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New Business Models for Sustainable Spare Parts Logistics: A Case Study

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Received: 13 March 2020; Accepted: 9 April 2020; Published: 11 April 2020

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Abstract: Additive manufacturing of spare parts significantly impacts industrial, social, and environmental aspects. However, a literature review shows that: (i) academic papers on the adoption of additive manufacturing have focused mainly on large companies; (ii) the methods required by SMEs to adopt new technologies differ from those employed by large companies; and (iii) recent studies suggest that a suitable way to help small- and medium-sized enterprises (SMEs) to adopt new additive manufacturing technologies from the academic world is by presenting case studies in which SMEs are involved. Given the increasing number of global SMEs (i.e., SMEs that manufacture locally and sell globally), we claim that these companies need to be assisted in adopting spare-parts additive manufacturing for the sake of resource and environmental sustainability. To bridge this gap, the purpose of this article is to present a case study approach that shows how a digital supply chain for spare parts has the potential to bring about changes in business models with significant benefits for both global SMEs (more effective logistic management), customers (response time), and the environment (reduced energy, emissions, raw materials, and waste).

Keywords: resource efficiency; digital supply chain; spare parts; additive manufacturing; small- and medium-sized enterprises (SMEs); business model; on-demand production

1. Introduction and Literature Review

Additive manufacturing (or 3D printing) allows the generation of components directly from 3D information and raw materials (i.e., without requiring the other resources needed for standard manufacturing, such as specific molds or tools). As a result, the incorporation of additive manufacturing into production processes has brought significant transformations in supply chain design and the organization of production and distribution to end users [1], to the extent that additive manufacturing is considered a disruptive technology within the supply chain [2]. In fact the incorporation of 3D printing, along with other innovative technologies, has resulted in the so-called digital supply chains (DSC) [3], whose impact has been widely studied in recent years [4–8].

Traditional supply chains are composed of a set of geographically dispersed facilities that need to be communicated through a physical network to transport materials (i.e., raw materials, final components, or spare parts, etc.). However, in a digital supply chain, manufacturing information can "travel" through a digital network from one facility to another. This means that, for example, although the information needed to manufacture a component is stored in a distant facility within the supply chain, the machine that generates the component can be located at a more convenient point (e.g., near the source of raw materials, or near the end user, etc.). This feature minimizes the need to transport materials between different points in the chain which, in turn, has a positive impact on the environment.

In this article, we focus on the additive manufacturing of spare parts. The production of spare parts using traditional supply chains involves many challenges [9,10]. Manufacturers need to ensure the availability of spare parts for their customers, but demand for spare parts is erratic [11]. One possible solution is to anticipate customers' demand and create a safety stock of spare parts. This favors shorter delivery times, but also entails high inventory needs (space requirements, insurance and maintenance costs, and product obsolescence risk, etc.). Beyond the need for a tradeoff between availability and inventory costs, once the spare part becomes available, it needs to be delivered to the customer. Large manufacturers do not usually deliver a product directly to the customer. Instead they use a multi-level distribution network (continental, national, or regional, etc.). By taking advantage of this infrastructure, they generally deliver the spare part to the next link in the supply chain, which also entails transport costs.

The work of Pérès and Noyes [12] was one of the first studies to analyze the potential of additive manufacturing for spare parts by proposing the idea of "manufacturing on the spot and on demand". Although technology at that time was not as mature as it is today, they forecasted that this production system was more efficient than traditional solutions for supplying spare parts. In fact, a few years later, an article published in Forbes magazine stated that "3D printing is already starting to threaten the traditional spare parts supply chain" [13]. More recently, several studies have analyzed the positive impact of additive manufacturing of spare parts on reducing production costs [10] and dealing with new approaches for spare parts management [14–16]. Indeed additive manufacturing is currently being used to supply spare parts in such diverse fields as the maritime industry [17], the automotive industry [18], and the aeronautics sector [19].

Interestingly, additive manufacturing does not only offer benefits in industrial terms, but also spells advantages from a social welfare perspective (e.g., shorter response time to customers, or the possibility of users disclosing their inventions) [20,21] and for environmental sustainability purposes (reducing energy, emissions, raw materials, and waste) [22–25]. However, after performing a literature review on the impact of additive manufacturing of spare parts from industrial, social, and environmental perspectives, we found that most studies have focused on the perspective of large companies. It seems clear that these companies can take advantage of their existing infrastructure to exploit the advantages of additive manufacturing of spare parts. Yet this is not the case for small- and medium-sized enterprises (SMEs), which often produce spare parts as they are demanded and send components directly to the end user. Given the increasing number of global SMEs [26] (i.e., SMEs that manufacture locally and sell globally), we claim that these companies need to be assisted in adopting spare-parts additive manufacturing for the sake of resource and environmental sustainability.

Some recent studies have analyzed the specific potential benefits of additive manufacturing in SMEs. A review of these studies can be found in [27]. However, the adoption of this technology also entails a number of challenges that SMEs find more difficult to address than large companies. According to Martinsuo et al. [28], an organization's size is critical for defining how to adopt new technologies, as theories that have proven useful for large enterprises are not applicable to small businesses. For this reason, several studies [29–31] explicitly claim that manufacturing SMEs need help in their digital transformation because they are competing under inferior conditions than large companies.

Additive manufacturing brings about changes in business models. A complete current review of the state of the art in this sense can be found in [32]. However, many recent papers ([27,33,34], to cite just a few) agree on the fact that academic research into adopting additive manufacturing has focused on large companies, and only marginally on SMEs. Our literature review confirms that, to date, very few publications have focused on the challenges that adopting additive manufacturing hold for SMEs (e.g., no special mention is made of SMEs in the comprehensive literature review by [32]). Recent publications in this field claim that one way to help SMEs in the academic field is by presenting case studies [35].

