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Benefits of Non-Planar Printing Strategies Towards Eco-Efficient 3D Printing

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Abstract: The present work focuses on studying and demonstrating the potential benefits of non-planar printing, as compared to conventional 3D printing, in terms of improved eco-impacts. To this end, a case study of a medical or ergonomic device, which may benefit from non-planar printing in different ways, is completely developed and manufactured employing alternative approaches, which are quantified, as regards production costs and environmental impacts. Three 3D printing processes are used: two of them relying on non-planar printing, one using conventional 2D printing trajectories. Relevant benefits are achieved thanks to the possibility, enabled by non-planar 3D printing, of manufacturing products upon reusable rapid tools. These support tools constitute an interesting alternative to the support meshes generally employed in additive manufacturing, which are normally a relevant source of waste and involve costly post-processes.

Keywords: 3D printing; non-planar printing; eco-impacts; eco-efficiency; additive manufacturing

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1. Introduction

Additive manufacturing technologies (AMTs), in the last couple of decades, have transformed the way products are developed and are making a transformative impact in several industries. Among these technologies, fused deposition modeling (FDM), popularly referred to as "3D printing", constitutes the most affordable and widespread AMT and, to a certain extent, has "democratized" product development in parallel with the rise of the "makers" movement. FDM works following a layer-by-layer approach, as most AMTs do, typically depositing a fused thermoplastic filament following 2D paths, which conform the layers. The addition of layers, by sequential 2D deposition, leads to three-dimensional products and enables the creation of complex and innovative geometries, designed for enhanced performance or the integration of different functionalities [1–3]. Most research in the AMT field has focused on improving the technical aspects of the different technologies and on finding industrial applications, but their environmental performance and impacts have not been so commonly addressed.

Among pioneering efforts, for systematically gathering research studies focused on the environmental impacts of 3D printing, it is important to highlight the special issue on "3D printing and industrial ecology" by Lifset [4]. This collection of studies helped to highlight the advantageous potential of 3D printing, and of AMTs in general, for minimizing eco-impacts in product development. Indeed, 3D printing may result in eco-efficient developments, thanks to a promotion of localized production, a reduction in the transportation of goods, an improved availability of spare parts, and the development of methods aimed at zero-waste manufacturing, through a reduction of tooling and recycling of supporting materials, to cite a few relevant aspects.

FDM, despite its relevance as a creativity promotion tool and affordable prototyping technology, still has some drawbacks that limit its industrial impacts and its application to final high-quality products. For example, the layer-by-layer approach is intrinsically anisotropic and leads to surface inhomogeneities, which are clearly visible in FDM. Additionally, the adhesion between layers is sometimes suboptimal, depending on the materials, processing conditions, and machines employed, and may lead to mechanical limitations and flaws. In addition, the need for supporting structures typical of FDM, if not adequately managed, can introduce important environmental impacts, compared to other powder-based AMTs, with a lower requirement of built supports. These aspects are especially critical in the more economic configurations of FDM machines, which, on the other hand, are proving to be the most transformative in terms of technology democratization.

Recent studies have put forward the benefits of applying non-planar printing trajectories to the final layers of a 3D-printed product to enhance the surface quality of fused-deposition-modeled components and devices [5,6]. Although the term “non-planar 3D printing” has been recently coined and gained popularity since the publication of the cited references, these non-planar strategies have been studied almost since the beginning of the maker’s movement. In fact, the possibility of 3D printing following non-planar paths has been a subject undergoing intense study and even patenting for some years now [7] and may also result in mechanical and functional benefits, beyond the clear application to improve surface quality. Seminal papers in the field used the terms “curved layer fused deposition modeling” (CLFDM) [8–11], which is being now replaced by “non-planar 3D printing”. Since the first studies [8], CLFDM was proposed as an especially suitable method for printing thin curved shapes and avoiding the “stair-case” effect common of most additive manufacturing using planar layer-by-layer deposition, more remarkable in low-cost FDM than in technologies like laser stereolithography, digital light processing, or selective laser sintering or melting. CLFDM and non-planar printing basically apply the concept of 3D computer numerical control to the deposition of a fused filament. According to Choudhury et al. [8], 5-axis computer numerical control (CNC) would be ideal to drive non-planar depositions, although 3-axis CNC is enough for most applications.

