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# Impact Assessment of Additive Manufacturing on Sustainable Business Models in Industry 4.0 Context

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Received: 17 June 2020; Accepted: 26 August 2020; Published: 30 August 2020

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**Abstract:** Additive manufacturing has the potential to make a longstanding impact on the manufacturing world and is a core element of the Fourth Industrial Revolution. Additive manufacturing signifies a new disruptive path on how we will produce parts and products. Several studies suggest this technology could foster sustainability into manufacturing systems based on its potential of optimizing material consumption, creating new shapes, customizing designs and shortening production times that, all combined, will greatly transform some of the existing business models. Although it requires reaching a certain level of design maturity to completely insert this technology in an industrial setting, additive manufacturing has the potential to favorably impact the manufacturing sector by reducing costs in production, logistics, inventories, and in the development and industrialization of a new product. The transformation of the industry and the acceleration of the adopting rate of new technologies is driving organizational strategy. Thus, through the lenses of Industry 4.0 and its technological concepts, this paper aims to contribute to the knowledge about the impacts of additive manufacturing technology on sustainable business models. This aim is accomplished through a proposed framework, as well as the models and scales that can be used to determine these impacts. The effects are assessed by taking into account the social, environmental and economic impacts of additive manufacturing on business models and for all these three dimensions a balanced scorecard structure is proposed.

**Keywords:** additive manufacturing; 3D printing; business models; Industry 4.0; local manufacturing; spare parts

## 1. Introduction

Additive manufacturing, often associated with 3D printing, is one of the most promising manufacturing technologies [1–3], merging in the Fourth Industrial Revolution also named Industry 4.0. The evolution of technology and the confinement due to COVID-19 allows us to affirm that we are at a turning point where additive manufacturing is ready to become a viable alternative to traditional production processes in many aspects [4]. The additive manufacturing is not limited to the development of new design, offering products with better performance, less waste and a production volume adaptable to the particularities of the project [5–7]. The increasing popularity of additive manufacturing comes from its ability to produce flexibly, with a simplified logistics, expanding the possibility of creating new markets. The automotive [8], the aerospace [9,10] and defence industries [11] were some of the first industries to adopt additive manufacturing technology in prototyping processes, with benefits in customising products, designing complex tools and parts, reducing costs and time to market and creating a new design and much lighter products. The European additive manufacturing platform identifies two distinct markets for additive manufacturing: the industrial market that includes the medical, aerospace and automotive sectors and consumer market, which includes accessories and entertainment [12]. In fact, a study estimates that by 2020 the additive manufacturing will reach a market volume of 11 billion euros generated by sales of prototypes, materials and component manufacturing and with an optimistic perspective being able to reach about 130 billion in the next decade [2]. Additive manufacturing technology, joined with artificial intelligence and Internet of things (IoT), is transforming the healthcare sector, enabling major innovations in medical technology and surgical procedures, such as orthopaedics [13], dentistry [14], pharmaceutical products [15], cardiology [16] and tissue engineering [17].

The companies using and willing to use this emerging technology are not only focused on obtaining economic benefits, but also on competitive advantages to stand out in the market, besides environmental and social benefits [18]. The need for customized and sustainable production coming from consumers and environmental control agencies are driving changes in the structure of the entire value chain [19–21]. One main problem related with the adoption of additive manufacturing technology, as in any new technology, is the lack of knowledge about the impacts that technology adoption will have on redesigning value chain configurations and adopting (create new) business models focused, more and more, on (almost mandatory for competitiveness pressures) sustainability goals [22–24].

According to an European Commission Report [25], additive manufacturing is one of the emerging technologies of the digital era, with a significant impact on the industry. This is based on its potential benefits, namely, it reduces supply chains complexity/dimension and increases the efficiency of production value chains through the reduction of the time and costs for new product development, design and testing, and significant increases in cost-effective product customisation. Indeed, large-scale product customisation (individualization) is seen as one of the challenges of this technology [26], which benefits from the optimisation of the digitisation processes that are emerging in the context of Industry 4.0 [27]. For example, additive manufacturing technology, embodied in 3D printers, interconnected with the IoT, through CNC control systems, can be decisive in automation, without losing the individualisation potential [28]. These systems can have huge benefits through the interaction between additive manufacturing technology and other Industry 4.0 technological concepts, gaining greater efficiency in production management, by stock control and logistics management, or by control of production parameters, such as wear of components and materials [29].

In the context of Industry 4.0, additive manufacturing technology emerges as one of the key technologic concepts of the next decade. The synergies of the Industry 4.0 technological concepts enable the digital transformation. Some authors refer this transformation integrates and connects manufacturing systems that accelerate the time of all processes [30] and is changing the manufacturing business models, increasing the customisation, the flexibility and the interaction production, suppliers and customers [31,32]. Other authors prefer to emphasize the concept of "smart factories", i.e., highly digitised, agile and connected production systems based on additive manufacturing, artificial intelligence, robotics, the internet of things (IoT) and the Big Data [33,34]. Even if there are challenges for additive manufacturing, such as limiting the size of the parts produced or the slow production speed, there are also significant benefits of this technology, such as freedom of production of parts of all shapes and reduced time to market, which are highly enabled in the context of Industry 4.0 (Figure 1) [35–38]. The IoT is one of the technological concepts of Industry 4.0 that appears to have the most significant impact on the gains from using additive manufacturing technology. Indeed, this technology, associated with industrial communication networks, supported by Big Data, allows monitoring and optimisation of additive manufacturing processes in real-time, with corrective interventions and rapid maintenance, reducing human intervention in the production process. Besides, this technology can favour the relocation processes of companies that can thus work from more remote locations [39,40].