To bridge this gap, this article presents a case study approach showing how a digital supply chain for spare parts has the potential to bring about changes in business models with a positive impact on efficiency and sustainability. A qualitative research case study was chosen as a methodology since case studies investigate "a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" [36]. Focusing on additive manufacturing, the conclusions of a recent study by [37] indicate that empirical studies are needed to identify the best practices that can lead companies to obtain competitive advantages in additive manufacturing management.

We illustrate the prototype of a business model that integrates global operating manufacturers and local producers into a digital supply chain. This business model will allow SMEs to decide to operate globally with sustainability criteria to guarantee their customers a supply of spare parts with the highest service level. This prototype was one of the results of the so-called FIL3D Project (FIWARE Service for Spare Parts Logistics in 3D Printing Digital Supply Chains). FIL3D stands for Future Internet Logistics with 3D Printing and is not commercially available. It was financed by the European Commission through the FABulous Project [38].

The rest of the article is organized as follows: Section 2 describes the FIL3D Project and the prototype of the business model; Section 3 firstly presents two case studies in which several SMEs are integrated into the prototype developed by the FIL3D Project, and then describes the potential benefits of their integration from both industrial and environmental perspectives. Finally, Section 4 offers the discussion and the main conclusions drawn from this work.

2. Materials and Methods: The FIL3D Project

The objective of the FIL3D Project (FIWARE Service for Spare Parts Logistics in 3D Printing Digital Supply Chains) is to provide the spare parts industry with an open platform to support a paradigm shift to a Digital Supply Chain (DSC) where "virtual stocks" are 3D-printed on demand by local producers.

This platform combines: (i) local fabrication and delivery; and (ii) integrating 3D printing technologies into the industrial segment. Together, both factors will reduce the costs associated with spare parts activities, generating savings for industry and customers and improving the quality of the delivered service. We claim that the implementation of this project will have an especially positive impact on global SMEs because it will allow them to guarantee the supply of spare parts in an environmentally sustainable way.

2.1. Proposed Service

The project has a worldwide target and communicates global operating manufacturers, local producers, and customers by covering the whole supply chain. The general scheme of the service is represented in Figure 1.

The platform is supported by a database (lower right of Figure 1) that contains the following information:

- Sets of 3D parts/models/designs of different owners/manufacturers, with their associated information about intellectual property rights (IPR), royalties, materials, tolerances, colors, and printing specifications, etc.
- 3D printing hubs: registered local 3D-printing producers (dealers/resellers), including their location, printing capabilities (materials, sizes, etc.), certifications (whether they are certified by certain manufacturers or not), costs, response/delivery times, and reviews, etc.
- Registered customers with personal profile, delivery address, billing information, and order history, etc.

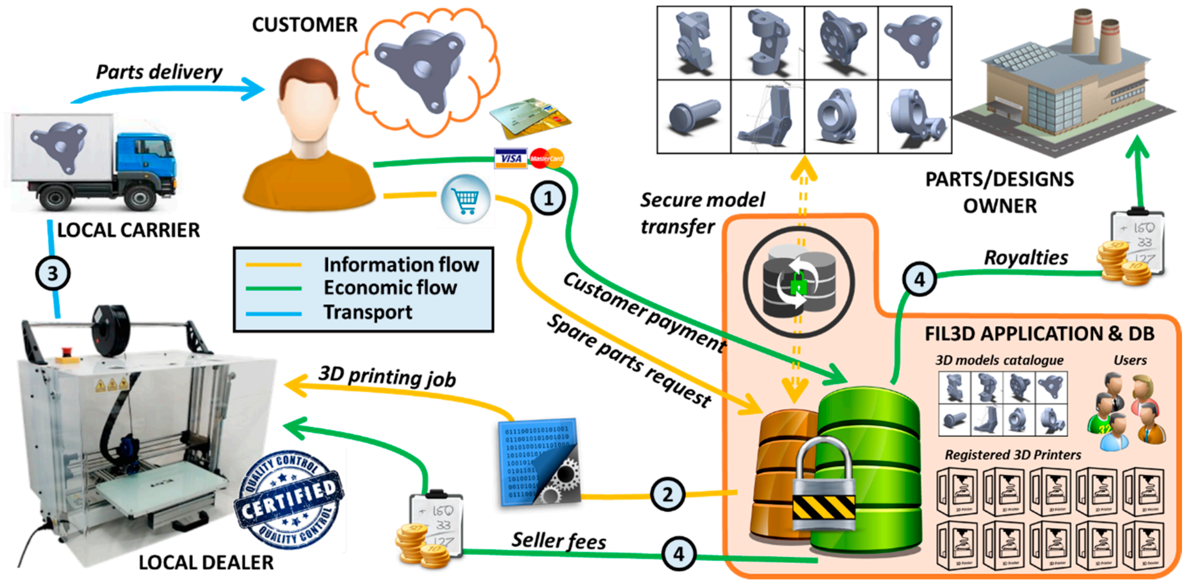

Figure 1. Flow diagram of the service provided by the FIL3D project.