Early studies in this area put forward the potential benefits of non-planar printing with smart materials. Conductive polymers, for example, have been employed for creating conductive circuits within additively manufactured devices [9], as a research direction for exploring applications of CLFDM beyond the creation of thin curved geometries. Other seminal studies focused on the mathematical modeling for curved slicing and continuous filament deposition and highlighted the improvement in terms of mechanical properties [10]. More recently [11], processes for variable-depth CLFDM of thin shells have been proposed. The influence of raster angle on final surface quality and mechanical performance has also been analyzed [12]. Nevertheless, the potential environmental benefits of shifting to non-planar 3D printing processes and taking advantage of curved layer deposition for creating objects upon reusable tools acting as supporting structures are analyzed here for the first time, to the authors’ best knowledge.

Considering all of the above, the present study aimed at studying and demonstrating the potential benefits of non-planar printing, as compared to conventional 3D printing, in terms of improved eco-impacts. To this end, a case study of a medical or ergonomic device (sport shoe insoles), which may benefit from non-planar printing in different ways, was completely developed and manufactured, employing alternative approaches, which are quantified as regards environmental impacts. Three 3D printing processes were used: method A, involving non-planar strategies upon reusable tools; method B, involving non-planar strategies upon conventional supporting structures; and method C, involving common 3D printing with 2D printing paths upon conventional supporting structures. The methodology employed to compare the environmental impacts among the 3D printing alternatives studied was a simplified life-cycle analysis previously applied by our team to the analysis of eco-impacts in laser stereolithography [13], but adapted here to the specific features, techniques, and materials of FDM.

2. Materials and Methods

2.1. Design Software and Geometries Designed

To compare the productivity and eco-impacts of conventional 3D printing and other innovative non-planar printing strategies, the manufacture of a set of shoe insoles for comfortable sports practice was chosen as a representative case study for the following reasons. Firstly, the non-planar surfaces of the insoles are very appropriate for their manufacturing using non-planar approaches, due to the relevance of surface quality and fatigue performance. Secondly, 3D printing technologies are starting to make an impact on the shoemaking industry, both for personalized solutions and for the mass production of shoes and garments with unconventional features [14]. Finally, both Italy and Spain are well-known for their shoemaking industries and the insole case study has connections to biomechanical studies and biomedical engineering, aspects which are relevant for the Spanish and Italian research institutions and researchers involved. The case study was designed following the geometry of a foot model from Thingiverse [15]. NX-11 (Siemens PLM Software solutions) was used as computer-aided design software, due to its versatile and user-friendly surface design operations. As schematically illustrated in Figure 1, the insole was designed by creating a collection of spline curves, drawn upon a set of reference planes transversally cutting the foot model. The splines followed the cut profiles of the sole of the foot and were joined to create a surface, which was thickened to create the desired insole. The external profile of the final insole was extruded to create a production tool, which authors refer to as “mold”, for enabling sequential non-planar printing of insoles employing a unique supporting tool, instead of the more common support structures used in additive manufacturing.