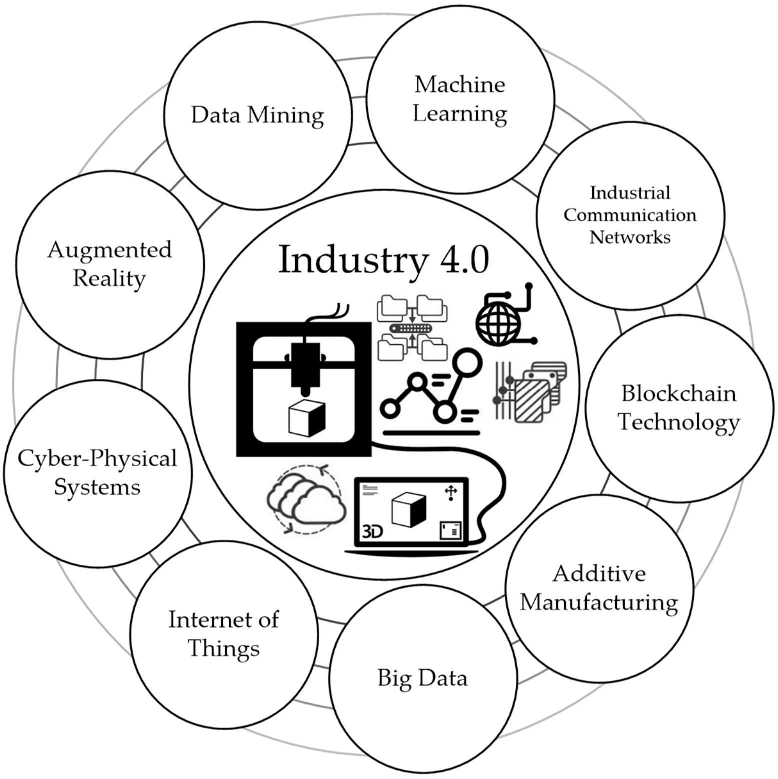


**Figure 1.** Additive manufacturing as a part of Industry 4.0, where the interaction with the other technological concepts allows to explore its potential.

Augmented reality is another technology that, combined with additive manufacturing, can increase processes reliability and effectiveness. This technology allows to monitor and control the production processes, to assess the additive manufacturing produced product quality in real time, making possible to use it in remote environments (e.g., airports and the cinema industry), or to give instructions to the operator in maintenance or troubleshooting. As an emerging and high flexible technology, these attributes might be of high importance to accelerate the use of additive manufacturing technologies [41,42].

Machine learning, also, could increase additive manufacturing capabilities, for example, by improving the quality of production, through artificial neural networks, that can oversee the entire production process, controlling geometric variations and identifying process deviations or component defects [43,44]. Blockchain technology could facilitate the traceability applications in various additive manufacturing industries, namely in industries with precision production processes, such as aeronautic or health industry [45].

With the expansion of the additive manufacturing associated with the achievements of IoT, it becomes possible to build a more flexible, decentralized and distributed manufacturing. However, despite the numerous gains from combining additive manufacturing technology and other technological concepts of Industry 4.0, there are still many challenges to be overcome in the additive manufacturing production chain. These limitations relate to ensuring interoperability and normalized communication between additive manufacturing equipment and the various systems (physic and cyber) and processes (equipment, smart objects and people). Achieving safe and quality interoperability between systems and subsystems at different stages of development is, therefore, a major challenge [46].

As in other industries, data security issues and compliance with international data protection standards have arisen. In the case of additive manufacturing, where there is no specific legislation, the legal problems related to production licenses, product protection and counterfeiting can be very complex. For example, any 3D model can be illegally copied and replicated and even transformed through incremental innovation from an original product. Consequently, data security and piracy control issues will still need to be solved for production processes to provide guarantees to producers, suppliers and consumers [47].

Despite that many impacts of this technology are potentially positive, others will have adverse effects on various industries, with job losses, notably in unskilled labour. Several challenges were identified regarding the dissemination of Industry 4.0 throughout South Africa [48], namely, how it will negatively impact the unemployment and how the reach is limited since it has a small domestic market. Nevertheless, the possibilities of working remotely will bring new opportunities and new types of work, creating new learning and qualification challenges. The balance between positive and negative impacts of technology is still not fully known [49,50].

In summary, it is clear that additive manufacturing technology, when coupled with other technological concepts of Industry 4.0 (IoT, augmented reality, machine learning tools, blockchain and Big Data) will revolutionise the production scenario. Thus, overcoming the constraints of the additive manufacturing process, such as interoperability of systems and subsystems, speed of production, material safety and the production of large parts, the industry of the future will rely on this technology for greater effectiveness, efficiency and quality, while increasing the individualization potential. Thus, the process of integration between digitisation and additive manufacturing will require new business models and new production solutions, bringing together challenges that may delay the process: new research can foster this path. Digital transformation of the industry and additive manufacturing will have an enduring impact on production based business models, and on business value-chains, and will are likely to change the current ways of manufacturing business value-creation, overall [51–53].

Several studies have been carried out for additive manufacturing technology, most of them focused on the creation of new software, development parameters for the additive manufacturing machines, creating materials and new manufacturing processes [6,30,54–59]. However, the knowledge about the impacts and challenges that this technology causes in business models is still very incipient. For the design sector (engineers, architects and designers), published studies state additive manufacturing will stress the importance of acquisitioning of new capabilities, skills and know-how to develop innovative products, including new materials compositions and combinations of production processes [60–62]. For the industrial sector, the challenge is to consider additive manufacturing not as an additional technology just for prototyping and trial tests, but as a main phase of the production process within the value chain [8]. These aspects will impact the current business models and allow the development of new ones–which trend is to be sustainable. Therefore, knowledge and assessment models are crucial to understand the actual economic, environmental and social impact of additive manufacturing. To contribute to cover this gap, this article presents the current state of knowledge in additive manufacturing and its impacts on business models. In addition, it summarizes the most relevant changes to business models, resulting from the use of additive manufacturing in a context the availability of the technological concepts of Industry 4.0 [63].