The platform works as follows. When a customer needs a replacement part:

1. Customers log into the system to request a spare part. The system will offer a list of registered 3D printers and their associated information (3D technology, speed, delivery time, and price, etc.). Customers may use this information to purchase the replacement part that they need by selecting their preferred local dealer. The system also processes customers' payments.
2. The system searches and processes the required 3D model in the database, where the instructions to print the spare part are stored. This information is sent through the digital supply chain to the selected local dealer. Note that IPR have been considered in this project. If printing a spare part requires obtaining permission from an owner, it is requested prior to sending the instructions to the local dealer. Then the system processes 3D models by remotely queuing the job in the dealer's hub.
3. Once the spare part has been printed, it is delivered to the customer directly from the local dealer.
4. The local dealer receives its fee from the FIL3D application and the design's owner receives their royalties.

For the service to work, designers firstly upload their models and establish their royalties or fees per print. Then makers (3D printing producers) establish their fabrication cost based on the technology, material, and the part's size. Basic access to the platform will be free for every user type. However, the service price for the final customer is the sum of the designer's royalties and the maker's tariff. DIMA3D (the FIL3D's project owner, see Section 2.5) will charge a fee from each transaction based on these prices (a given % from the designer's fee, and a given % from the maker's tariff). In this way, the cost of the service (in terms of DIMA3D's income) is not charged to final users. The service price charged to the designer can be understood as a fee that they pay as a share from their royalties in exchange for targeting more potential customers and obtaining more possibilities. Similarly, the service price charged to the maker is a fee paid from its manufacturing tariff in exchange for a bigger number of potential users. When customers place orders, they select a local printer (i.e., one of the 3D printers of the maker's network) and make a payment on the platform. Royalties are then transferred to the designer. When the local producer has printed and delivered the order, it receives its payment according to the cost that it stated.

2.2. FIWARE

The core of the FIL3D platform is a FIWARE-enabled service. FIWARE (Future Internet WARE) is a smart open platform made up of open-source components which aims to accelerate the development of smart solutions. FIWARE is an open community whose mission is *"to build an open sustainable ecosystem around public, royalty-free and implementation-driven software platform standards that will ease the development of new Smart Applications in multiple sectors"* [39]. FIWARE has been promoted by the EU Public Private Partnership on the Future Internet (which has allocated over €700 MM). It was articulated in different programs of these projects: FIWARE (software platform development); FIWARE Lab (Experiments and Innovation); FIWARE Ops (Infrastructure); FIWARE Accelerate (funding startups); FIWARE Mundus (globalization).

FIWARE enables connection to the Internet of Things with Context Information Management and Big Data services in the Cloud. It also provides standard application program interfaces APIs for data management and exchange and allows the automation of processes across the entire value chain.

FIWARE is, in fact, a combination of open-source platform components. Each component, called a Generic Enabler (GE), provides advanced APIs for the Internet of Things elements: devices, users, networks, applications, or services. GEs are used to provide a series of functionalities, such as authentication, web-based user interfaces, and device management, etc. [40].

Table 1 provides an overview of the challenges tackled by the FIL3D project and how they were addressed using FIWARE components.

Table 1. FIWARE applications used to develop the FIL3D project.

Challenge	FIWARE Specific Platform	Applications
Crowd-sourced and cloud-based design and services for 3D Printing	FITMAN DyVisual	Standard 3D model visualization.
	FITMAN 3DScan	Handle 3D model acquisition and storage: input files, database exchanges, and 3D scanning, etc.
	FITMAN 3D Web Viewer	Visualization and collaborative edition or customization of 3D models by users/designers.
Manufacturing and Logistics Tools and Services	FITMAN DyCEP	Real-time control and decision-making in the manufacturing process.
	FITMAN SEM	Arrange transfers between authorized peers for Intellectual Property Rights (IPR) management. Action triggering on production events.
	FITMAN-BPM	Implementation of the business logic, including task management.
	FITMAN-CAM	Specify and store users' information assets and attributes.
	FITMAN-Anlzer	Analyze customer satisfaction and evaluate the social impact of the service and its marketing actions.
	GE Orion Context Broker	Handle and publish application context information.
	GE Application Mashup	Create a dashboard with key management indicators for users.
	GE Data Visualization and Analysis	Statistical analysis of application data and report generation.
	GE Identity Management	Provide a secure access system for the application so that each user is identified and Intellectual Property Rights (IPR) issues can be considered.

GE = Generic Enabler; IPR = Intellectual Property Rights

2.3. Implementation

The FIWARE-enabled service that supports the FIL3D project covers the whole logistics chain by integrating all the involved actors: industrial manufacturers ("Designers and Parts Providers" who own the Intellectual Property Rights, IPR), local 3D printing producers ("Makers"), and Customers and the System Administrator (DIMA3D). A video showing the functionalities of the prototype can be found at: https://youtu.be/sUI3nT9U6lY. Figure 2 shows the actors involved in the supply chain, and the FIWARE components used for its implementation and their interrelations.

