and medication, need to be measured against health and safety standards to assure consumer safety. “Medical Additive Manufacturing” needs to be monitored closely to ensure that it serves the medical purpose without posing risks to the patient’s health and safety. “Food Printing” is no exception. Evidence from the literature suggests that AM meets the food safety requirements to produce highly customized food that contains the exact amount of nutrients consumers need. “Medical Additive Manufacturing” is also relevant to the health and safety of consumers since AM technology is used to customize and replace human tissue, organs, and bones. Unauthorized use of AM to manufacture health-related products, e.g., medical equipment, medicine, "Personal Protective Equipment", raises concerns since the manufacturing of such products can take place in unregulated settings through the use of unapproved designs created by the consumers themselves, i.e., "Digital Prosumption”.

“Feedback Mechanism” is a way by which consumers and organizations can communicate. Using AM and the “Design Capabilities” offered by this technology, organizations can communicate with their customers and get prompt feedback by including them in the design phase, i.e., “Co-Creation/Co-Design”. Also, AM enables “Consumer-Centric Production” that facilitates focusing on consumers’ needs and their feedback. Additionally, AM warrants “Open Innovation” that allows consumers to better express their needs and ideas to the manufacturers. Moreover, “Social Manufacturing” through AM allows consumers to be actively engaged in the manufacturing of products, and thus allows them to take part in the decision-making processes. Finally, “Digital Prosumption” allows consumers to interact more effectively with AM service providers regarding product designs.

"Privacy" subcategory concerns the protection of personal consumer data against misuse or external theft. Some applications of AM, e.g., “Medical Additive Manufacturing” require a granular level of data exchange between producers/AM service providers and consumers, which can have confidentiality implications for the consumers’ data. Therefore, the introduction of “New Policies and Regulations” are required to minimize the occurrence of legal disputes, e.g., instances of “Intellectual Property Infringement”. The same logic applies to “Consumer-Centric Production” and “Co-Creation/Co-Design” using AM technology where consumers may be required (by producers) to disclose their data to complete their order requests. However, “Digital Prosumption” may have an opposite effect since consumers may either purchase the already existing product designs or create designs of their own without the need to exchange their data with the producer/AM service provider on a granular level.

“Transparency” enables consumers to make informed choices about products in terms of their performance and social responsibility implications. In this regard, labels, certification standards, and special indices can be used to provide the necessary information for the consumer. AM contributes to transparency through “Co-Creation/Co-Design” and “Consumer-Centric Production” as they both grant consumers to be involved in the manufacturing of the products and make informed decisions. Also, AM "Digital Prosumption" grants consumers access to certified designs that contain detailed product specifications. The transparent way of production through AM can contribute to reducing the number of legal disputes between consumers and producers.

Within the product life cycle, the “End-of-Life Responsibility” is mainly concerned with product disposal, reuse, or recycling. UNEP/SETAC (2013) states that “product disposal can lead to significant environmental and social concerns, such as environmental and public health impacts that stem from the accumulation of hazardous material in electronic waste”. As mentioned earlier, AM contributes to "Environmental Impacts", e.g., by reducing the amount of generated waste through “Sustainable Production” and/or “Degrowth”. It also supports “Circular Economy” via material reuse/recycle. AM also enables “Product Life Extension” by part/product repair that requires “Product Disposal Management”.

3.4. Worker

“Hours of Work” aims to confirm if the working hours comply with the International Labor Organization standards. Some experts believe that AM permits “Flexible Work Schedule” since portable AM machines can be used almost everywhere. Also, working remotely, i.e., "Remote Work", is a possibility with AM that adds to working hours' flexibility.

The “Health and Safety” subcategory is defined by the promotion and maintenance of the physical, mental, and social well-being of the workers in all occupations, including the protection of workers from risk factors adverse to their health. AM processes are likely to decrease hazards prevalent among conventional manufacturing processes as they allow workers to avoid long-term exposure to harsh work environments. For instance, AM-enabled “Automation” is capable of reducing physical contact necessary for machine operation. However, AM processes can cause new health problems of their own. AM makes it possible to create customized “Personal Protective Equipment” that are compatible with the needs of individuals in their work environment. Another health and safety aspect is the flexibility to perform “Remote Work” by AM that can help workers keep away from harsh work environments but isolate them from their workplace and create psychosocial risks. Hence, “Occupational Hazards and Health Risks” should be considered as an AM social impact of AM.

“Social Benefit/Social Security” subcategory is defined by non-monetary employment compensation such as education and training. Therefore, the AM social impact “Education and Training” fits this subcategory since it is a social benefit for the worker.

3.5. Society

“Public Commitment to Sustainability Issues” evaluates to what extent an organization is engaged in reducing its negative sustainability impacts. Therefore, according to the provided explanations in previous subsections, the following identified AM impacts can be associated with this subcategory: “Employment Structure”, “Environmental Impacts”, “Modern Infrastructure”, “Sustainable Production”, “Circular Economy”, “Degrowth”,

The "Prevention and Mitigation of Conflicts" subcategory evaluates situations that can potentially develop into future conflicts. Hence, it is important to assess the impact of new technologies on conflicts. UNEP/SETAC (2013) declares some specific regions around the globe as conflict zones that are known for enduring turbulences. Even though “Production of Weapons” is not region-oriented, the ease of producing weapons by AM technology may promote armed conflicts in these regions, as well as others.

“Contribution to Economic Development” refers to improving the economy in different ways, e.g., generating revenue, creation of jobs, education, and training. AM affects “Education and Training” and “Employment Structure” since the demand for a qualified workforce by organizations is expected to increase. The existing literature suggests that AM affects “Production Costs” and “Production Time” mainly in a positive way, both of which subsequently affect the organizations’ revenues. Another implication is “Supply Chain Efficiency and Responsiveness” since AM allows organizations to be more cost-effective and responsive. Also, AM technology facilitates “Sustainable Production”, which also contributes to economic growth. AM-enabled “Local Manufacturing” and consequently “Import/Export Imbalance” are two other impacts of AM relevant to economic development. Through AM, “Economies of One” (as opposed to economies of scale) will be viable for customizable products at low volumes that have no economic rationale for mass production. Also, “Economies of Technology” will be possible through the utilization of multiple AM machines by a single operator, which reduces the demand for labor and consequently brings production back from low wage economies. Additionally, AM impacts the economic development through “Automation”, “Circular Economy”, “Degrowth”, “Market Entry”, and “New Business Models”.

“Corruption” subcategory appraises the implementation of proper measures to prevent corruption. As the use of AM is prone to acts of corruption, e.g., “Intellectual Property Infringements” and theft, “New Policies and Regulations” should be introduced by the responsible authorities.

"Technology Development" refers to the development of new technology and its transfer, which is the process of using the technology and its know-how for a purpose not originally intended. Due to the growing use of AM and its diffusion among different industries, e.g., medicine, food, construction, “Technology Transfer” is considered a social impact relatable to this subcategory.

4. Results

The critical review allowed for the association of the 42 identified AM social impacts to relevant stakeholders. Considering that many of these impacts are relevant to different subcategories within each stakeholder category, a cumulative number of 100 impacts was obtained. Figure 2 illustrates a typology that indicates how these impacts affect the stakeholder categories/subcategories.

>insert Figure 2 here<

The first layer of this typology indicates the relative distribution (%) of AM social impacts among the stakeholders. For instance, 29 out of the 100 discussed impacts are associated with the “Local Community” that corresponds to a 29% AM social impact on this category. Similarly, the second layer of the typology represents the distribution of AM social impacts among the stakeholder subcategories. For example, out of the total 29 social impacts associated with Local Community category, 5 affect “Access to Material Resources” that corresponds to a 17% AM social impact on this subcategory. These calculations are valid under the assumption that the importance and weight assigned to each impact is the same. Also, the percentages are rounded to the second decimal place for simplifying calculations. By extending the same analysis to other categories, it is possible to estimate AM's social life cycle impact on each stakeholder.

Figure 2 shows that AM has the most social life cycle impact on “Local Community”, “Society” and “Consumer”, whereas “Value Chain Actors”, and “Worker” are not affected by the use of AM to a great extent. The typology also provides information regarding the degree of AM impact on each stakeholder subcategory. For example, “Contribution to Economic Development” accounts for 60% of the AM social impact, which implies that AM has the most impact on the economic development within “Society”. Such analysis based on the derived typology can act as a roadmap for managers to recognize the stakeholder categories and subcategories that are more likely to be affected by AM, and thus help them make more socially sustainable decisions when dealing with this technology. Moreover, this typology provides a classification scheme for future work that can facilitate comparison between studies that focus on the social impacts of AM, or even other emerging technologies.

Another relevant aspect of this research is how to measure AM social impacts. The existing literature has not addressed this knowledge shortfall properly (Matos and Jacinto 2019). To the best of the authors’ knowledge, by the time this research was carried out, only one research article addressed AM's sustainability performance indicators (Taddese, Durieux and Duc, 2020). However, this work does not provide an exact discussion on the AM social indicators. Nevertheless, in this work, we have provided a list of illustrative indicators that could be used to measure some of the AM social impacts (Table 2).

>insert Table 2 here<

Finally, Figure 3 presents a holistic framework organized by stakeholder categories and subcategories. This structured framework represents the essence of the current study. It already includes a few measurement indictors, only to serve as illustrative examples. The development of a comprehensive collection of assessment indicators is an avenue for future work.