In the light of the undergoing Fourth Industrial Revolution, this study aims to increase the knowledge about the impacts of additive manufacturing technology on sustainable business models, as well as the models and scales that can be used to determine these impacts. This paper is structured as follows. In this Introduction, the theoretical background and the study objectives are described. In Section 2 the impact on the business models of additive manufacturing and the literature regarding this topic is addressed. The measurement of the social, economic and environmental impacts of additive manufacturing on business models and the balanced scoreboard (BSC) structure proposal can be found in Section 3. In Section 4, the challenges of the new business models of additive manufacturing are discussed. Finally, conclusions are drawn in Section 5.

## 2. Business Models and Additive Manufacturing

The importance of business models for taking advantage and increase the value the value-chain of a new technology is to lead the market a schematic view of how to produce, transport and generate value to the product, giving greater security and agility to process innovation [64,65]. The additive manufacturing feature of promote the manufacture of unique and customized and even individualized orders in contrast to mass production requires innovative business models for economic gains with this technology [66]. Two research studies review and intensely analyzed the literature on business models on additive manufacturing and found that the many studies focus mainly on the manufacturing optimization and empirical data; however, studies focusing beyond that are scarce [51,67]. This highlights the need to address distinct approaches to develop business models in the context of additive manufacturing, namely by taking into account sustainability.

According to some authors, business models for additive manufacturing technology are still immature for large-scale adoption [68]. However, the market range of emerging additive manufacturing technology is growing and belonging to the most varied sectors, namely construction [69], general manufacturing [70], aerospace [71], electronics [72], security [73], fashion in jewels, architecture, decoration and medicine [74]. The particularities and growth potential of additive manufacturing requires the study of new forms of business. According to Zhang et al. [75], the innovation of the business modelling can be described as a process to optimize the reengineering of complex resources. It is useful to use a systems engineering approach to identify, develop, optimize and redesign these business models [18]. In addition, the technology of additive manufacturing not only impacts manufacturing companies but also has profound effects on society, which requires new corporate strategies and policies [75]. A study published by Oyesola et al. [76] developed an additive manufacturing aerospace business model for the South African market to verify market opportunities for laser additive manufacturing based products. South Africa is a competitor in the global market as the country is a major producer of minerals, such as aluminum and vanadium. The strategy used to create the business model was based on a methodological approach that defines the deployment of products, processes and services [77,78] together with the complex interactions between technology, research and development for additive manufacturing technology. The model allows verifying the feedback effects as well as tracking production results by analyzing performance indicators for continuous improvement, thus ensuring the success of uninterrupted, fast and affordable demand products.

Several authors have verified the existence of business models for the additive manufacturing technology. However, few are focused on encompassing overall business analysis, focusing in general on cost modeling. In recent years, some cost models have been developed for specific additive manufacturing processes aiming to allow these technologies to be better leveraged and marketed [65,79–82]. Furthermore, in another study, it is stated in that the several cost models proposed in the literature do not fully analyze the additive manufacturing process [82]. In this study, authors develop a business model and implement it in a software tool that allows the evaluation of cost structure of additive manufacturing technologies applicable to various generating processes. Several case studies for distinct product types are given. The cost model from [82] allows companies to increase the quality of price calculations for their products. In [53], the authors address the overall value chain overview of the competitive circumstances of additive manufacturing consulting service companies are now finding themselves, across vital sectors of the value chain.

With the focus on using technologies from Industry 4.0 to reuse and recycle waste for the delivery of new products, the authors from [83] developed a business model capable of integrating the practices of Circular Economy (CE) in a manufacturing context which takes into account additive manufacturing, smart production systems and sustainable supply chain management. The proposed model aims to reduce the disposal of non-organic solid materials and optimize natural resources considering a circular structure grouped in seven phases, where each phase is associated with a reverse logistics of the materials: Product life cycle, Selective waste collection, Waste sorting, Waste treatment, Product printing, Product assembly and Product selling. The results suggest a positive influence of improving business sustainability, reinserting waste in the supply chain to make on-demand products [83].

Turning the perspective to the different stages of technology, another study analyzed the impact of the four stages of additive manufacturing adoption [68]: (1) rapid prototyping, (2) tools, (3) direct manufacturing and (4) domestic manufacturing. Although the impact of prototyping and tooling is limited in extent, direct manufacturing and domestic manufacturing has the potential to be highly disruptive. The study shows one of the main aspects of additive manufacturing technology is allowing a quick change and experiment with business models, making them adaptable and mobile (upstream or downstream, lateral, long or short).

The relentless pursuit of strategic reinvention is considered essential for cutting-edge technologies and in areas of rapid change [68]. Taking into account these rapid changes in the market, Bugdahn and Rogers [53] studied a business model within the consulting sector. Through this analysis, they verified where there was a change in the model, pointing out that the value preposition aims to fill the lack of specialized knowledge in additive manufacturing. Key activities include employee training, Research and development (R&D) and project management. There was a change in the channels, making the additive manufacturing consulting firm to have a sales team in events and media. Furthermore, the need for a strategic construction to maintain the relationship with the customer, as this market cannot operate independently [53]. In another study, it is suggested that additive manufacturing can be an essential technology facilitator for entrepreneurs looking to use disruptive innovations with business models that use distributed manufacturing [84]. From this point of view, Holzmann et al. classify several business models of this technology, which are open to user entrepreneurs according to their attractiveness [85] and propose that the business models found in their study could be used as blueprints for potential user entrepreneurs in additive manufacturing.