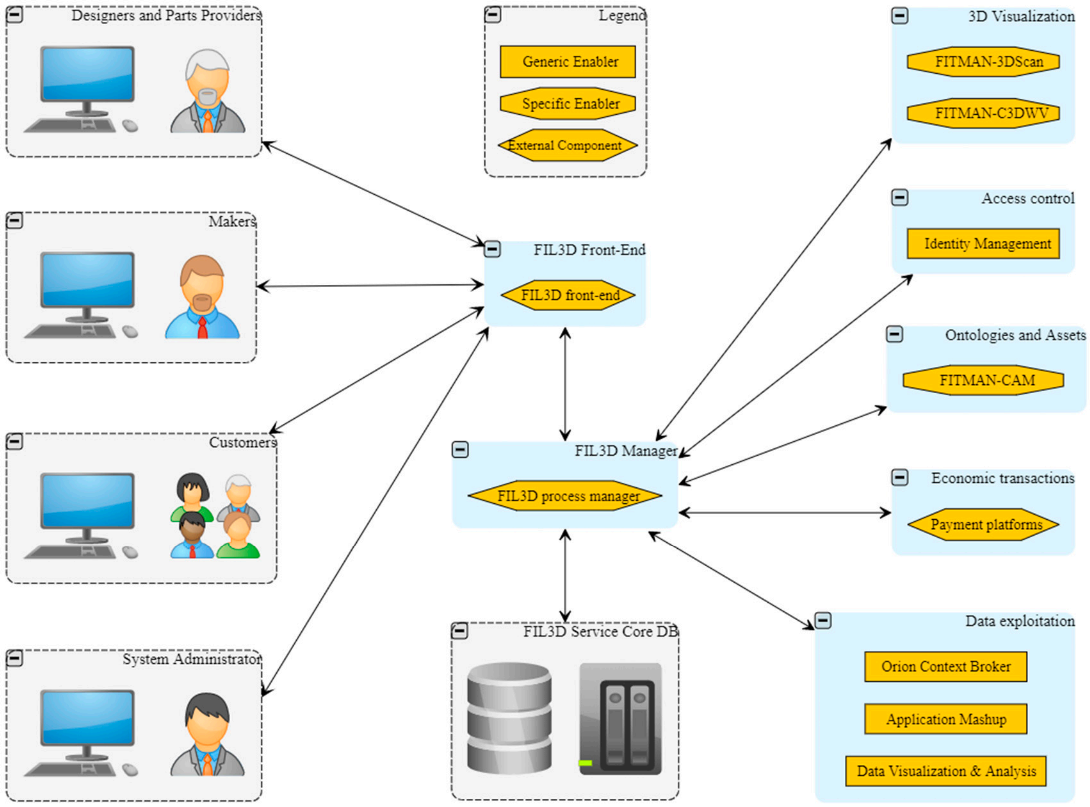

Figure 2. The FIL3D platform implementation.

The system incorporates:

- A secure payment platform which guarantees that each party pays/receives the corresponding fee. It also handles cancelations and service claims.
- An IPR-consistent data management system which guarantees that the IPR issues associated with data exchanges are fulfilled.
- A Business Core Module that implements all business processes (represented to the lower right part of Figure 1), including:
    - ○ Registration of actors of the service platform (customers, parts owners, and local producers);
    - ○ Uploading 3D models by owners into the database (with their associated information);
    - ○ Ordering, selecting models from the repository database, and the preferred local dealer;
    - ○ Order Processing, to generate, place and track the orders assigned to dealers;
    - ○ Acceptance and confirmation of service, when it has been accepted and performed by the dealer, and that parts have been delivered to the customer;
    - ○ Cancelations, by either customers or dealers, and service claims (late deliveries, or low quality, etc.);
    - ○ Secure economic exchanges platform: i) customers will be able to pay using several secure methods; ii) if the dealer accepts the job, the corresponding royalties are paid to the owner; iii) when the job is printed and delivered, the dealer receives its commission;

   - Requests of new models to owners for their inclusion in the catalog.

- User Interface for each actor and business process integrated into the service, including 3D edition and visualization, task information, management dashboard, and user profiles, etc.:

   - A Secure Data Management System, as most designs will be protected by IPR;
   - A 3D Model Processing Module, to generate and queue a secure printing job;
   - A Secure Payment Platform for customer payments, warranty coverages, royalties, and retributions, etc.

2.4. The FABulous Project

FABulous formed part of the FIWARE Accelerator Programme. The mission of the FIWARE Accelerator Programme is "to boost the new promising FIWARE ideas, products or services developed by entrepreneurs and start-ups through funding, mentoring, training and networking" [39]. The FABulous Project, financed by the European Commission, forms part of the FIWARE Accelerator Program that aims to create and support a Future Internet (FI) service ecosystem for 3D printing technologies [38]. While the FABulous Project was underway, infrastructures and investors were joined to innovators and entrepreneurs in the fields of design, manufacturing, logistics, and content-based services. According to a final report, the FABulous Project accelerated 100 start-ups and entrepreneurs: 10 of them consolidated their businesses, 40 developed a commercial application, and the other 60 launched a web service prototype [http://fabulous-fi.eu/about-us/].

The DIMA3D company was one of the start-ups that participated in FABulous through Project FIL3D [http://fabulous-fi.eu/portfolio/fil3d/].

2.5. The Company: Dima3D

DIMA 3D, S.L. (Digital Manufacturing, Ltd.) was founded in 2013 to manufacture and market innovative 3D printers and to offer 3D printing added value services. Its General Headquarters are located in Valladolid, a middle-sized city in northwest Spain. It is a firm that manufactures 3D printers and offers 3D printing added value services. Almost half of the company's efforts are spent on Research and Development (R&D). This company also collaborates with several research groups from different universities in fields like materials and bio-applications, etc. The company's partnership with traditional digital printing companies helps to involve those local manufacturers willing to be involved in FIL3D and eager to develop their business.

DIMA3D's mission is to offer 3D printers to the market and high technological added value services to companies. In particular, it manufactures and sells its own 3D printers, and also manufactures a product that eliminates warping in heated bed printers. It is also a leader in training and e-learning in 3D printing technologies. DIMA 3D is very much involved in developing 3D printing technologies related to the "Internet of Things" and "Industry 4.0" concepts. Precisely in this context, DIMA 3D participated in the FABulous Project while it was underway (2015–2016) and led the FIL3D platform.