>insert Figure 3 here<

Although the existing literature had briefly investigated the AM social impacts, no research had comprehensively addressed the social life cycle impacts of this technology on different stakeholders. Among the first studies, Huang et al. (2013) reviewed the social impacts of AM from a technical point of view. However, their research does not provide a comprehensive record of AM social impacts outlining their importance from a stakeholder perspective. They addressed this issue by mentioning the need for a critical review of the subject, and they stated that AM is highly likely to have considerable social impacts in the near future. Drawing on a global sustainability perspective, Gebler, Schoot Uiterkamp and Visser (2014) briefly explain some of the social implications of AM based on the existing literature. Nevertheless, they do not present a detailed analysis of the AM’s social aspect, but rather emphasize the importance for societal decision-makers to become aware of the AM's sustainability potentials. Chen et al. (2015) underline the necessity for investigating the impacts of AM by considering a societal point of view. As opposed to the present research, they do not specify what the social impacts of AM are, but rather stress the need for further research, especially in terms of employment structure, waste management, and work safety. Vijayavenkataraman, Lu, and Fuh (2016) propose a framework for 3D bioprinting comprised of ethical, legal and social aspects. While their proposed framework is insightful, the social aspect only touches on soft impacts, which reflect the technological effects on human life, and cultural and religious perspectives relevant to 3D bioprinting. Nonetheless, they explicitly point out the need for a critical analysis of social aspects on a broader level. Ford and Despeisse (2016) discuss the impacts of AM on sustainability based on a life cycle perspective. However, their work does not provide an elaborate analysis of the AM's social impacts. They highlight the need to further research the social aspect of AM, which is in line with the objective of this research. Employing a different research approach, Vijayavenkataraman, Lu, and Fuh (2016) develop eighteen projections for the economic and social implications of AM through a Delphi survey. Yet, they do not focus on developing a comprehensive framework including a large number of social impacts, and acknowledge the fact that only few studies have engaged in identifying the social impacts of AM. More recently, Matos and Jacinto (2019) examined the literature by using a computer-aided content analysis to identify relevant keywords for AM social impacts. Their findings indicated that AM social impacts are yet to be explored. Later, Matos et al. (2019) studied some of the social impacts that are due to the adoption of AM technology. Through an exploratory case study approach, they mainly examined the social implications of AM in terms of health and well-being, working conditions, and economic growth. They encourage future research to propose indicators as a means of quantifying the social impacts of AM. In their study, Ribeiro et al. (2020) focused on investigating the sustainability aspects of AM based on a life cycle analysis. Their findings showed that even though the economic and environmental sustainability aspects of AM are widely investigated, the social aspect of this technology has received scant attention. Based on a literature review of the life cycle studies, Taddese, Durieux and Duc (2020) took a step further and proposed thirty performance indicators for assessing the social sustainability of AM products. However, they did not explicitly associate the identified performance indicators to respective social impacts.

The present study addresses the mentioned concerns by previous research regarding the identification and critical analysis of AM social impacts. This study has addressed this issue by drawing on disperse pieces of information in the existing literature and consolidating them into a holistic framework. The diversity of studies employed in this research across a time span of ten years helped to identify 42 of AM social impacts. Also, in an attempt to make the findings more practicable, this research provided illustrative indicators for each identified social impact.

5. Conclusions, limitations and future research

The present study contributes to the knowledge area of AM technology in different ways. Most studies in this area are about the technology behind the AM processes or the economic and environmental advantages of using AM processes. However, there is a gap in these studies in terms of recognizing the social impacts of AM. This research contributes to overcoming this gap by identifying 42 AM social impacts from extant literature and classifying them based on the stakeholders they affect using a validated methodology, i.e., UNEP/SETAC (2013). Also, by relating the identified social impacts to relevant stakeholder categories and subcategories, this work proposes a typology that illustrates the extent to which stakeholders are affected by AM. Also, some indicators for assessing social impacts are suggested for illustrative purposes. These indicators were either selected from UNEP/SETAC (2013) guidelines or proposed by the authors to add more practicality to the research findings. Another useful contribution of this work lies in its ability to bring together important information that has been dispersed within different publications and across a variety of sectors. The proposed framework puts together these pieces of information in the form of a single picture and contributes to a better understanding of AM technology's social impacts from a life cycle perspective.

The main academic implication of this research is the creation of a stakeholder-driven framework for AM social impacts that can be used for devising evaluation tools or methodological frameworks that integrate and quantify different aspects of sustainability, i.e., economic, environmental and social. The results of the extensive literature review showed that so far, no other work has addressed this knowledge gap by proposing such a comprehensive framework and mapping multiple AM social impacts from a wide range of literature. Also, as mentioned earlier in section 4, the managerial implication of this study is evident in its capability to provide valuable information for sustainable decision-making when dealing with AM technology and its ensuing social impacts on different stakeholders. Furthermore, two main research implications that are derived from this review are: 1) given the current lack of understanding towards the social impacts of AM technology, there is a need for an agreement on how to assess them; the illustrative indicators presented in this study provide the basis for discussion. 2) An agreed-upon typology can provide an unambiguous foundation for those involved in S-LCA of AM products.

This research, like many others, has limitations. It is possible that some social impacts are not identified and discussed in this study. Also, a few UNEP/SETAC (2013) subcategories, i.e., “Freedom of Association and Collective Bargaining”, “Child Labour”, “Fair Salary”, “Forced Labour”, “Respect of Indigenous Rights” and “Equal Opportunities/Discrimination” that were not used in this work can be further investigated for relevant AM social impacts. The stakeholders used in this research are the ones that UNEP/SETAC (2013) considers, and it is possible that some stakeholders were not reflected. Another limitation is the assumption that the identified impacts are of equal weight and importance, which can affect the robustness of the calculations illustrated within the typology (Figure 2). Also, the proposed indicators are merely illustrative to show their importance and usefulness, and they need further development.

This research provides a foundation for future work. For instance, this includes determining the potential interrelations between the identified AM social impacts, extending the research to finding more social impacts, and using other methodologies to identify other stakeholders. Another future research possibility is investigating the importance of each identified impact and subsequently assigning relative weights to each one in order to recalculate the numbers presented by the typology. Future research can also focus on proposing AM-specific indicators for the identified social impacts and develop a broader and more complete collection of indicators. Furthermore, there is a need to validate and extend the proposed framework with a set of specialists in the technology, social, and industrial areas. Case studies can be used to validate the framework in specific contexts. For instance, in the case of the Covid-19 pandemic, AM technology is being used by communities, companies, and research centers/universities around the globe to produce ventilators, ventilator parts, and face shields, i.e., Personal Protective Equipment. The proposed framework can be used to carry out a structured case study to provide insights into the social impacts of AM technology in this specific context.

Acknowledgments

The authors gratefully acknowledge the funding of project FIBR3D (POCI-01- 0145-FEDER-016414), co-financed by Fundo Europeu de Desenvolvimento Regional (FEDER) and by national funds through Fundação para a Ciência e Tecnologia, Portugal. Also acknowledge Fundação para a Ciência e Tecnologia (FCT-MCTES) for its financial support via the project UIDB/00667/2020 (UNIDEMI) and project KM3D (PTDC/EME-SIS/32232/2017).

References

Angioletti, Cecilia Maria, Mélanie Despeisse, and Roberto Rocca. 2017. "Product Circularity Assessment Methodology." In *IFIP Advances in Information and Communication Technology*. https://doi.org/10.1007/978-3-319-66926-7_47.

Assessment, S.I., 1995. "Guidelines and principles for social impact assessment. " *Environmental Impact Assessment Review.*

Atzeni, Eleonora, and Alessandro Salmi. 2012. "Economics of Additive Manufacturing for End-Usable Metal Parts." *International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-011-3878-1.

Beltagui, A., N. Kunz, and S. Gold. 2020. "The Role of 3D Printing and Open Design on Adoption of Socially Sustainable Supply Chain Innovation." *International Journal of Production Economics*. https://doi.org/10.1016/j.ijpe.2019.07.035.

Benoît, Catherine, Gregory A. Norris, Sonia Valdivia, Andreas Ciroth, Asa Moberg, Ulrike Bos, Siddharth Prakash, Cassia Ugaya, and Tabea Beck. 2010. "The Guidelines for Social Life Cycle Assessment of Products: Just in Time!" International Journal of Life Cycle Assessment. https://doi.org/10.1007/s11367-009-0147-8.

Berman, Barry. 2012. "3-D Printing: The New Industrial Revolution." *Business Horizons*. https://doi.org/10.1016/j.bushor.2011.11.003.

Birtchnell, Thomas, and John Urry. 2013a. "3D, SF and the Future." *Futures*. https://doi.org/10.1016/j.futures.2013.03.005.

Bogers, Marcel, Ronen Hadar, and Arne Bilberg. 2016. "Additive Manufacturing for Consumer-Centric Business Models: Implications for Supply Chains in Consumer Goods Manufacturing." *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2015.07.024.

Calderon, Ariel, James Griffin, and Juan Cristóbal Zagal. 2014. "BeamMaker: An Open Hardware High-Resolution Digital Fabricator for the Masses." *Rapid Prototyping Journal*. https://doi.org/10.1108/RPJ-01-2013-0006.

Cesare, Silvia Di, Federica Silveri, Serenella Sala, and Luigia Petti. 2018. "Positive Impacts in Social Life Cycle Assessment: State of the Art and the Way Forward." *International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-016-1169-7.

Chan, Hing Kai, James Griffin, Jia Jia Lim, Fangli Zeng, and Anthony S.F. Chiu. 2018. "The Impact of 3D Printing Technology on the Supply Chain: Manufacturing and Legal Perspectives." *International Journal of Production Economics*. https://doi.org/10.1016/j.ijpe.2018.09.009.

Chen, Danfang, Steffen Heyer, Suphunnika Ibbotson, Konstantinos Salonitis, Jón Garar Steingrímsson, and Sebastian Thiede. 2015. "Direct Digital Manufacturing: Definition, Evolution, and Sustainability Implications." *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2015.05.009.

Despeisse, M., M. Baumers, P. Brown, F. Charnley, S. J. Ford, A. Garmulewicz, S. Knowles, et al. 2017a. “Unlocking Value for a Circular Economy through 3D Printing: A Research Agenda.” *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2016.09.021.

Despeisse, Mélanie, Miying Yang, Steve Evans, Simon Ford, and Tim Minshall. 2017b. “Sustainable Value Roadmapping Framework for Additive Manufacturing.” In *Procedia CIRP*. https://doi.org/10.1016/j.procir.2016.11.186.

Diegel, Olaf, Sarat Singamneni, Stephen Reay, and Andrew Withell. 2010. “Tools for Sustainable Product Design: Additive Manufacturing.” *Journal of Sustainable Development*. https://doi.org/10.5539/jsd.v3n3p68.

Fleischmann, Katja, Sabine Hielscher, and Timothy Merritt. 2016. “Making Things in Fab Labs: A Case Study on Sustainability and Co-Creation.” *Digital Creativity*. https://doi.org/10.1080/14626268.2015.1135809.

Ford, Simon, and Mélanie Despeisse. 2016. “Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges.” *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2016.04.150.