Additive manufacturing not only influences the creation and value proposition of companies, but also influencing communication, distribution and capturing value to a greater extent than the literature suggests [86]. Through the categorization of business types in five segments (manufacturers of final products, manufacturers of 3D printers, companies that use 3D for internal prototyping, 3D service providers and developers), it was verified that in all of them there is a change in value proposition, value communication and value creation. In value communication there is an increase in the relationship of customers with the possibility of co-creation, often increasing sales through the real prototype of the product traded or through long-term technical support. In value criterion through lean management processes, flexibility in manufacturing, reducing manufacturing time and increasing service and product offerings. A business model was developed in [65] for the promising additive manufacturing applications that are geared to the prospect of cloud manufacturing to drive the digital economy market. Currently, as additive manufacturing processes are more profitable for small productions, it becomes unfeasible to make adhesion of equipment for each type of manufacturing. One way to remedy this problem is with the approach of cloud manufacturing, since it allows collaboration and sharing of resources between the platform's customers and participants. This exchange also maximizes the use value of intellectual property, which is an essential element of an open business plan. In the work, the model created was inspired by multisided platforms and open source [87], where the first step is to analyze the whole project before a sequence of questions based on the Canvas model [88]. The tool consists of nine inter-related building blocks around four critical components: "value proposition, value creation, value capture and value delivery" [89–91]. In [92], a case study of a business model for sustainable additive manufacturing spare parts logistics is presented and the authors show how a digital supply chain for spare parts has the potential to change business models, with clear benefits for small and medium size companies, environment and the customers in general.

China is currently the third country in the world with the most 3D industrial printing systems and the second in terms of total publications and patent applications in this industry [3]. A study in the Chinese context showed the need for better connections between each sub-system, especially between technology and business ecosystems [93]. It is important for emerging technology industries that companies leverage local research resources for innovation openly [94]. The adoption of additive manufacturing technology fosters changes in business models; thus, analysing within the business models canvas framework [95], it was found that in the addressed cases there was a change in value proposition, mainly due to issues involving innovation and customization [67,84,86,96,97]. The optimization of natural resources [83] and the fast cycle time [65] are also mentioned by some authors. In addition, in most cases the customer segments are geared towards small productions [82,84] and single production parts [65] or consultancy [53]. In a particular case, the key resources field of the business models canvas change is mentioned, where additive manufacturing technology changes the resource base to the knowledge base. As such, several stakeholders have their part in this key technology and all of them will impact at some level the emerging business models, from government bodies and research centers to consulting firms and customer's service providers.

The several gaps identified between the research and the market value generation demonstrates the importance of creating business models aimed at the emerging additive manufacturing area. The growth of AM's focused research, technology and market has not been followed by business model study development practices focused on this technology. Currently, the literature is still lacking and has gaps in the creation of business models as well as impact analysis with global perspectives of additive manufacturing, but in recent years it can be observed that the number of research papers and discussion on the subject has been increasing [50]. However, almost none address the sustainability aspect of these models, and certainly not in a context of what the Industry 4.0 revolution might bring.

*A Proposed Framework of the Industry 4.0 Impact on the Additive Manufacturing Business Models*

Industry 4.0 promises major improvements to the current production processes and it is essential for additive manufacturing to be an integral part of Industry 4.0. Many areas with a high potential, such as big data could have vast influence on the shape of new business models [98], but only a few studies address it. For instance, Jack Francis and Linkan Bian [98] propose a model using cloud-computing, connected, manufacturing environment of Industry 4.0 by wisely using Big Data to obtain an increased geometrical accuracy for parts fabricated using laser-based additive manufacturing [98]. By combining product design and additive manufacturing, manufacturing costs can be calculated by evaluating more product model features with big data [99]. As it can be seen, there is some research on the topic, yet no business models are proposed.

From a sustainability perspective, businesses are struggling to recognize and understand the full potential of the additive manufacturing technology [100]. To further understand how Industry 4.0 will impact additive manufacturing sustainable business models a framework is proposed here by taking all key stakeholders' contribution. Industry 4.0 executives need to be familiar with these business models as well as with the high-volume data analysis techniques, being able to lead new digital workers; and, above all, putting sustainability to the forefront. They must know about the most disruptive technologies, know their effect on the cost structure and understand the impact on the company now and in the future. Figure 2 shows the framework of the additive manufacturing value chain overview of all these stakeholders and the Industry 4.0 impact on the additive manufacturing evolving business models, by always having sustainable goals in the background.

By analyzing the framework proposed in Figure 2, it can be noticed how the adoption of Industry 4.0 has a high impact on the value chain configurations by adopting (or creating new) business models which are focused, more and more, on sustainability goals. The incorporation of all key stakeholders, by taking into account both socio-economic and technological assets, delivers the desired information to design new sustainable business models that represent the operational goal to integrate additive manufacturing, in light of the Industry 4.0 transition, into the business of the enterprise. Industry 4.0 will directly impact technological suppliers, additive manufacturing technical firms and technological service providers. At the same time, policy makers and the research community can establish new standards and propose new goals and thus push more towards sustainability targets. Companies, policy makers and research community should be able to standardize and regulate intellectual property rights. Industry 4.0 will allow us to extract information from the production lines, machines and products, and build a considerable amount of statistical data to be exchanged and analyzed [27], thus ensuring the effective use of the existing information by researchers and policy makers, which in turn can use all this information to make better and more informed decisions. Using additive manufacturing through the context of integration of Industry 4.0 information technologies could have an important role on sustainability and economic competitiveness of all the involved stakeholders.