3. Experimentation and Results

An increasing number of small- and medium-sized equipment manufacturers and parts designers sell products in widely distributed areas, e.g., different countries or even worldwide. These manufacturers need to provide their customers with spare parts but cannot afford such a large stock and logistic capability. To validate the platform, two experiments were conducted.

3.1. Description of the Business Trial

To test the platform prototype, two experiments with industrial partners were carried out. Two different type companies played the role of the "Designer/manufacturer" in each experiment. The role of the "Local maker" was played by the same company in both experiments. Table 2 summarizes the criteria adopted to select these partners and the expectations from their participation.

Table 2. Criteria and expectations for the partners participating in the FIL3D platform's trial phase.

Company (Role)	Reasons	Expectations from the Participation of the Partner
Designer/manufacturer (a company that needs to guarantee the supply of spare parts at a distant location from the manufacturing site)	Besides their own designs, these companies may be in contact with many other designers and manufacturers. They may have several patents for innovative furniture parts. They have already prototyped some of their designs by 3D printing.	They are expected to provide some designs to be included in the service catalog. They can provide a realistic approach to the spare parts market for their sector (prices, design fees, certifications, etc.).
Local maker (a 3D printing company whose equipment is located near the end customer)	They have experience in 3D printers of several manufacturers and technologies. They have experience in prototyping for different customers: private, companies, etc. Large printing capability based on several 3D printing machines. They have experience in testing other online printing platforms.	Feedback from using the functionalities for makers. Refinement of 3D printers' parameterization to specify both technical and economic aspects so that makers can provide more accurate budgets for designs.

The service platform was presented to each partner with detailed explanations about their role and specific actions in trials:

1. The company that played the "Local maker" role had to refine the parameterization of 3D printers because it determined the way that designs had to be analyzed so they could provide accurate quotations for each model and 3D printing technology. The company DIMA3D played this role.
2. The companies that played the "Designer/manufacturer" role had to create a categorized catalog based on 3D designs and how they had to be specified, so that the system could calculate quotations for customers according to the makers' specifications.
3. These companies defined the printers' certifications process and the specifications for the printed spare parts. The royalties, fees, and tariffs were also determined at this point.
4. Finally, a fictitiously created customer simulated orders, which were attended to by the FIL3D platform.

The generated information and business flows (Figure 1) were monitored for each role. This analysis not only allowed us to test the prototype's functionalities, but also to:

- Test the consistency of all the platform features.
- Make a realistic approach to 3D printers' specification for different technologies.
- Analyze user experience and refine interfaces and administration indicators.
- Test the business process, information and payment flows.
- Refine the service platform according to the test results and partners' feedback.

3.2. *Experiment 1: The Furniture Manufacturer*

The company that played the "Designer/manufacturer" role was a Spanish furniture manufacturer. It is, in fact, one of the main furniture manufacturers in Spain and an innovative pioneer in its sector, with several patents for integrated IoT (Internet of Things) accessories and designs in furniture. This innovation created the need to provide spare parts for the electronic devices that are embedded in different furniture elements. Its headquarters are located in Valladolid, Spain, but it also has points of sale all over Spain and Portugal. EU regulations determine a minimum two-year warranty period for electronic devices. To provide this after-sales service, the company planned to rent a new building to manage the inventories of all these references. The top directors are aware that this is a growing need, as more and more of their goods will be fitted with cameras, sensors, and batteries, etc. Moreover, creating this new infrastructure and allocating this investment is not considered a source of value *per se*, but a cost that has to be included in the current business model.

This company is very much involved in 3D printing for prototyping. In fact, it has developed a patent for a wireless charger for mobile devices that is embedded in the armrest of sofas. Since the charger cannot be directly attached to wood, the electronic component is encapsulated in a plastic frame that is inserted into the armrest (Figure 3).

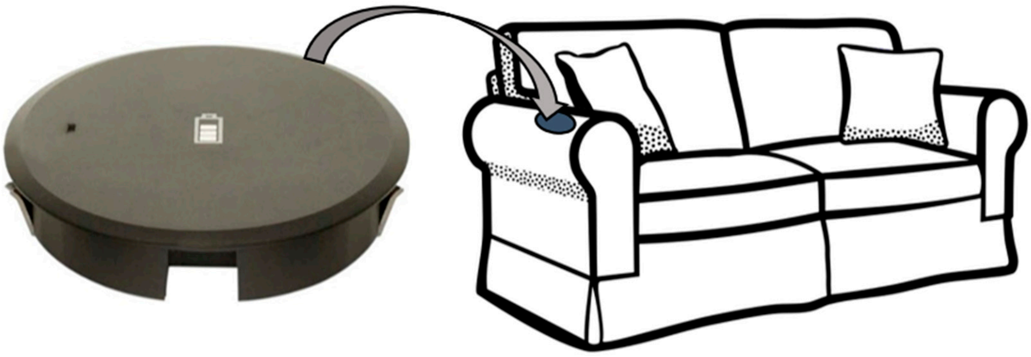

Figure 3. Schematic representation (not the actual patent) of the plastic frame that covers the wireless charger patented by the furniture company.

As such a device (on which mobile devices are placed for wireless charging) is regularly employed, the plastic capsule is prone to wear and tear. So, despite being an opportunity, incorporating this electronic component is actually a challenge because the company needs to guarantee the spare parts for these plastic boxes. Being a furniture factory, this company already has extensive logistics warehouses, which means that the additional volume required for storing small plastic parts is not a problem in terms of warehouse size. However, it does involve another problem, that of the administrative management of these new small components. The inclusion of technological elements in furniture means having to handle a large number of new references, which will also change rapidly as the technology of electronic components integrated into furniture rapidly evolves.