Freeman, R. Edward, and John McVea. 2001. “A Stakeholder Approach to Strategic Management. Working Paper No. 01-02.” *The Blackwell Handbook of Strategic Management.* https://doi.org/10.2139/ssrn.263511.

Galimberti, Giorgia, Mario Guagliano, Barbara Previtali, and Lucia Rampino. 2015. “Digital Aesthetic of New Products Obtained by Selective Laser Melting Process.” *Proceedings of the International Conference on Engineering Design*.

Gao, Wei, Yunbo Zhang, Devarajan Ramanujan, Karthik Ramani, Yong Chen, Christopher B. Williams, Charlie C.L. Wang, Yung C. Shin, Song Zhang, and Pablo D. Zavattieri. 2015. “The Status, Challenges, and Future of Additive Manufacturing in Engineering.” *Computer-Aided Design* 69: 65–89. https://doi.org/10.1016/j.cad.2015.04.001.

Garrett, Banning. 2014. “3D Printing: New Economic Paradigms and Strategic Shifts.” *Global Policy*. https://doi.org/10.1111/1758-5899.12119.

Gebler, Malte, Anton J.M. Schoot Uiterkamp, and Cindy Visser. 2014. “A Global Sustainability Perspective on 3D Printing Technologies.” *Energy Policy*. https://doi.org/10.1016/j.enpol.2014.08.033.

Giraud, Stéphanie, and Christophe Jouffrais. 2016. “Empowering Low-Vision Rehabilitation Professionals with ‘Do-It-Yourself’ Methods.” In *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics).* https://doi.org/10.1007/978-3-319-41267-2_9.

Grant, Maria J., and Andrew Booth. 2009. “A Typology of Reviews: An Analysis of 14 Review Types and Associated Methodologies.” *Health Information and Libraries Journal*. https://doi.org/10.1111/j.1471-1842.2009.00848.x.

Griffiths, C. A., J. Howarth, G. De Almeida-Rowbotham, A. Rees, and R. Kerton. 2016. “A Design of Experiments Approach for the Optimisation of Energy and Waste during the Production of Parts Manufactured by 3D Printing.” *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2016.07.182.

Hankammer, Stephan, and Robin Kleer. 2018. “Degrowth and Collaborative Value Creation: Reflections on Concepts and Technologies.” Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2017.03.046.

Hartl, Richard F., and Peter M. Kort. 2017. “Possible Market Entry of a Firm with an Additive Manufacturing Technology.” *International Journal of Production Economics*. https://doi.org/10.1016/j.ijpe.2017.06.013.

Huang, Runze, Matthew E. Riddle, Diane Graziano, Sujit Das, Sachin Nimbalkar, Joe Cresko, and Eric Masanet. 2017. “Environmental and Economic Implications of Distributed Additive Manufacturing: The Case of Injection Mold Tooling.” *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12641.

Huang, Samuel H., Peng Liu, Abhiram Mokasdar, and Liang Hou. 2013. “Additive Manufacturing and Its Societal Impact: A Literature Review.” *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-012-4558-5.

Jiang, Ruth, Robin Kleer, and Frank T. Piller. 2017. “Predicting the Future of Additive Manufacturing: A Delphi Study on Economic and Societal Implications of 3D Printing for 2030.” *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2017.01.006.

Kang, Yeonghoon, and Sungmin Kim. 2019. “Development of Helmet Mold Design System Using 3D Anthropometric Analysis.” *International Journal of Clothing Science and Technology*. https://doi.org/10.1108/IJCST-02-2019-0022.

Kapetaniou, Chrystalla, Alison Rieple, Alan Pilkington, Thomas Frandsen, and Paola Pisano. 2018. “Building the Layers of a New Manufacturing Taxonomy: How 3D Printing Is Creating a New Landscape of Production Eco-Systems and Competitive Dynamics.” *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2017.10.011.

Khajavi, Siavash H., Jouni Partanen, and Jan Holmström. 2014. “Additive Manufacturing in the Spare Parts Supply Chain.” *Computers in Industry*. https://doi.org/10.1016/j.compind.2013.07.008.

Khan, Mohammad S., Florence Sanchez, and Hongyu Zhou. 2020. “3-D Printing of Concrete: Beyond Horizons.” *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2020.106070.

Khorram Niaki, Mojtaba, Fabio Nonino, Giulia Palombi, and S. Ali Torabi. 2019. “Economic Sustainability of Additive Manufacturing: Contextual Factors Driving Its Performance in Rapid Prototyping.” *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-05-2018-0131.

Kietzmann, Jan, Leyland Pitt, and Pierre Berthon. 2015. "Disruptions, Decisions, and Destinations: Enter the Age of 3-D Printing and Additive Manufacturing." *Business Horizons*. https://doi.org/10.1016/j.bushor.2014.11.005.

Kim, Hyeon-Chang. 2015. "A Study on the Socio-Economic Impact of 3D Printing." *Journal of Digital Convergence*. https://doi.org/10.14400/jdc.2015.13.7.23.

Kohtala, Cindy, and Sampsa Hyysalo. 2015. "Anticipated Environmental Sustainability of Personal Fabrication." *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2015.02.093.

Kostakis, Vasilis, Kostas Latoufis, Minas Liarokapis, and Michel Bauwens. 2018. "The Convergence of Digital Commons with Local Manufacturing from a Degrowth Perspective: Two Illustrative Cases." *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2016.09.077.

Kühnen, Michael, and Rüdiger Hahn. 2017. "Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience." *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12663.

la Torre, N. De, M. M. Espinosa, and M. Domínguez. 2016. "Rapid Prototyping in Humanitarian Aid To Manufacture Last Mile Vehicles Spare Parts: An Implementation Plan." *Human Factors and Ergonomics In Manufacturing*. https://doi.org/10.1002/hfm.20672.

Lee Ventola, C. 2014. "Medical Applications for 3D Printing: Current and Projected Uses." P and T.

Lind, Johanna, Sofia Kälvemark Sporrong, Susanne Kaae, Jukka Rantanen, and Natalja Genina. 2017. "Social Aspects in Additive Manufacturing of Pharmaceutical Products." *Expert Opinion on Drug Delivery*. https://doi.org/10.1080/17425247.2017.1266336.

Liu, Peng, Samuel H. Huang, Abhiram Mokasdar, Heng Zhou, and Liang Hou. 2014. "The Impact of Additive Manufacturing in the Aircraft Spare Parts Supply Chain: Supply Chain Operation Reference (Scor) Model Based Analysis." *Production Planning and Control* 25. https://doi.org/10.1080/09537287.2013.808835.

Loy, Jennifer, Samuel Canning, and Natalie Haskell. 2016. "3D Printing Sociocultural Sustainability." In *Environmental Footprints and Eco-Design of Products and Processes*. https://doi.org/10.1007/978-981-10-0549-7_4.

Lupton, Deborah, and Bethaney Turner. 2017. "'Both Fascinating and Disturbing': Consumer Responses to 3D Food Printing and Implications for Food Activism." In *Digital Food Activism*. https://doi.org/10.4324/9781315109930_8.

Ma, Junfeng, James D. Harstvedt, Daniel Dunaway, Linkan Bian, and Raed Jaradat. 2018. "An Exploratory Investigation of Additively Manufactured Product Life Cycle Sustainability Assessment." Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2018.04.249.

Mami, Fares, Jean Pierre Revéret, Sophie Fallaha, and Manuele Margni. 2017. "Evaluating Eco-

Efficiency of 3D Printing in the Aeronautic Industry." *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12693.

Mangat, Amarveer Singh, Sunpreet Singh, Munish Gupta, and Ravinder Sharma. 2018. "Experimental Investigations on Natural Fiber Embedded Additive Manufacturing-Based Biodegradable Structures for Biomedical Applications." *Rapid Prototyping Journal*. https://doi.org/10.1108/RPJ-08-2017-0162.

Matos, Florinda, Radu Godina, Celeste Jacinto, Helena Carvalho, Inês Ribeiro, and Paulo Peças. 2019. "Additive Manufacturing: Exploring the Social Changes and Impacts." *Sustainability (Switzerland)*. https://doi.org/10.3390/su11143757.

Matos, Florinda, and Celeste Jacinto. 2019. "Additive Manufacturing Technology: Mapping Social Impacts." *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-12-2017-0263.

Meisel, Nicholas A., Christopher B. Williams, Kimberly P. Ellis, and Don Taylor. 2016. "Decision Support for Additive Manufacturing Deployment in Remote or Austere Environments." *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-06-2015-0040.

Milewski, John O. 2017. "Trends in AM, Government, Industry, Research, Business." In *Springer Series in Materials Science*. https://doi.org/10.1007/978-3-319-58205-4_12.

Minetola, Paolo, and Daniel Eyers. 2018. "Energy and Cost Assessment of 3D Printed Mobile Case Covers." In *Procedia CIRP*. https://doi.org/10.1016/j.procir.2017.11.065.

Minguella-Canela, Joaquim, Sergio Morales Planas, Joan Ramon Gomà Ayats, and M. Antonia de los Santos López. 2018. "Assessment of the Potential Economic Impact of the Use of AM Technologies in the Cost Levels of Manufacturing and Stocking of Spare Part Products." *Materials*. https://doi.org/10.3390/ma11081429.

Mohajeri, Babak, Timo Nyberg, Jesse Karjalainen, Taina Tukiainen, Mark Nelson, Xiuqing Shang, and Gang Xiong. 2014. "The Impact of Social Manufacturing on the Value Chain Model in the Apparel Industry." In *Proceedings of 2014 IEEE International Conference on Service Operations and Logistics, and Informatics, SOLI 2014*. https://doi.org/10.1109/SOLI.2014.6960754.

Mohr, Sebastian, and Omera Khan. 2015. "3D Printing and Its Disruptive Impacts on Supply Chains of the Future." *Technology Innovation Management Review*. https://doi.org/10.22215/timreview942.

Naghshineh, Bardia, and Helena Carvalho. 2020. "The Impact of Additive Manufacturing on Supply Chain Resilience." In , 214–21. Springer, Cham. https://doi.org/10.1007/978-3-030-45124-0_20.

Nascimento, Daniel Luiz Mattos, Viviam Alencastro, Osvaldo Luiz Gonçalves Quelhas, Rodrigo Goyannes Gusmão Caiado, Jose Arturo Garza-Reyes, Luis Rocha Lona, and Guilherme

Tortorella. 2019. “Exploring Industry 4.0 Technologies to Enable Circular Economy Practices in a Manufacturing Context: A Business Model Proposal.” *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-03-2018-0071.