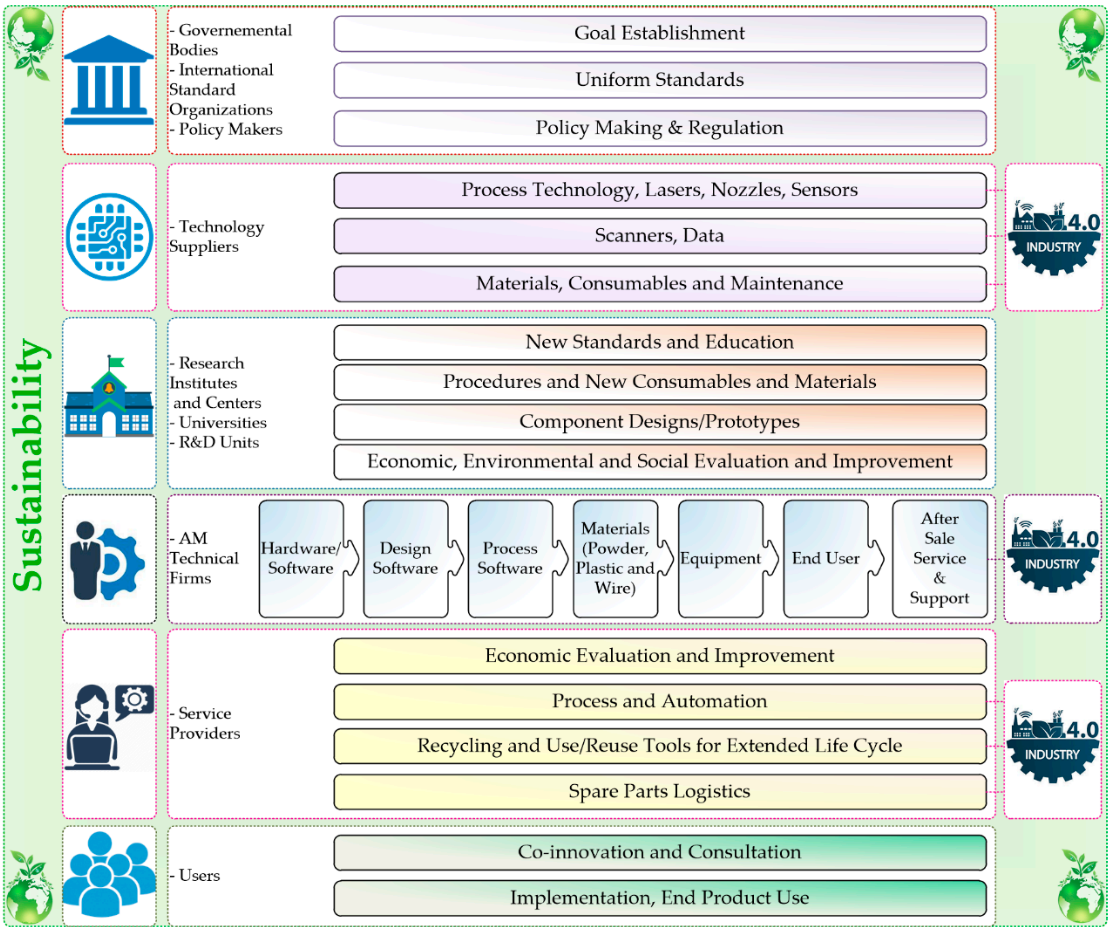


**Figure 2.** The prosed framework of all key stakeholders contribution of additive manufacturing based on [53,67,92,101,102] and where they able to act, in light of Industry 4.0 transition.

## 3. Measuring Impacts of Additive Manufacturing on Business Models

### 3.1. Sustainable Business Models

Today, the materials that can be printed include plastics, wood and metal, among others. In essence, with additive manufacturing at the center, innovative business models and concepts are being shaped, proposing increasingly advanced technological solution alternatives [92], ever more so with the advent of Industry 4.0 [27]. In order to evaluate the impact do additive manufacturing on business models, namely to access which impacts are expected in economic, environmental and social perspective it is necessary to use a performance measurement system that considers a proper balance between the triple-bottom-line perspective (3BL). Among the most cited approaches of performance measurement is the balanced scorecard (BSC) developed by Kaplan and Norton [103]. In this multidimensional approach, it is considered that performance measures should represent the critical success factors necessary for the organisation success. Traditional four areas of performance are defined as (i) financial; (ii) customer, (iii) internal business and (iv) innovation and learning. In this approach, the performance measures should be linked to the strategy, in this case, with the business models that can be used for additive manufacturing. Since Kaplan and Norton [103] proposed the BSC structure, many organizations have tried to implement it for strategy management development; namely, to clarify the organization vision and strategy, focusing management's attention on a few but critical value drivers, and giving an insight on how performance measurement is perceived by supply chain stakeholders [104].

The BSC suggests that the adoption of performance measures from four different perspectives that can be viewed as a template; it can have more or less different perspectives depending on organization strategy [103]. Although the BSC is not a standard sustainability tool, this compatibility is supported by four perspectives: (i) the financial perspective, by delivering value to stakeholders (economic perspective); (ii) the customer perspective, supporting the focus satisfying on final customers (economic perspective); (iii) the internal business process perspective, which highlights the importance of organizations to adopt a continuous improvement culture reducing negative environmental impact (environmental perspective); and (iv) the innovation and learning perspective, which intends to promote organizational cultural changes and respect for people (social perspective). In order to develop a sustainable BSC, several authors [105–108] contributed with several publications with the purpose to integrate the social and environmental perspectives on the organisation strategy. The authors in [109] refer to three different ways to integrate environmental aspects in BSC: (i) measures can be integrated in the existing four standard perspectives, (ii) an additional perspective can be added to take environmental and social aspects into account and (iii) a specific environmental and social scorecard can be formulated. The same rationale could be applied to the social aspects, namely, [109] proposed the "non-market perspective" with the aim to integrate social issues, such as "child labour", although issues such as "employee potential" are included in the traditional "the innovation and learning perspective". Furthermore, these authors propose a sustainable BSC model that makes explicit the 3BL dimensions along the BSC perspectives (Figure 3).