The FIL3D platform prototype was used to test how the furniture company could guarantee replacing this plastic frame. We simulated the case of a consumer whose plastic frame was broken and needed to order a replacement of this part. The customer does not need to contact the furniture manufacturer, but only has to log into the FIL3D system to see a list of available printers (which belong to the 3D printing company, namely the "Maker") and their location. This allows the selection of a printer located near the customer. Once the order has been placed, the Maker does not need to contact the Designer. The instructions to print the spare part are securely stored in the FIL3D database (see Figure 1) and are sent directly to the Maker's 3D printer. It is worth mentioning that these instructions are not stored in the Maker's company to guarantee the Designer's IPR. At this point, when the final FIL3D platform is implemented, and once the spare part has been printed, it will be delivered to the customer by a local carrier. The customer's payment will be processed (considering the article's commercial guarantee). The Maker will receive its fee from the FIL3D application, and the Designer will receive its royalties.

The final assessments of FIL3D in terms of value for the company were:

- They could avoid the investment to manage new inventories, while reducing costs due to the compulsory warranty period.

- The after-sales service will be a new source of value for the company, which will allow it to exploit its innovations with zero marginal costs.

3.3. Experiment 2: The Manufacturer of Electronic Components in the Healthcare Sector

In this case, the role of the "Designer/manufacturer" was played by a Spanish manufacturer of electronic components for healthcare equipment. The headquarters of this company are located in Madrid, Spain. Although it operates in Europe and the Americas, most of its customers are in Latin America.

The electronic components manufactured by this company need to be protected by a plastic box before they are integrated into healthcare equipment. The company needs to develop a specific plastic box for each electronic component (different shapes and sizes, etc.). Given this wide variety of boxes, attempting to guarantee the supply of spare parts through traditional systems would entail high inventory requirements. Furthermore, the spare parts would need to be distributed through a warehouse network until they eventually reached end customers, which would involve high transport costs and long lead times. Besides, the time that a part takes to reach an end customer would significantly increase if the item was held at customs before entering the consumer's country.

This implies a high cost in stocks and managing references, especially for the oldest references in the warehouse. Two years ago, the company decided that all the plastic boxes would be produced by additive manufacturing with a reliable producer. It found a good partner 400 km away from its headquarters. It validated that this supplier met the specifications needed to ensure the quality level required by the company. They lowered the stock level in recent years, but the management process to return a spare part to clients was quite long and expensive. It could not charge the whole cost to clients, and the after-sales service became an increasing source of problems: clients negatively valued the time required to return plastic boxes, as well as the cost that had to be applied (with no commercial margin).

In Figure 4a, we can see the sequence of steps from the time the customer places an order of a spare part with the manufacturer to the time the item is finally delivered to the customer:

1. The customer orders replacements for one or more boxes from the manufacturer.
2. The manufacturer requests a quotation (and delivery time) from several of the 3D printing manufacturers that it works with. It sends the STereoLithography (STL) files for a quotation.
3. The manufacturer places the order with one of the providers.
4. The manufacturer receives the order and proceeds with its packaging. An exportation invoice is attached. Some procedures with take place the logistics operator.
5. The shipment goes through customs in the destination country. The administrative process is followed.
6. The customer pays the import taxes and a logistic operator delivers the shipment.

This traditional logistics procedure entails a cost of administrative operations of 25 h and a lead time of 28 days.

Figure 4b shows the sequence of steps when the spare part order is placed through the FIL3D platform:

1. The customer orders the spare part directly from the FIL3D application.
2. The customer either selects a local supplier or FIL3D automatically assigns the order to the certified supplier that provides the best conditions in time and cost terms.
3. The spare part is sent to the customer.

This alternative to traditional logistics entails a cost of administrative operations of 1 h and a delivery time of 5 days.

This industrial partner especially valued the following as the main benefits of the FIL3D:

- Quality Service: reducing the time to deliver spare parts, while ensuring their quality with a certified local maker.

- Cost reduction: the administrative process and logistics required to deliver spare parts to end customers were fully minimized. This is also relevant during the warranty period as the company can proceed with orders to ensure that components are in place on time, while zero stocks are required.
- After-sales service: it can be a source of extra income instead of a cost driver. The company will receive the set royalties, if it decides to, or simply provides the way to acquire spare parts at a low cost from a local provider.