Olla, Phillip. 2015. “Opening Pandora?S 3D Printed Box.” *IEEE Technology and Society Magazine*. https://doi.org/10.1109/MTS.2015.2461197.

Ostuzzi, Francesca, Valentina Rognoli, Jelle Saldien, and Marinella Levi. 2015. “+TUO Project: Low Cost 3D Printers as Helpful Tool for Small Communities with Rheumatic Diseases.” *Rapid Prototyping Journal*. https://doi.org/10.1108/RPJ-09-2014-0111.

Palaniappan, A., S. Vinodh, and R. Ranganathan. 2020. “Analysis of Factors Influencing AM Application in Food Sector Using ISM.” *Journal of Modelling in Management*. https://doi.org/10.1108/JM2-11-2018-0190.

Pearce, Joshua M., Christine Morris Blair, Kristen J. Laciak, Rob Andrews, Amir Nosrat, and Ivana Zelenika-Zovko. 2010. “3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development.” *Journal of Sustainable Development*. https://doi.org/10.5539/jsd.v3n4p17.

Petrick, Irene J., and Timothy W. Simpson. 2013. “3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition.” *Research-Technology Management*. https://doi.org/10.5437/08956308x5606193.

Petrovic, Vojislav, Juan Vicente Haro Gonzalez, Olga Jordá Ferrando, Javier Delgado Gordillo, Jose Ramon Blasco Puchades, and Luis Portoles Grinan. 2011. “Additive Layered Manufacturing: Sectors of Industrial Application Shown through Case Studies.” *International Journal of Production Research*. https://doi.org/10.1080/00207540903479786.

Petrulaityte, Aine, Fabrizio Ceschin, Eujin Pei, and David Harrison. 2017. “Supporting Sustainable Product-Service System Implementation through Distributed Manufacturing.” In *Procedia CIRP*. https://doi.org/10.1016/j.procir.2017.03.070.

Piller, Frank T., Christian Weller, and Robin Kleer. 2015. “Business Models with Additive Manufacturing—Opportunities and Challenges from the Perspective of Economics and Management.” In *Advances in Production Technology*. https://doi.org/10.1007/978-3-319-12304-2_4.

Pinna, Claudia, Lucia Ramundo, Francesco G. Sisca, Cecilia Maria Angioletti, Marco Taisch, and Sergio Terzi. 2016. “Additive Manufacturing Applications within Food Industry: An Actual Overview and Future Opportunities.” In *Proceedings of the Summer School Francesco Turco*.

Potstada, Michael, and Jan Zybura. 2014. “The Role of Context in Science Fiction Prototyping: The Digital Industrial Revolution.” *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2013.08.026.

Rayna, Thierry, and Ludmila Striukova. 2016. “From Rapid Prototyping to Home Fabrication: How 3D Printing Is Changing Business Model Innovation.” *Technological Forecasting and*

Social Change. https://doi.org/10.1016/j.techfore.2015.07.023.

Rayna, Thierry, Ludmila Striukova, and John Darlington. 2015. "Co-Creation and User Innovation: The Role of Online 3D Printing Platforms." *Journal of Engineering and Technology Management - JET-M*. https://doi.org/10.1016/j.jengtecman.2015.07.002.

Rejeski, David, Fu Zhao, and Yong Huang. 2018. "Research Needs and Recommendations on Environmental Implications of Additive Manufacturing." *Additive Manufacturing*. https://doi.org/10.1016/j.addma.2017.10.019.

Ribeiro, Inês, Florinda Matos, Celeste Jacinto, Hafiz Salman, Gonçalo Cardeal, Helena Carvalho, Radu Godina, and Paulo Peças. 2020. "Framework for Life Cycle Sustainability Assessment of Additive Manufacturing." *Sustainability (Switzerland)*. https://doi.org/10.3390/su12030929.

Rindfleisch, Aric, Matthew O'Hern, and Vishal Sachdev. 2017. "The Digital Revolution, 3D Printing, and Innovation as Data." *Journal of Product Innovation Management*. https://doi.org/10.1111/jpim.12402.

Rumpala, Yannick. 2016. "A New Printing Revolution? 3D Printing as an Agent of Socio-Political Change." *International Journal of Technoethics*. https://doi.org/10.4018/IJT.2016070107.

Schniederjans, Dara G. 2017. "Adoption of 3D-Printing Technologies in Manufacturing: A Survey Analysis." *International Journal of Production Economics*. https://doi.org/10.1016/j.ijpe.2016.11.008.

Steenhuis, Harm Jan, and Leon Pretorius. 2017. "The Additive Manufacturing Innovation: A Range of Implications." Journal of Manufacturing Technology Management. https://doi.org/10.1108/JMTM-06-2016-0081.

Sutherland, John W., Justin S. Richter, Margot J. Hutchins, David Dornfeld, Rachel Dzombak, Jennifer Mangold, Stefanie Robinson, et al. 2016. "The Role of Manufacturing in Affecting the Social Dimension of Sustainability." *CIRP Annals - Manufacturing Technology*. https://doi.org/10.1016/j.cirp.2016.05.003.

Taddese, G., Durieux, S. and Duc, E., 2020. "Sustainability performance indicators for additive manufacturing: a literature review based on product life cycle studies". *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-020-05249-2

Tatham, Peter, Jennifer Loy, and Umberto Peretti. 2015. "Three Dimensional Printing – a Key Tool for the Humanitarian Logistician?" Journal of Humanitarian Logistics and Supply Chain Management. https://doi.org/10.1108/JHLSCM-01-2014-0006.

Thomas Campbell, Christopher Williams, Olga Ivanova, and Banning Garrett. 2011. "Could 3D Printing Change the World?" Atlantic Council.

Torres, Bruna, Bardia Naghshineh, Gonçalo Cardeal, Duarte Filipe, Helena Carvalho, Paulo

Peças, and Inês Ribeiro. 2020. “The Impacts of Additive Manufacturing Technology on Lean/Green Supply Chain Management Practices.” *In European Lean Educator Conference*. https://doi.org/10.1007/978-3-030-41429-0_16.

Tuck, Christopher, Richard Hague, and Neil Burns. 2007. “Rapid Manufacturing: Impact on Supply Chain Methodologies and Practice.” *International Journal of Services and Operations Management*. https://doi.org/10.1504/IJSOM.2007.011459.

UNEP Setac Life Cycle Initiative 2009. Guidelines for Social Life Cycle Assessment of Products, Management, United Nations Environment Programme, Washington, DC, USA, DTI/1164/PA. Available online:http://www.fao.org/sustainable-food-value-chains/library/details/en/c/266243/// (accessed on 9 June 2020).

UNEP/Setac 2013, The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA), United Nations Environment Programme, Paris. Available online: https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf (accessed on 9 June 2020).

Vijayavenkataraman, S., W. F. Lu, and J. Y.H. Fuh. 2016. “3D Bioprinting – An Ethical, Legal and Social Aspects (ELSA) Framework.” *Bioprinting*. https://doi.org/10.1016/j.bprint.2016.08.001.

Villamil, C., J. Nylander, S. I. Hallstedt, J. Schulte, and M. Watz. 2018. “Additive Manufacturing from a Strategic Sustainability Perspective.” In *Proceedings of International Design Conference, DESIGN*. https://doi.org/10.21278/idc.2018.0353.

Waller, Matthew A., and Stanley E. Fawcett. 2014. “Click Here to Print a Maker Movement Supply Chain: How Invention and Entrepreneurship Will Disrupt Supply Chain Design.” *Journal of Business Logistics*. https://doi.org/10.1111/jbl.12045.

Walther, Gerald. 2015. “Printing Insecurity? The Security Implications of 3D-Printing of Weapons.” *Science and Engineering Ethics*. https://doi.org/10.1007/s11948-014-9617-x.

Wang, Sheng-Wen, Chia-Wei Hsu, and Allen H. Hu. 2016. “An Analytic Framework for Social Life Cycle Impact Assessment—Part 1: Methodology.” *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-016-1114-9.

Wang, Steve Hsueh Ming, Yan Rui Qu, Chao Chang A. Chen, and Shu Ping Chang. 2014. “A Survey of Sustainable Design-Centered Integration for Medical Additive Manufacturing.” In *Advanced Materials Research*. https://doi.org/10.4028/www.scientific.net/AMR.939.635.

Weller, Christian, Robin Kleer, and Frank T. Piller. 2015. “Economic Implications of 3D Printing: Market Structure Models in Light of Additive Manufacturing Revisited.” *International Journal of Production Economics*. https://doi.org/10.1016/j.ijpe.2015.02.020.

West, Joel, and George Kuk. 2016. “The Complementarity of Openness: How MakerBot Leveraged Thingiverse in 3D Printing.” *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2015.07.025.

Yoo, Byounghyun, Heedong Ko, and Sungkuk Chun. 2016. “Prosumption Perspectives on Additive Manufacturing: Reconfiguration of Consumer Products with 3D Printing.” *Rapid Prototyping Journal*. https://doi.org/10.1108/RPJ-01-2015-0004.