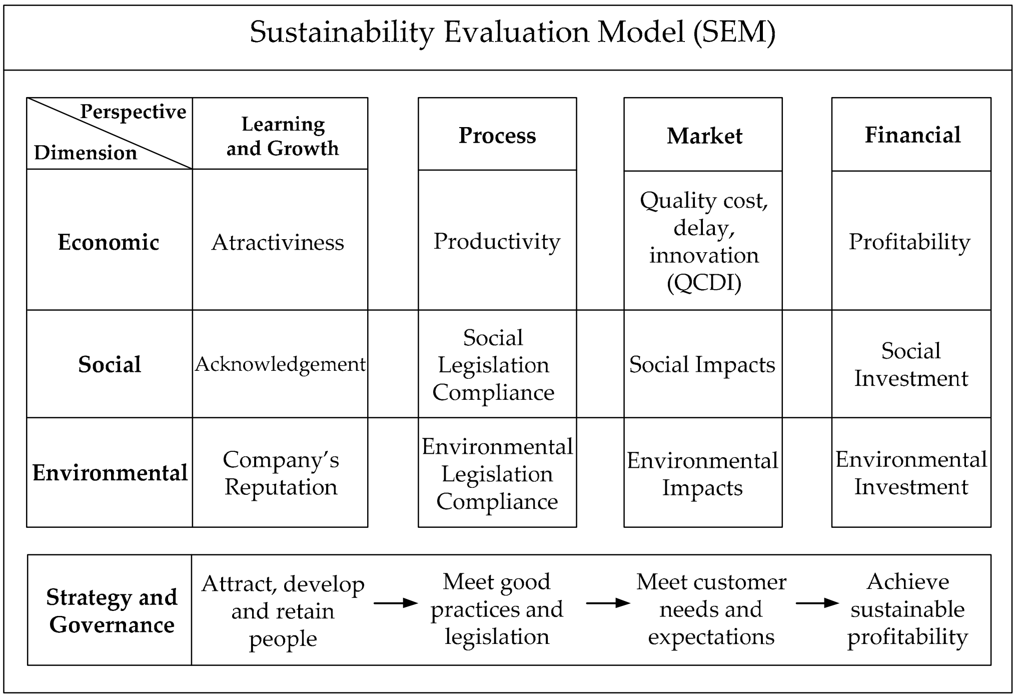


**Figure 3.** Sustainability evaluation model, adapted from [109].

In the present study, the model proposed by Nicoletti Junior et al. [109] is used to propose a set of indicators that can be used to assess the impacts of additive manufacturing on business models. To support the identification of the performance measures to be used in each sustainable BSC dimension, Table 1 provides the definition proposed in [109] for each one.

**Table 1.** Definition of the sustainable BSC dimensions. Adapted from [109].

| | Leaning and Growth | Process | Market | Financial |
|---|---|---|---|---|
| Economic | The organization is attractive to talents, allowing retaining the best professionals. | The practices consider by the organization minimize the wastes and assures the social and environmental dimensions. | The organization is prepared to meet the market with efficiency in quality, cost, delivery time, and innovation. | If the organization is profitable. |
| Social | The organization manages to retain their talent, the internal environment and employee perception. | The organization's concern with the employees and, consequently, with society. Internally, it considers also safe and work initiatives. | If the organization generates some social impact and what it's reaction in an eventual occurrence. | The organization invests in social actions and their benefits generated to the society. |
| Environmental | The society considers the organization as a place to work. | The organization respects the environmental legislation. | If the organization generates some environmental impact and its reaction in an eventual occurrence. | The organization invests in environmental actions and the consequent benefits obtained. |

### 3.2. Social Impacts of AM

The Interorganizational Committee on Guidelines and Principles for Social Impact Assessment 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, organise themselves so as to meet their needs and generally cope as members of society" [110]. The United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) life cycle initiative identified the social impacts of a product as consequences of social interactions formed between the product's surrounding system and the stakeholders engaged in the product life cycle [111].

Papers currently published in the literature focusing on the social impacts of additive manufacturing technology are limited. To date, the most detailed studies on this topic are the research papers published in [50,112,113]. These studies identify the social impacts of additive manufacturing technology in on population health and well-being, energy consumption and environmental impact, manufacturing supply chains and potential health and occupational hazards and pinpoint several social impacts areas.

The progress in the direction of Industry 4.0 involves the integration of new production technologies, the increase in quality and productivity and the improvement of the working conditions. However, none address the impact that Industry 4.0 might have.

Social Life Cycle Assessment, according to Garrabé and Feschet [114], is expected to have a link between performances and impacts, by reaching as much as possible to effects. These authors propose a link between a performance, such as "vocational training", and an impact, such as "the satisfaction of the worker is changing", which results in "increase in knowledge" and "skills learned", thus creating talent. It is adequate to oversee, in real time, the operational performance and flows, and consequently enhance and further develop the quality of stakeholder decision-making by merging the respect for the principles of corporate social responsibility with the necessity for competitiveness [115].

The measurement of social impacts is not a trivial task. Some social impacts can be better captured using quantitative indicators, while others may be better captured by semi-quantitative or qualitative indicators measure social impacts. The recent work published in [116] provides details on how to collect data and calculate the different types of indicators. In this study, the indicators are classified through a scoring system consistent with their type and intended direction for sustainability.

The main source of social indicators is the UNEP/SETAC Methodological sheets for Subcategories in Social Life Cycle Assessment [111]. It provides a list of more than 100 inventory indicators to assess each subcategory. Using this database on indicators and after a literature review, a set of indicators for each additive manufacturing social impact categories is proposed in [116]. Table 2 provides a match between the indicators proposed by Lourenço et al. [117] and the social dimension of the sustainable BSC as defined in [118].

**Table 2.** A match between the indicators and the social dimension of the sustainable BSC.

| | Leaning and Growth | Process | Market | Financial |
|---|---|---|---|---|
| **Social indicators** | Presence of female employees in management positions. Gender pay gap Average monthly basic remuneration of employees Percentage of employees receiving minimum wages Employee work satisfaction Access to legal social benefits Percentage of workers educated by the organization regarding additive manufacturing technology. Percentage of qualified workers in the organization | Percentage of on-fatal occupational accidents incidence. Use of Personal Protective Equipment (PPE). Preventive measures and emergency protocols regarding accidents and injuries. Average weekly hours of work by a full-time employee. Presence of child labour in the organization. Organization's efforts and measures to ensure the protection of consumer privacy. Organization's efforts and measures to protect consumer health and safety. Organization's policy and practice regarding the protection of intellectual properties rights. Organizations' efforts to prevent the manufacturing of armed conflicts weapons using AM | Percentage of spending on locally based suppliers Percentage of local suppliers. Percentage of the workforce hired locally. Integration of ethical, social and environmental criterions in purchasing and distribution policy. Payments on time to suppliers. Percentage of consumers negatively affected regarding their health and safety. Percentage of the consumers affected by situations of breach of privacy or loss of data | Organization's efforts in promoting additive manufacturing education initiatives in the local community |

### 3.3. *Environmental Impacts of Additive Manufacturing*

A noticeable growth in smart infrastructures, due to Industry 4.0, might inflict severe burdens on the environment, the typical Life Cycle Assessment practices are mostly unable or inadequate to quantify such types of impacts. Therefore, in [119] a gap is identified between the environmental assessment field and the perceptible advances in the manufacturing domain. Frequently, a compromise is made between the efficient use of resources and possible benefits by advanced technologies in reducing materials and other undesirable effects such as the increase in energy consumption.