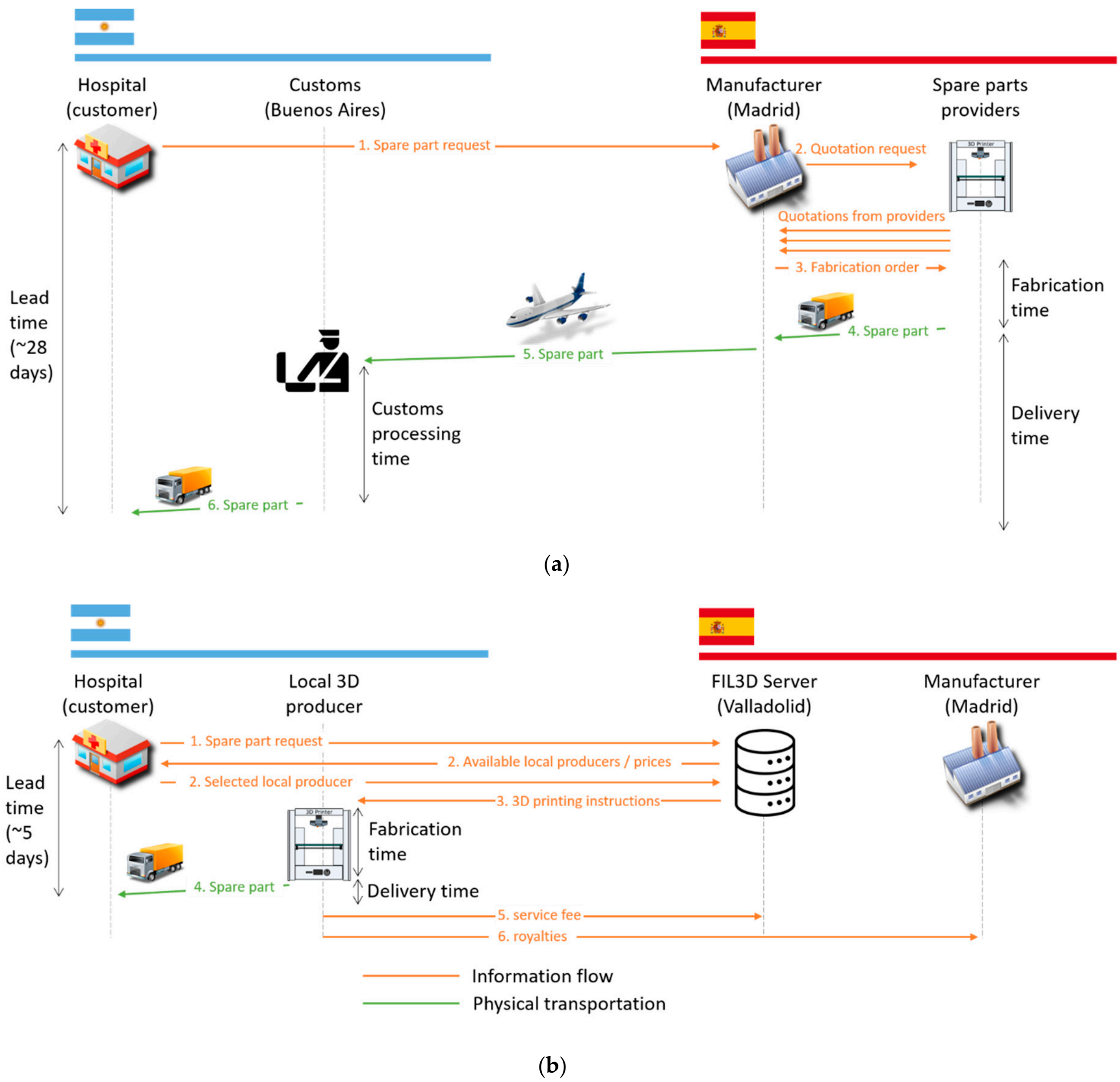

Figure 4. (**a**). Representation of the delivery of a replacement part by current traditional logistics. (**b**). Representation of the delivery of a replacement part by the FIL3D platform.

4. Discussion and Conclusions

In this article, we have presented a case study approach that shows how a digital supply chain for spare parts has the potential to bring about changes in business models with significant benefits for both global SMEs, customers, and the environment. Changes in business models will affect all the companies involved in the new digital supply chain. However, we have focused on SMEs' business models: manufacturers (that will be able to guarantee a supply of spare parts more efficiently and sustainably and receive royalties from the 3D printing of the pieces subject to IPR) and local producers (that will be able to gain access to more customers). Although we focused on SMEs, the conclusions of our work can be extrapolated to large companies. However, in our opinion, and based on the facts found in the literature, the main beneficiaries of our work will be SMEs. Other stakeholders, whose business models may also change, are local carriers and companies in charge of certifying local producers' 3D printers.

The implementation of the FIL3D project will offer opportunities to increase SMEs' service level. FIL3D aims to enable a novel integrated logistics framework for the spare parts industry based on distributed 3D printing by means of local dealers. It represents a paradigm shift from the traditional approach to the DSC, which will mean economic savings, increased efficiency, and better customer service.

To validate the platform, two experiments were conducted, and confirmed the benefits of the FIL3D platform for:

- Small and medium manufacturers (the "Designer/manufacturer" who owns the IPR) that wish to guarantee the supply of spare parts without having to increase their logistics costs.
- Local 3D printer owners and businesses located closely to end customers ("Local makers").

An important aspect for the sustainability of this business model is to protect manufacturers' IPR. To avoid piracy issues, the file containing the 3D instructions to print the spare part will never be stored on the local maker's equipment. Instead it will be securely stored on an FIL3D server (Figure 1). When a customer requests a local dealer to produce a replacement part, the information to generate it will travel in real time over the Internet from the FIL3D's server to the local dealer's printing server. However, the instruction file, whose intellectual property belongs to the "Designer/manufacturer", will never be stored anywhere else other than in the FIL3D database. At the end of the process, both the designer and the owner of the IPR of that part will receive their royalties.

A recent study by Westerweel et al. [41] endorses the economic sustainability of the business model herein described. By means of an economic model, they conclude that if "Designers/manufacturers" act as intellectual property licensors by selling spare part designs rather than physical spare parts, the local printing of spare parts will become a major benefit for buyers compared to centralized production. They also conclude that any surplus created by this model can be efficiently extracted by the manufacturer through relatively simple Intellectual Licensing contracts.

4.1. What Benefits does FIL3D Offer to the Participants in This Project?

The additive manufacturing industry needs systems to reduce some current inefficiencies: 3D manufacturing centers have underutilized capacity, which means that amortization costs have a very significant impact on unit costs. The companies that need this technology face very high transaction costs. The process of obtaining tenders from various suppliers, and negotiating the terms associated with delivery, copyright, deadlines, quality, and after-sales guarantees, etc., mean that the goods manufactured by 3D printing have a very high effective cost.