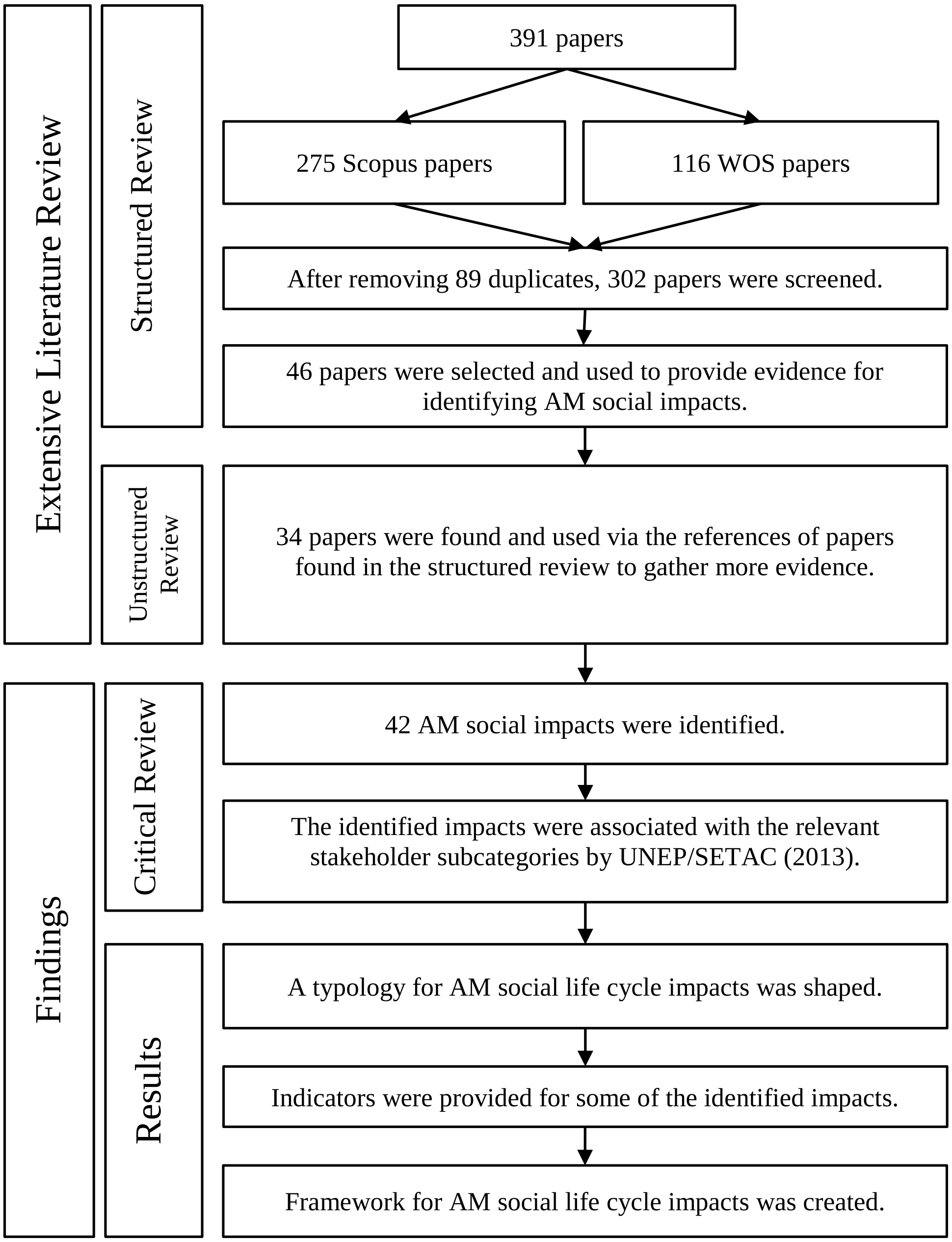

Figure 1. Methodological approach

Figure 2. Typology for the AM social life cycle impacts

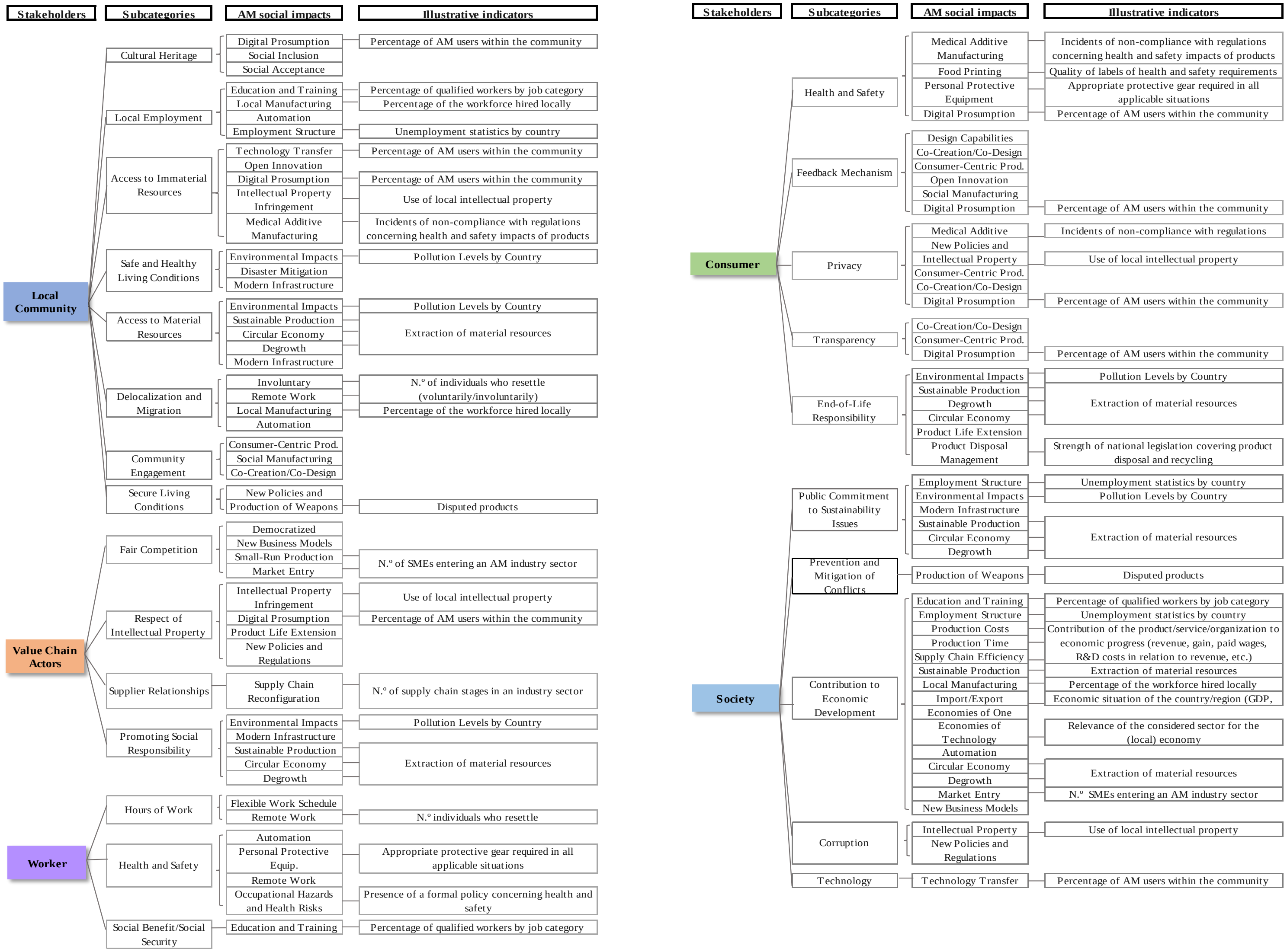

Figure 3. Framework for AM social life cycle impacts

Table 1. Sample summary statistics

Year	Journal	Conference proceedings	Book (Chapter)	Total
2020	4	2		6
2019	4			4
2018	8	2		10
2017	10	2	2	14
2016	12	1	1	14
2015	11	2		13
2014	7	1	1	9
2013	3			3
2012	2			2
2011	1	1		2
2010	2			2
2007	1			1
Total	65	11	4	80
Percent	81%	14%	5%	100%

Table 2. Proposed Indicators

No.	AM social impact name	Suggested indicator	Indicator Type
1	Circular Economy	Extraction of material resources (*)	Q.n
2	Degrowth	Extraction of material resources (*)	Q.n
3	Digital Prosumption	Percentage of AM users within the community (+)	Q.n
4	Economies of Technology	Relevance of the considered sector for the (local) economy (share of GDP, the number of employees in relation to the size of the working population, wage level, etc.) (*)	Q.n/Q.l
5	Education and Training	Percentage of qualified workers by job category (+)	Q.n
6	Employment Structure	Unemployment statistics by country (*)	Q.n
7	Environmental Impacts	Pollution Levels by Country (*)	Q.n
8	Food Printing	Quality of labels of health and safety requirements (*)	Q.l/ s.Q.n
9	Import/Export Imbalance	Economic situation of the country/region (GDP, economic growth, unemployment, wage level, etc.) (*)	Q.n/Q.l
10	Intellectual Property Infringement	Use of local intellectual property (*)	Q.n/s.Q.n/Q.l
11	Involuntary Resettlement	Number of individuals who resettle (voluntarily and involuntarily) (*)	Q.n
12	Local Manufacturing	Percentage of the workforce hired locally (*)	Q.n
13	Market Entry	Number of SMEs entering an AM industry sector (+)	Q.n
14	Medical Additive Manufacturing	Incidents of non-compliance with regulations concerning health and safety impacts of products (*)	Q.n/s.Q.n/Q.l
15	Occupational Hazards and Health Risks	Presence of a formal policy concerning health and safety (*)	s.Q.n
16	Personal Protective Equipment	Appropriate protective gear required in all applicable situations (*)	Q.l/s.Q.n
17	Product Disposal Management	Strength of national legislation covering product disposal and recycling (*)	s.Q.n
18	Production Costs	Contribution of the product/service/organization to economic progress (revenue, gain, paid wages, R&D costs in relation to revenue, etc.) (*)	Q.n/Q.l
19	Production of Weapons	Disputed products (*)	s.Q.n/Q.l
20	Production Time	Contribution of the product/service/organization to economic progress (revenue, gain, paid wages, R&D costs in relation to revenue, etc.) (*)	Q.n/Q.l
21	Remote Work	Number of individuals who resettle (voluntarily and involuntarily) (*)	Q.n
22	Small-Run Production	Number of SMEs entering an AM industry sector (+)	Q.n
23	Supply Chain Efficiency and Responsiveness	Contribution of the product/service/organization to economic progress (revenue, gain, paid wages, R&D costs in relation to revenue, etc.) (*)	Q.n/Q.l
24	Supply Chain Reconfiguration	Number of supply chain stages in an industry sector (+)	Q.n
25	Sustainable Production	Extraction of material resources (*)	Q.n
26	Technology Transfer	Percentage of AM users within the community (+)	Q.n

Notes: (*) UNEP/SETAC (2013), (+) Authors, (Q.n) Quantitative, (s.Q.n) Semi-quantitative, (Q.l) Qualitative