Several studies address the environmental impact of additive manufacturing [120], and it is a subject that should not be dismissed, since, despite all the benefits that additive manufacturing can bring, achieving a manufacturing method that increasingly is less environmentally harmful than conventional manufacturing is one of the pillars of the newer sustainable business models. Several studies address the ecological footprint, based on the same points (e.g., the scale of production, the materials and the life cycle of the manufactured products) [120,121], yet none mention how Industry 4.0 could impact these elements, or if it will have a positive impact at all.

The authors in [120] argue that the impact of additive manufacturing production is high. However, in their point of view, and from an environmental perspective, the high environmental impact present during the additive manufacturing manufacturing stage could be offset by functional improvements during use stage of the fabricated parts. The energetic and environmental impact studies that exist on additive manufacturing are not enough and require additional data on diverse materials, equipment, processes, product designs and supply chain players [121]. For instance, regarding energy consumption, some studies have reported values for additive manufacturing which are 1 to 2 orders of magnitude higher when compared with the values of conventional injection molding processes [122] or conventional machining processes [123].

In order to address these challenges, there are many researchers in materials science who are constantly looking for new raw materials, including pulp or wood pulp from industrial waste, for example for use in architecture or industrial design, or filaments from seaweed [124–126].

However, there are two key elements, according to Timothy G. Gutowski et al. [127,128], that gives additive manufacturing the quality of an environmentally friendly technology and consider it a sustainable manufacturing method. First, it reduces waste, since unlike subtractive manufacturing, additive manufacturing employs only the necessary material when adding layer by layer, therefore the waste is lower. Additionally, it is capable of reusing plastic waste, converting it into printing filaments and creating new products. The second key point is the improved accessibility of additive manufacturing technologies, enhanced by Industry 4.0, provided to manufacturers, since they can now produce directly in-house, reducing logistics and travel costs.

Regarding the life cycle of the product, the higher this cycle is, the lower the environmental impact derived from the manufacturing of this product. In this sense, products made by additive manufacturing can be fairly advantageous [68]. When a product comprised of several pieces is fabricated by injection molding and one of them is damaged, in general, a new product must be purchased. Additive manufacturing, on the other hand, allows the manufacturer to produce isolated parts, which extends the life cycle of that product. Therefore, additive manufacturing also allows the addition of new parts or the replacement by better ones, which optimizes and extends the life of the original product. Several aspects related to the life cycle are also considered, such as the possibility of creating lighter parts affects the use of the object, for example, fuel consumption and the emissions caused by it. Furthermore, the prospect of the possible recycling and use/reuse tools for extended life cycle of additive manufacturing, since some researchers already explore the recycling of some metal powder [129]. The benefits of the environmental aspect of additive manufacturing are summarized in Table 3, adapted from [130].

**Table 3.** The benefits of the environmental aspect of additive manufacturing.

| | Learning and Growth | Process | Market | Financial |
|---|---|---|---|---|
| **Environmental** | Affordable additive manufacturing training. Self-awareness of the machine regarding environmental impacts | 0 hazardous waste produced 0 kg of landfill waste 0 kg of water usage per component | Benefits obtained from being known as an environmentally responsible enterprise. Green products. Customer satisfaction | Benefits obtained from energy efficiency improvements. Waste reduction Level. Recapturing value |

### 3.4. Economic Impacts of Additive Manufacturing

Costs are a key factor to analyze the economic viability of any technology or product for decision making. The economic impact of additive manufacturing could be quite significant [131]. By switching to additive manufacturing, the waste is practically eliminated, since the necessary material is supplied to produce almost exclusively the required shape, and parts with defects can be completely recycled. This contributes to building the circular economy and favors the sustainability of manufacturing resources [132].

The material used can be optimized through design modifications, allowing for even stronger and lighter parts [30]. Parts assemblies can be produced in one operation, reducing the number of final assembly operations and increasing the reliability of the resulting product. The impact on the supply chain is evident, although with many challenges regarding its quantification. The possibility of producing locally at a reduced cost means a radical transformation of the current supply chain: the transport routes can be greatly reduced [133–135]. The benefits of the economic aspect of additive manufacturing can be seen in Table 4, adapted from [136–138].

**Table 4.** The benefits of the economic aspect of additive manufacturing.

| | Learning and Growth | Process | Market | Financial |
|---|---|---|---|---|
| **Economic** | Increased presence of additive manufacturing in higher education Knowledge sharing | Delay reduction Efficiency of an improved lean supply chain Inventory turn over | The organization able to meet the market with better efficiency higher quality, lower cost and lower delivery time. Market share | Contribution to economic development Cost reduction Profitability |

### *3.5. Strategy and Governance*

By thriving in an innovative environment, organizations investing in additive manufacturing attract, develop and retain people. This is highlighted in a recent study, which showed how it increased the motivation and engagement of the students during the additive manufacturing course [139]. As shown by the proposed framework in Figure 2, policy makers and the research community will be able to establish new standards and propose new goals and thus push towards sustainability targets in a more effective way. Companies, policy makers and the research community should be able to standardize and regulate intellectual property rights with sustainable goals as a background in order to meet good practices and legislation. All of these trends and mindsets will lead to companies being able to meet the customer's needs and expectations, whether by being known as environmentally responsible enterprises or by ensuring higher efficiency, higher quality, lower cost and lower delivery times. Only then, sustainable profitability can be achieved.