The FIL3D platform facilitates the processes of searching for professional quotations, reducing the transaction costs associated with acquiring one part or more made with any additive manufacturing technology (fused filament fabrication FFF, sintering, etc.). It also provides companies the possibility of offering processes linked to the after-sales service to customers/end users through the platform. This has a significant impact on the SMEs operating in global markets, as their ability to provide after-sales support to customers increases exponentially. On the one hand, response times are cut by not having to wait for a part to arrive from a warehouse located thousands of miles away. On the other hand, logistics management is made much simpler and more efficient. All these facts have a very strong impact on: i) reducing the cost associated with after-sales services/warranty; ii) sustainability terms, as it does not consume resources (materials and energy) to manufacture parts that will never be used and will eventually be destroyed, and if used, need to be transported thousands of miles away, with the consequent CO_2 emissions.

The first expected benefit for the "Maker" companies is obtaining a competitive channel through which they will receive requests for quotations from customers distributed "worldwide" to manufacture their products locally. 3D printers can theoretically operate 24 h a day, 365 days a year (discounting maintenance stops for cleaning and lubrication processes and mechanical adjustments). Increasing the annual operating hours of a 3D printer boosts its productivity and makes companies more competitive than traditional technologies. In addition, the FIL3D platform makes it easier to promote professional 3D manufacturing with guarantees and certified equipment.

The companies that perform eco-design can consider 3D printing (for example, [19]) and the benefits it brings (see Table 2) in cost reduction terms in the use phase of the product lifecycle. It is, therefore, essential for SMEs to decide to operate globally with sustainability criteria to guarantee that their customers have spare parts with the highest service level [42]. With FIL3D, both local technical support service and the customer can quickly access a spare part for repair at a reduced cost; and all this without negatively affecting the company with the intellectual property of its own designs, which can receive the corresponding royalties for the on-demand manufacturing of its designs without having to create "tangible assets" that negatively impact its balance sheet.

The use of the FIL3D platform will allow the manufacturer to carry out a more efficient spare parts management: it will no longer be necessary for it to store (and manage the references) of the new small plastic spare parts. This will bring companies close to the end consumer that will produce the spare parts and will, thus, reduce the manufacturer's inventory management costs.

An unexpected beneficiary of the FIL3D project was identified while the prototype platform was being tested. It was an independent professional that repaired antiques (clocks, radio sets, etc.). As most of the components of these devices have already been discontinued, this person needed to make his own designs of the spare parts needed for each repair. Designing exclusive components for each device to be repaired meant that this design was usually used only once. The FIL3D platform will offer significant benefits for such professionals. On the one hand, once the spare part has been designed, these professionals will be able to make the design of that component (not the component itself, but the 3D information to generate the component) available worldwide, which means that they will be able to reach a significantly higher number of potential customers. On the other hand, as these professionals will maintain the IPR of their designs—although spare parts are generated in a local producer close to the end user—designers will be paid royalties for each component printed through the platform. Therefore, the implementation of FIL3D is expected to bring substantial opportunities for not only SMEs, but also for such independent professionals.

4.2. Limitations and Aspects to Develop

Some of the advantages/obstacles with implementing this project were already identified in the work by Chekurov et al. [15]. However, unlike their conceptual model, the DSC described in the FIL3D project does not focus exclusively on companies and subcontractors. It also integrates more stakeholders into the model to increase the generated value and sustainability. The users involved in the project are not only companies, but also local designers who will be able to sell their products globally and sustainably.

Although additive manufacturing produces some waste (especially from unexpected defects or auxiliary materials), it has a huge potential to reduce both the energy and raw materials required in the supply chain, which is an environmentally benign practice [25]. However, some studies have suggested that DSCs have limitations in environmental impact terms. The fact that production is decentralized also implies a number of challenges that need to be addressed: raw materials need to be transported to local producers, which also implies transport needs [23]. This fact is especially relevant today, as suppliers of raw materials for additive manufacturing are limited and highly concentrated [22]. However, a high percentage of the material out of which spare parts are generated by additive manufacturing is recyclable. Indeed in recent years, several studies have proposed models for 3D-generated parts, waste recycling, and the creation of new products in a circular economy context [43,44]. Therefore, once a spare part generated by additive manufacturing completes its lifecycle it also serves as raw material to generate new spare parts, which contributes to minimizing the use of resources and the negative environmental impacts.

For this business model to work properly, it is essential that the parts manufactured by the Makers meet the quality standards required by the Designer/manufacturer. For this reason, the FIL3D Project proposes a certification process that must be applied to all the Makers that decide to join the FIL3D platform. These companies will have to prove that the printers they put at the FIL3D's service allow the generation of spare parts that comply with certain tolerances, and not only dimensionally [45], but also in terms of mechanical strength [46], texture, or color [47].

Author Contributions: Investigation, J.M.G.-V. and J.P.; software, F.V.; validation, F.A. and J.M.G.-V.; visualization, J.M.G.-V.; writing—original draft preparation, A.L.-P. and D.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been partially financed by the project "Lonja de Impresión 3D para la Industria 4.0 y la Empresa Digital (LONJA3D)" funded by the Regional Government of Castile and Leon and the European Regional Development Fund (ERDF, FEDER) with Grant VA049P17.

Acknowledgments: This article was developed as part of the EU research project FABulous. We thank the anonymous reviewers for their careful reading of our manuscript and their many insightful comments and suggestions. The usual disclaimer applies.

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

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