Appendix A. Sample results

Authors	Title	Journal	Type
(Beltagui, Kunz, and Gold 2020)	The Role of 3D Printing and Open Design on Adoption of Socially Sustainable Supply Chain Innovation.	International Journal of Production Economics	Journal
(Khan, Sanchez, and Zhou 2020)	3-D Printing of Concrete: Beyond Horizons.	Cement and Concrete Research	Journal
(Naghshineh and Carvalho 2020)*	The Impact of Additive Manufacturing on Supply Chain Resilience.	Doctoral Conference on Computing, Electrical and Industrial Systems	Conference proceedings
(Palaniappan, Vinodh, and Ranganathan 2020)	Analysis of Factors Influencing AM Application in Food Sector Using ISM.	Journal of Modelling in Management	Journal
(Ribeiro et al. 2020)	Framework for Life Cycle Sustainability Assessment of Additive Manufacturing.	Sustainability	Journal
(Torres et al. 2020)*	The Impacts of Additive Manufacturing Technology on Lean/Green Supply Chain Management Practices.	European Lean Educator Conference	Conference proceedings
(Kang and Kim 2019)	Development of Helmet Mold Design System Using 3D Anthropometric Analysis.	International Journal of Clothing Science and Technology	Journal
(Khorram Niaki et al. 2019)	Economic Sustainability of Additive Manufacturing: Contextual Factors Driving Its Performance in Rapid Prototyping.	Journal of Manufacturing Technology Management	Journal
(Matos et al. 2019)	Additive Manufacturing: Exploring the Social Changes and Impacts.	Sustainability	Journal
(Nascimento et al. 2019)	Exploring Industry 4.0 Technologies to Enable Circular Economy Practices in a Manufacturing Context: A Business Model Proposal.	Journal of Manufacturing Technology Management	Journal
(Chan et al., 2018)*	The Impact of 3D Printing Technology on the Supply Chain: Manufacturing and Legal Perspectives.	International Journal of Production Economics	Journal
(Hankammer and Kleer 2018)*	Degrowth and Collaborative Value Creation: Reflections on Concepts and Technologies.	Journal of Cleaner Production	Journal
(Kapetaniou et al. 2018)*	Building the Layers of a New Manufacturing Taxonomy: How 3D Printing Is Creating a New Landscape of Production Eco-Systems and Competitive Dynamics.	Technological Forecasting and Social Change	Journal

(Kostakis et al. 2018)*	The Convergence of Digital Commons with Local Manufacturing from a Degrowth Perspective: Two Illustrative Cases.	Journal of Cleaner Production	Journal
(Ma et al. 2018)	An Exploratory Investigation of Additively Manufactured Product Life Cycle Sustainability Assessment.	Journal of Cleaner Production	Journal
(Mangat et al. 2018)	Experimental Investigations on Natural Fiber Embedded Additive Manufacturing-Based Biodegradable Structures for Biomedical Applications.	Rapid Prototyping Journal	Journal
(Minetola and Eyers 2018)	Energy and Cost Assessment of 3D Printed Mobile Case Covers.	Procedia CIRP	Conference proceedings
(Minguella-Canela et al. 2018)	Assessment of the Potential Economic Impact of the Use of AM Technologies in the Cost Levels of Manufacturing and Stocking of Spare Part Products.	Materials	Journal
(Rejeski, Zhao and Huang, 2018)*	Research Needs and Recommendations on Environmental Implications of Additive Manufacturing.	Additive Manufacturing	Journal
(Villamil et al. 2018)*	Additive Manufacturing from a Strategic Sustainability Perspective.	Proceedings of International Design Conference, DESIGN	Conference proceedings
(Angioletti, Despeisse, and Rocca 2017)	Product Circularity Assessment Methodology.	IFIP Advances in Information and Communication Technology	Book Series
(Despeisse et al. 2017a)	Unlocking Value for a Circular Economy through 3D Printing: A Research Agenda.	Technological Forecasting and Social Change	Journal
(Despeisse et al. 2017b)*	Sustainable Value Roadmapping Framework for Additive Manufacturing.	Procedia CIRP	Conference proceedings
(Hartl and Kort 2017)	Possible Market Entry of a Firm with an Additive Manufacturing Technology.	International Journal of Production Economics	Journal
(Huang et al. 2017)	Environmental and Economic Implications of Distributed Additive Manufacturing: The Case of Injection Mold Tooling.	Journal of Industrial Ecology	Journal
(Jiang, Kleer, and Piller 2017)	Predicting the Future of Additive Manufacturing: A Delphi Study on Economic and Societal Implications of 3D Printing for 2030.	Technological Forecasting and Social Change	Journal
(Lind et al. 2017)	Social Aspects in Additive Manufacturing of Pharmaceutical Products.	Expert Opinion on Drug Delivery	Journal
(Lupton and Turner 2017)	Both Fascinating and Disturbing': Consumer Responses to 3D Food Printing and Implications for Food Activism.	SSRN	Journal

(Mami et al. 2017)	Evaluating Eco-Efficiency of 3D Printing in the Aeronautic Industry.	Journal of Industrial Ecology	Journal
(Milewski 2017)	Trends in AM, Government, Industry, Research, Business.	Springer Series in Materials Science	Book Series
(Petrulaityte et al. 2017)	Supporting Sustainable Product-Service System Implementation through Distributed Manufacturing.	Procedia CIRP	Conference proceedings
(Rindfleisch, O'Hern, and Sachdev 2017)*	The Digital Revolution, 3D Printing, and Innovation as Data.	Journal of Product Innovation Management	Journal
(Schniederjans 2017)*	Adoption of 3D-Printing Technologies in Manufacturing: A Survey Analysis.	International Journal of Production Economics	Journal
(Steenhuis and Pretorius 2017)	The Additive Manufacturing Innovation: A Range of Implications.	Journal of Manufacturing Technology Management	Journal
(Bogers, Hadar, and Bilberg 2016)*	Additive Manufacturing for Consumer-Centric Business Models: Implications for Supply Chains in Consumer Goods Manufacturing.	Technological Forecasting and Social Change	Journal
(De la Torre, Espinosa, and Domínguez 2016)*	Rapid Prototyping in Humanitarian Aid To Manufacture Last Mile Vehicles Spare Parts: An Implementation Plan.	Human Factors and Ergonomics In Manufacturing	Journal
(Fleischmann, Hielscher, and Merritt 2016)	Making Things in Fab Labs: A Case Study on Sustainability and Co-Creation.	Digital Creativity	Journal
(Ford and Despeisse 2016)*	Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges.	Journal of Cleaner Production	Journal
(Giraud and Jouffrais 2016)	Empowering Low-Vision Rehabilitation Professionals with 'Do-It-Yourself' Methods.	Lecture Notes in Computer Science	Book Series
(Griffiths et al. 2016)	A Design of Experiments Approach for the Optimisation of Energy and Waste during the Production of Parts Manufactured by 3D Printing.	Journal of Cleaner Production	Journal
(Loy, Canning, and Haskell 2016)	3D Printing Sociocultural Sustainability.	Environmental Footprints and Eco-Design of Products and Processes	Journal
(Meisel et al. 2016)*	Decision Support for Additive Manufacturing Deployment in Remote or Austere Environments.	Journal of Manufacturing Technology Management	Journal
(Pinna et al. 2016)	Additive Manufacturing Applications within Food Industry: An Actual Overview and Future Opportunities.	Proceedings of the Summer School Francesco Turco	Conference proceedings
(Rayna and Striukova 2016)	From Rapid Prototyping to Home Fabrication: How 3D Printing Is Changing Business Model Innovation.	Technological Forecasting and Social Change	Journal

(Rumpala 2016)	A New Printing Revolution? 3D Printing as an Agent of Socio-Political Change.	International Journal of Technoethics	Journal
(Vijayavenkataraman, Lu, and Fuh 2016)	3D Bioprinting – An Ethical, Legal and Social Aspects (ELSA) Framework.	Bioprinting	Journal
(West and Kuk 2016)*	The Complementarity of Openness: How MakerBot Leveraged Thingiverse in 3D Printing.	Technological Forecasting and Social Change	Journal
(Yoo, Ko, and Chun 2016)	Prosumption Perspectives on Additive Manufacturing: Reconfiguration of Consumer Products with 3D Printing.	Rapid Prototyping Journal	Journal
(Chen et al. 2015)*	Direct Digital Manufacturing: Definition, Evolution, and Sustainability Implications.	Journal of Cleaner Production	Journal
(Galimberti et al. 2015)	Digital Aesthetic of New Products Obtained by Selective Laser Melting Process.	Proceedings of the International Conference on Engineering Design, ICED	Conference proceedings
(Gao et al. 2015)*	The Status, Challenges, and Future of Additive Manufacturing in Engineering.	Computer-Aided Design	Journal
(Kietzmann, Pitt, and Berthon 2015)*	Disruptions, Decisions, and Destinations: Enter the Age of 3-D Printing and Additive Manufacturing.	Business Horizons	Journal
(Kim 2015)	A Study on the Socio-Economic Impact of 3D Printing.	Journal of Digital Convergence	Journal
(Kohtala and Hyysalo 2015)	Anticipated Environmental Sustainability of Personal Fabrication.	Journal of Cleaner Production	Journal
(Mohr and Khan 2015)*	3D Printing and Its Disruptive Impacts on Supply Chains of the Future.	Technology Innovation Management Review	Journal
(Ostuzzi et al. 2015)	TUO Project: Low Cost 3D Printers as Helpful Tool for Small Communities with Rheumatic Diseases.	Rapid Prototyping Journal	Journal
(Piller, Weller, and Kleer 2015)*	Business Models with Additive Manufacturing—Opportunities and Challenges from the Perspective of Economics and Management.	Advances in Production Technology	Conference proceedings
(Rayna, Striukova, and Darlington 2015)	Co-Creation and User Innovation: The Role of Online 3D Printing Platforms.	Journal of Engineering and Technology Management - JET-M	Journal
(Tatham, Loy, and Peretti 2015)	Three Dimensional Printing – a Key Tool for the Humanitarian Logistician?	Journal of Humanitarian Logistics and Supply Chain Management	Journal
(Walther 2015)	Printing Insecurity? The Security Implications of 3D-Printing of Weapons.	Science and Engineering Ethics	Journal
(Weller, Kleer, and Piller 2015)*	Economic Implications of 3D Printing: Market Structure	International Journal of	Journal