## 4. Discussion

As additive manufacturing technology includes various sub-technologies and single manufacturer equipment at different maturity stages, it is not possible to precisely identify their possible impacts [113,140]. However, the integration of this technology in an Industry 4.0 environment will have impact in the manufacturing processes and in the way production system supports and is supported by the business model of the organization [50,141].

The growth of problems related to the impacts of additive manufacturing in the sustainability of new business models has been increasing the utilization of assessment models to support decision-making in different areas, especially with the advent of Industry 4.0. One important difference is the nature of impacts. Environmental and impacts tend to be negative, while social and economic impacts can be positive or negative, depending on the context, the value people give to them or even pre-established standards.

Measuring the impacts of additive manufacturing on business models through a BSC could help the strategic orientation of companies by facilitating decision making and management in face of an external competitive environment. The fruition of BSC relies on a well-defined and transparent strategy as the cornerstone for the fruition of relevant and specific performance measures. Overall, BSC can be used to disclose orientation on the markets, strategic objectives, potential products and the lowest economic performance to reach.

However, the novelty in the use of additive manufacturing technology and the fact that many of the new business models are still at an early stage, with scarcity of information on social, environmental and economic impacts, makes it difficult to accurately predict these impacts and still more difficult to identify their evaluation models. Therefore, more empirical investigations are required to prove what is listed in the literature.

The following topics attempts to summarize the main impacts listed:

- Variety of additive manufacturing technologies available that makes it difficult to choose the best ones in some areas.
- Conflicts with traditional and new business models.
- Industry 4.0 dissemination will allow production centered on the manufacturer to become consumer centered production with co-creation, forcing the producer to move from a business to business relationship to a business to consumer with, impacts in all of the the value chain.
- Growth of differentiation and specialized customization focused on special editions of products that may have significant impacts on prices and their regulation.
- The democratization of production can lead to an increasing violation of intellectual property rights, calling into question the value of patents. In some countries, more permissible for this type of infringement, this may jeopardize the viability of business models focused on the exclusivity of some patents.

- The new business models will potentially be complementary to the traditional models, but in some cases, they may cannibalize the traditional.
- The new business models when they are consumer-cantered will have impacts in several areas, especially in the technological development brought by Industry 4.0 and in the innovation that will emerge to support these new business models.
- The simultaneous evolution of technology and new business models, with the interaction of different types of knowledge, should lead to the growth of open innovation.
- The possibility of production or co-creation having several origins (companies or home productors) raises complex issues of security, standardization and traceability of the supply chain, namely in areas such as aerospace, automobile or medicine.
- Furthermore, the aspects of controlling environmental sustainability aspects, such as energy management, waste management, recycling of returned products, etc., raise many questions.
- Decentralized production, allowing the production of parts to be just in time and tailored to the consumer, will lead to a reduction in stocks and a reduction in global footprints. However, this will have an impact on companies producing traditional systems that are usually located on economies that need to base their production on the use of labor intensive.
- Concerns about intellectual property aspects are expected to lead to changes in the licensing of property rights.
- With the growing demand for printers for both industrial and personal use, this market is expected to expand and adapt to new requirements.
- The possibility to explore a possible recycling and use/reuse tools for extended life cycle, since the recycling of some metal powder and use/reuse technologies could be developed to save metal powder [129].

## 5. Conclusions

Additive manufacturing is part of the new industrial revolution linked to the digital world. It signifies an entirely new form of production which is carried out by superimposing layers of material until the desired product is obtained. This new manufacturing model will, in the long run, allow us to abandon many manufacturing tools and adapt production processes to market needs in a much more flexible way. The rapid evolution of technology indicates that additive manufacturing is at a turning point to become a viable alternative to traditional production processes in many aspects.

Additive manufacturing has become a powerful tool in the business industry and its innovative functions and scope have streamlined several processes in manufacturing enterprises. Additive manufacturing has evolved in a remarkable way thanks to several technological advances in which it is already possible to replicate complex and functional machinery equipment. Therefore, new and radically different business models are emerging due to additive manufacturing and the advent of Industry 4.0 in industry. As such, in this paper, the empirical knowledge regarding the impacts of additive manufacturing technology on sustainable business models is addressed, as well as the models and scales that can be used to determine these impacts. A framework is proposed in order to illustrate how Industry 4.0 will impact additive manufacturing sustainable business models by taking all key stakeholders' contribution. The effects are assessed by taking into account the social, environmental and economic impacts of additive manufacturing on business models and a BSC structure was proposed. The existing additive manufacturing technologies are still slow, ineffective and cost per part too high to compete with traditional methods. However, additive manufacturing has a very ambitious projection in the future and many efforts are made in different directions to turn additive manufacturing economically, socially and environmentally viable. The use of additive technology and the fact that many of the new business models are still at an early stage and more research is required.

**Author Contributions:** Conceptualization, I.R. and R.G.; Methodology, F.M. and P.P.; Validation, H.C., I.R. and P.P.; Formal Analysis, F.M.; Investigation, B.T.F. and P.P.; Resources, I.R. and P.P.; Data Curation, H.C. and B.T.F.; Writing—Original Draft Preparation, B.T.F. and R.G.; Writing—Review & Editing, I.R., F.M. and R.G.; Visualization, R.G.; Supervision, P.P.; Project Administration, F.M.; Funding Acquisition, F.M., H.C. and I.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors gratefully acknowledge: (a) The funding of Project FIBR3D (ref: POCI-01-0145-FEDER-016414), co-financed by Fundo Europeu de Desenvolvimento Regional (FEDER) and by National Funds through FCT—Fundação para a Ciência e Tecnologia, Portugal; (b) FCT grant (ref: UIDB/00667/2020 (UNIDEMI)); (c) the funding of Project KM3D (PTDC/EME-SIS/32232/2017), supported by Fundação para a Ciência e Tecnologia, Portugal; and (d) the four organizations participating in the case studies. This work was also supported by FCT, through IDMEC, under LAETA, project UID/EMS/50022/2019.

**Conflicts of Interest:** The authors declare no conflict of interest.

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