	Models in Light of Additive Manufacturing Revisited.	Production Economics	
(Calderon, Griffin, and Zagal 2014)	BeamMaker: An Open Hardware High-Resolution Digital Fabricator for the Masses.	Rapid Prototyping Journal	Journal
(Garrett 2014)*	3D Printing: New Economic Paradigms and Strategic Shifts.	Global Policy	Journal
(Gebler, Schoot Uiterkamp, and Visser 2014)*	A Global Sustainability Perspective on 3D Printing Technologies.	Energy Policy	Journal
(Lee Ventola 2014)*	Medical Applications for 3D Printing: Current and Projected Uses.	Pharmacy and Therapeutics	Journal
(Liu et al. 2014)*	The Impact of Additive Manufacturing in the Aircraft Spare Parts Supply Chain: Supply Chain Operation Reference (Scor) Model Based Analysis.	Production Planning and Control	Journal
(Mohajeri et al. 2014)	The Impact of Social Manufacturing on the Value Chain Model in the Apparel Industry.	In Proceedings of 2014 IEEE International Conference on Service Operations and Logistics, and Informatics, SOLI 2014	Conference proceedings
(Potstada and Zybura 2014)	The Role of Context in Science Fiction Prototyping: The Digital Industrial Revolution.	Technological Forecasting and Social Change	Journal
(Waller and Fawcett 2014)*	Click Here to Print a Maker Movement Supply Chain: How Invention and Entrepreneurship Will Disrupt Supply Chain Design.	Journal of Business Logistics	Journal
(Wang et al. 2014)	A Survey of Sustainable Design-Centered Integration for Medical Additive Manufacturing.	Advanced Materials Research	Book Series
(Birtchnell and Urry 2013)*	3D, SF and the Future.	Futures	Journal
(Huang et al. 2013)	Additive Manufacturing and Its Societal Impact: A Literature Review.	The International Journal of Advanced Manufacturing Technology	Journal
(Petrick and Simpson 2013)	3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition.	Research Technology Management	Journal
(Atzeni and Salmi 2012)*	Economics of Additive Manufacturing for End-Usable Metal Parts.	The International Journal of Advanced Manufacturing Technology	Journal
(Berman 2012)*	3-D Printing: The New Industrial Revolution.	Business Horizons	Journal
(Petrovic et al. 2011)*	Additive Layered Manufacturing: Sectors of Industrial Application Shown through Case Studies.	International Journal of Production Research	Journal

(Thomas Campbell et al. 2011)*	Could 3D Printing Change the World?	Atlantic Council	Conference proceedings
(Diegel et al. 2010)*	Tools for Sustainable Product Design: Additive Manufacturing.	Journal of Sustainable Development	Journal
(Pearce et al. 2010)*	3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development.	Journal of Sustainable Development	Journal
(Tuck, Hague, and Burns 2007)	Rapid Manufacturing: Impact on Supply Chain Methodologies and Practice.	International Journal of Services and Operations Management	Journal

Note: * = Papers found in the unstructured literature review

Appendix B. Identified AM social impacts

No.	AM social impact name	Example of supporting evidence	Other references
1	Automation	"3DP induces changes in social and labour structures due to high degrees of automation and an expected shift towards more localized means of production in consumer countries." (Gebler, Schoot Uiterkamp, and Visser 2014)	(Despeisse et al. 2017b) (Thomas Campbell et al. 2011)
2	Circular Economy	"Additive manufacturing technologies provide opportunities to support sustainable manufacturing and the circular economy paradigm." (Angioletti, Despeisse, and Rocca 2017)	(Nascimento et al. 2019) (Minetola and Eyers 2018) (Birtchnell and Urry 2013)
3	Co-Creation/Co-Design	"With additive manufacturing, consumers are able not only to customize existing products (by modifying their design files with an easy-to-use toolkit), but also to create and co-design their very own offerings." (Jiang, Kleer, and Piller 2017)	(Chan et al., 2018) (Fleischmann, Hielscher, and Merritt 2016) (Rayna, Striukova, and Darlington 2015) (Weller, Kleer, and Piller 2015) (Ostuzzi et al. 2015) (Birtchnell and Urry 2013)
4	Consumer-Centric Production	"The characteristics of AM technologies, as presented earlier, give rise to the opportunity to implement a consumer-centric business model through a decentralized supply chain." (Bogers, Hadar, and Bilberg 2016)	(Jiang, Kleer, and Piller 2017) (Ostuzzi et al. 2015) (Rayna, Striukova, and Darlington 2015) (Weller, Kleer, and Piller 2015) (Birtchnell and Urry 2013)
5	Degrowth	"The concept of degrowth aims fundamentally at reducing material and energy throughput equitably, while questioning the desirability of further economic growth […] The same applies to the assessment of (new) technologies, such as additive manufacturing, web-based user interfaces for co-creation, and other flexible production technologies that allow for collaborative and individualized production." (Hankammer and Kleer 2018)	(Kostakis et al. 2018)
6	Democratized Production	"A second social dimension relates to the democratisation of production that direct digital manufacturing technologies such as AM provides." (Ford and Despeisse 2016)	(Yoo, Ko, and Chun 2016) (Chen et al. 2015) (Calderon, Griffin, and Zagal 2014)
7	Design Capabilities	"However, AM allows design optimization that can lead to products with the same functionality but having less weight compare to that to be produced using conventional	(Beltagui, Kunz, and Gold 2020) (Ribeiro et al. 2020) (Mangat et al. 2018)

		manufacturing processes.” (Huang et al. 2013)	(Ford and Despeisse 2016) (Griffiths et al. 2016) (Loy, Canning, and Haskell 2016) (West and Kuk 2016) (Galimberti et al. 2015) (Tatham, Loy, and Peretti 2015) (Birtchnell and Urry 2013) (Petrick and Simpson 2013) (Atzeni and Salmi 2012) (Berman 2012) (Petrovic et al. 2011) (Diegel et al. 2010)
8	Digital Prosumption	“Such 'printing', or 'personal fabrication', could permit many objects to be produced near to or even by consumers themselves on just-in-time 'printing' machines.” (Birtchnell and Urry 2013b)	(Matos et al. 2019) (Chan et al., 2018) (Jiang, Kleer, and Piller 2017) (Bogers, Hadar, and Bilberg 2016) (Giraud and Jouffrais 2016) (Loy, Canning, and Haskell 2016) (Rumpala 2016) (Yoo, Ko, and Chun 2016) (Kohtala and Hyysalo 2015) (Rayna, Striukova, and Darlington 2015) (Potstada and Zybura 2014) (Calderon, Griffin, and Zagal 2014) (Mohajeri et al. 2014) (Waller and Fawcett 2014) (Petrick and Simpson 2013) (Berman 2012)
9	Disaster Mitigation	“3DP has the potential to improve the response to disasters and development operations through the swift production of items of equipment or replacement spare parts.” (Tatham, Loy, and Peretti 2015)	(Meisel et al. 2016) (De la Torre, Espinosa, and Domínguez 2016)
10	Economies of One	“In essence, future manufacturers will be governed by two sets of rules: economies of scale for interchangeable parts produced at high volumes, and economies of one for highly customizable products that can be built layer by layer.” (Petrick and Simpson 2013)	(Galimberti et al. 2015) (Tuck, Hague, and Burns 2007)
11	Economies of Technology	“Multiple RM machinery can currently be operated by a single operator, thus reducing the demands placed on the labour force, and consequently, bringing manufacturing back from low wage	

		economies. Thus the economies of the global work place could be replaced by the economies of technology.” (Tuck, Hague, and Burns 2007)	
12	Education and Training	“Due to the rapid acceleration of industrial interest and recent adoption of AM technologies, there exists a significant need for educating a workforce knowledgeable about how to employ AM.” (Gao et al. 2015)	(Matos et al. 2019) (Fleischmann, Hielscher, and Merritt 2016) (Giraud and Jouffrais 2016)
13	Employment Structure	“3DP induces changes in social and labour structures due to high degrees of automation and an expected shift towards more localized means of production in consumer countries.” (Gebler, Schoot Uiterkamp, and Visser 2014)	(Matos et al. 2019) (Pearce et al. 2010) (Tuck, Hague, and Burns 2007)
14	Environmental Impacts	“Applied to an aircraft doorstop manufacturing, results show that 3D printing has clear benefits both in terms of costs and environmental impacts compared to conventional machining.” (Mami et al. 2017)	(Ma et al. 2018) (Rejeski, Zhao and Huang, 2018) (Villamil et al. 2018) (Jiang, Kleer, and Piller 2017) (Huang et al. 2017) (Loy, Canning, and Haskell 2016) (Kohtala and Hyysalo 2015) (Gebler, Schoot Uiterkamp, and Visser 2014) (Huang et al. 2013)
15	Flexible Work Schedule	“Two of the interviewees considered that “more flexible work schedules” has a positive impact, since several portable 3D machines can be easily used anywhere (i.e., the home, office, events, etc.). Two others considered that there will be no impact concerning this factor.” (Matos et al. 2019)	
16	Food Printing	“Fabricated food using 3D printing technologies has the potential to address challenges that have been identified by food activists and those contributing to scholarship on the politics of food. These include food sustainability, food waste, ethical consumption, environmental degradation and world hunger issues.” (Lupton and Turner 2017)	(Palaniappan, Vinodh, and Ranganathan 2020) (Pinna et al. 2016)
17	Import/Export Imbalance	“This localization of production could potentially reduce global economic imbalances as export countries’ surpluses are reduced and importing countries’ reliance on imports shrink with a new form of ‘import substitution’ taking hold.” (Garrett 2014)	(Khan, Sanchez, and Zhou 2020) (Thomas Campbell et al. 2011)
18	Intellectual Property Infringement	“The main drawbacks of 3D printing includes the following: It might cause 3D printing-related crimes (e.g. printed weapons, intellectual property infringement, etc.)” (Kim 2015)	(Matos et al. 2019) (Chan et al. 2018) (Jiang, Kleer, and Piller 2017) (Steenhuis and Pretorius 2017)

			(Vijayavenkataraman, Lu, and Fuh 2016) (Birtchnell and Urry 2013) (Garrett 2014) (Pearce et al. 2010)
19	Involuntary Resettlement	“3DP induces changes in social and labour structures due to high degrees of automation and an expected shift towards more localized means of production in consumer countries.” (Gebler, Schoot Uiterkamp, and Visser 2014)	(Petrick and Simpson 2013) (Huang et al. 2013) (Tuck, Hague, and Burns 2007)
20	Local Manufacturing	“Proximity between supplier, manufacturer, and customer will matter, and localized production will be not only more feasible but more desirable.” (Petrick and Simpson 2013)	(Beltagui, Kunz, and Gold 2020) (Kostakis et al. 2018) (Jiang, Kleer, and Piller 2017) (Bogers, Hadar, and Bilberg 2016) (Ford and Despeisse 2016) (Rumpala 2016) (Kohtala and Hyysalo 2015) (Mohr and Khan 2015) (Piller, Weller, and Kleer 2015) (Gebler, Schoot Uiterkamp, and Visser 2014) (Birtchnell and Urry 2013) (Huang et al. 2013) (Thomas Campbell et al. 2011) (Tuck, Hague, and Burns 2007)
21	Market Entry	“Our findings demonstrate that consumer 3DP may support market entry when small firms leverage open design to overcome their resource constraints.” (Beltagui, Kunz, and Gold 2020)	(Hartl and Kort 2017) (Chen et al. 2015) (Birtchnell and Urry 2013)
22	Medical Additive Manufacturing	“A number of materials have been used for Medical Additive Manufacturing (MAM), such as stem cells, biopolymers, metals, bio-ceramics, and bio-glass. Recent research includes potential applications in the replacement of human tissues, organs, and bones by using the bio-printing technology.” (Wang et al. 2014)	(Jiang, Kleer, and Piller 2017) (Lind et al. 2017) (Vijayavenkataraman, Lu, and Fuh 2016) (Ostuzzi et al. 2015) (Lee Ventola 2014) (Huang et al. 2013) (Petrovic et al. 2011)
23	Modern Infrastructure	“Emerging economies are seeing the advantages of developing AM capabilities without the burden of historical infrastructures and as a potential means to leap frog the development of costly infrastructure or creating an advanced manufacturing infrastructure well suited to regional needs.” (Milewski 2017)	(De la Torre, Espinosa, and Domínguez 2016) (Tatham, Loy, and Peretti 2015)
24	New Business Models	“Whereas the impact of rapid prototyping and rapid tooling on business models component is rather limited, the next stage of	(Nascimento et al. 2019) (Kostakis et al. 2018)

		development – direct manufacturing – has the potential to profoundly disrupt business models.” (Rayna and Striukova 2016)	(Villamil et al. 2018) (Jiang, Kleer, and Piller 2017) (Bogers, Hadar, and Bilberg 2016) (Pinna et al. 2016) (Piller, Weller, and Kleer 2015) (Gebler, Schoot Uiterkamp and Visser, 2014) (Potstada and Zybura 2014) (Birtchnell and Urry 2013) (Petrick and Simpson 2013) (Berman 2012)
25	New Policies and Regulations	“Policy decisions and appropriate regulatory concerns have to be made and addressed, even at an earlier stage of technology development. With bioprinting, the technology which has the potential to save lives and revolutionize the medical field deserves special attention in having a legal framework.” (Vijayavenkataraman, Lu, and Fuh 2016)	(Rejeski, Zhao and Huang, 2018) (Jiang, Kleer, and Piller 2017)
26	Occupational Hazards and Health Risks	“AM processes have the potential to reduce hazards that are endemic to many conventional manufacturing processes–they may in principle be self-contained, use less materials, and produce less waste.” (Rejeski, Zhao, and Huang 2018)	(Ford and Despeisse 2016) (Chen et al. 2015) (Huang et al. 2013)
27	Open Innovation	“Consumer-owned printers, for instance, are one of the many means of production that firms can use within a co-creation activity.” (Rayna, Striukova, and Darlington 2015)	(Beltagui, Kunz, and Gold 2020) (Rindfleisch, O’Hern, and Sachdev 2017) (Schniederjans 2017) (Steenhuis and Pretorius 2017) (Pinna et al. 2016) (Ford and Despeisse 2016) (Rumpala 2016) (West and Kuk 2016) (Yoo, Ko, and Chun 2016) (Piller, Weller, and Kleer 2015) (Pearce et al. 2010)
28	Personal Protective Equipment	“Safety equipment produced using AM technology has the potential to provide excellent protection without sacrificing personal comfort of the user. As a result, the user can achieve a high level of performance while receiving maximum protection.” (Huang et al. 2013)	(Kang and Kim 2019)
29	Product Disposal Management	“Moreover, in the framework of circular economy, 3D printing empowers the final user with full control of the end-of-life product disposal management.” (Minetola and Eyers 2018)	

30	Product Life Extension	"Another positive sustainability potential with AM technology is the possibility to use it to repair or re-design, and thereby extend the life-time of the product." (Villamil et al. 2018)	(Matos et al. 2019) (Angioletti, Despeisse, and Rocca 2017) (Petrulaityte et al. 2017) (Yoo, Ko, and Chun 2016)
31	Production Costs	"The opportunities available for reduction in costs of production, through the natural rationalisation of logistics, labour, stock holding and the ability to deal with unstable demand patterns are all apparent." (Tuck, Hague, and Burns 2007)	(Khan, Sanchez, and Zhou 2020) (Khorram Niaki et al. 2019) (Mangat et al. 2018) (Minguella-Canela et al. 2018) (Mami et al. 2017) (Milewski 2017) (Huang et al. 2017) (Ford and Despeisse 2016) (Tatham, Loy, and Peretti 2015) (Chen et al. 2015) (Gebler, Schoot Uiterkamp, and Visser 2014) (Atzeni and Salmi 2012)
32	Production of Weapons	"In the longer term, 3DP provides the opportunity to substantially redesign weapons systems themselves as well as the individual parts of weapons." (Garrett 2014)	(Matos et al. 2019) (Rumpala 2016) (Kim 2015) (Walther 2015)
33	Production Time	"Delays due to tooling, that normally take several weeks of work, are avoided. Delays are costly. Eliminating those leads to a considerable financial benefit." (Atzeni and Salmi 2012)	(Huang et al. 2017) (Ford and Despeisse 2016) (Tatham, Loy, and Peretti 2015) (Berman 2012) (Petrovic et al. 2011)
34	Remote Work	"Remote work allows higher professional flexibility, but it can also "isolate" individuals from their workplace and organization, creating risks inherent to "work alone" situations, typically psychosocial risks." (Matos et al. 2019)	
35	Small-Run Production	"3D printing has been tipped as a prospective game-changer and the ability to produce and deliver small quantities, tailor made and complex products more flexibly and rapidly for local customers allows new value creation and business opportunities" (Kapetaniou et al. 2018)	(Rejeski, Zhao, and Huang 2018) (Liu et al. 2014)
36	Social Acceptance	"A critical analysis of the social aspects of this technology should be made, including the cultural, political and religious perspectives and […]"(Vijayavenkataraman, Lu, and Fuh 2016)	(Gebler, Schoot Uiterkamp, and Visser 2014)
37	Social Inclusion	"The possibility of using AM technology to reproduce replicas from museum objects and develop "3D museums" was also	(Giraud and Jouffrais 2016) (Ostuzzi et al. 2015)

		mentioned, resulting in opportunities of social inclusion (e.g., people with visual impairment).” (Matos et al. 2019)	
38	Social Manufacturing	“[…] in social manufacturing, the role of customers changes from being passive to being fully active agents in the manufacturing of products. This shift allows for the opportunity to produce customized products according to the needs of every single customer in the society.” (Mohajeri et al. 2014)	(Yoo, Ko, and Chun 2016) (Ostuzzi et al. 2015)
39	Supply Chain Efficiency and Responsiveness	“The ability to produce innovative customised products through an efficient and responsive supply chain could mean both increases in overall market share for organisations and increased satisfaction for the consumer.” (Tuck, Hague, and Burns 2007)	(Huang et al. 2017) (Ford and Despeisse 2016) (Tatham, Loy, and Peretti 2015) (Gebler, Schoot Uiterkamp, and Visser 2014) (Huang et al. 2013) (Atzeni and Salmi 2012)
40	Supply Chain Reconfiguration	“This new structure could eliminate many stages of the traditional supply chain, affecting lead times, inventory management, and transaction and logistics costs.” (Liu et al. 2014)	(Beltagui, Kunz, and Gold 2020) (Naghshineh and Carvalho 2020) (Torres et al. 2020) (Chan et al., 2018) (Lind et al. 2017) (Jiang, Kleer, and Piller 2017) (Steenhuis and Pretorius 2017) (Ford and Despeisse 2016) (Rumpala 2016) (Bogers, Hadar, and Bilberg 2016) (Piller, Weller, and Kleer 2015) (Weller, Kleer, and Piller 2015) (Gebler, Schoot Uiterkamp, and Visser 2014) (Potstada and Zybura 2014) (Birtchnell and Urry 2013) (Petrick and Simpson 2013) (Huang et al. 2013) (Thomas Campbell et al. 2011) (Berman 2012) (Tuck, Hague, and Burns 2007)
41	Sustainable Production	“Additive manufacturing technologies provide opportunities to support sustainable manufacturing and the circular economy paradigm.” (Angioletti, Despeisse, and Rocca 2017)	(Beltagui, Kunz, and Gold 2020) (Nascimento et al. 2019) (Hankammer and Kleer 2018) (Ma et al. 2018) (Mangat et al. 2018) (Villamil et al. 2018)

			(Lupton and Turner 2017) (Despeisse et al. 2017a) (Huang et al. 2017) (Ford and Despeisse 2016) (Griffiths et al. 2016) (Yoo, Ko, and Chun 2016) (Kohtala and Hyysalo 2015) (Chen et al. 2015) (Mohr and Khan 2015) (Gebler, Schoot Uiterkamp, and Visser 2014) (Birtchnell and Urry 2013) (Huang et al. 2013) (Atzeni and Salmi 2012) (Berman 2012) (Diegel et al. 2010) (Pearce et al. 2010)
42	Technology Transfer	"Additive Manufacturing processes are rapidly evolving in order to enable their increasing diffusion in all those industrial contexts where a flexible, customized and low volume production is needed." (Galimberti et al. 2015)	(Khan, Sanchez, and Zhou 2020)

3DP = 3D Printing, AM = Additive Manufacturing, RM = Rapid Manufacturing

Highlights

- 42 social impacts of Additive Manufacturing (AM) technology are identified.
- A typology is created that illustrates stakeholders impacted by AM.
- Indicators are proposed for assessing several AM social impacts.
- A comprehensive social life cycle framework for AM technology is proposed.