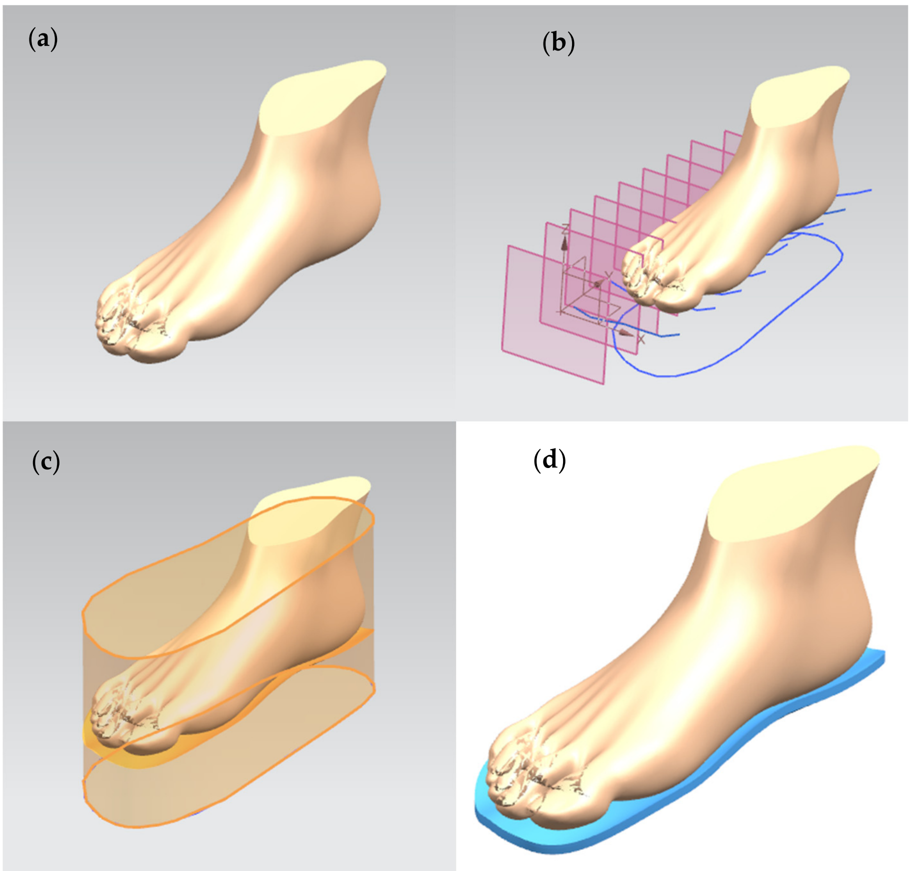

Figure 1. Step-by-step illustration of computational modeling of a personalized insole. (**a**) Foot model [15]. (**b**) Cutting planes and splines for generating the insole surface. (**c**) Projected profile for defining the boundaries of the insole surface. (**d**) Final insole design.

2.2. Fabrication Methods and Materials

A conventional 3-axis 3D printer, Tevo Tornado Gold, with some minor modifications to enable both planar and non-planar printing strategies, was used as fabrication technology. Polylactic acid (PLA) filament with a diameter of 1.75 mm (green color), purchased from BQ (Las Rozas, Madrid, Spain), was employed as printing material for the insole prototypes. Polyethylene terephthalate glycol-modified (PETG) filament, purchased from SD3D (San Diego, CA, USA), was used for printing the production tool or mold for method A. The CAD files aimed at planar or conventional 3D printing were sliced with the support of Slic3r software (slic3r.org).

Non-planar printing paths were implemented following the process described by Ahlers [5,6] with some adaptations for enabling 100% non-planar processes. To this end, Ubuntu (ubuntu.com), Notepad++ (notepad-plus-plus.org), Matlab (The Mathworks Inc., Nattick, MA, USA), and Excel (Microsoft, Albuquerque, NM, USA) were used as supporting software resources.

In short, the non-planar strategy relies on modifying the printing paths, allowing 3D trajectories for the printing head, although minor modifications are needed for avoiding collisions. In our case, the removal of the layer fan attached to the printing head was necessary, although modifications to the nozzle geometry may also be used as an alternative.

Three printing methods, whose applications are shown in Figures 2 and 3, were applied for the comparative purposes of the study. As advanced in the introduction, method A was based on a non-planar strategy upon a reusable tool or mold, also printed partially non-planarly; method B also followed a non-planar strategy but with conventional supporting structures; and method C corresponded to the state-of-the-art 3D printing method, which employs 2D printing paths upon conventional supporting structures planarly printed.

To better illustrate the slicing and path generation, Figure 2 presents the different printing paths resulting from the planar and non-planar slicing strategies for parts (shoe insoles), supporting molds or reusable tools, and conventional supports. Isometric and frontal views, in which the slices can be appreciated, are also presented.

More concretely, Figure 2a shows non-planar slicing and printing paths for the shoe insole and Figure 2b illustrates the reusable mold or support tool benefiting from a combination of planar and non-planar slicing and printing paths. In this approach, which applies processes described elsewhere [5,6], planar paths are firstly employed to create the main structure and two final layers deposited following non-planar paths are applied for achieving an improved surface quality. This planar/non-planar method differs from the process shown in Figure 2a, through which the whole insole is 100% printed using a non-planar process or curved deposition layers, by modifying previously described processes [5,6], as detailed above. In addition, Figure 2c presents conventional planar slicing and printing paths for the shoe insole. Finally, Figure 2d shows the conventional supports structure obtained using planar slicing and printing paths. Summarizing, method A combined Figure 2a,b, method B combined Figure 2a,d, and method C combined Figure 2c,d.

The innovative production tool, which covers a conventional support structure with two continuous curved layers, hence improving surface quality, providing structural integrity to the supports, and transforming them into a reusable production tool, was central to the presented strategy for sustainable production, as further discussed, and enabled through non-planar strategies.

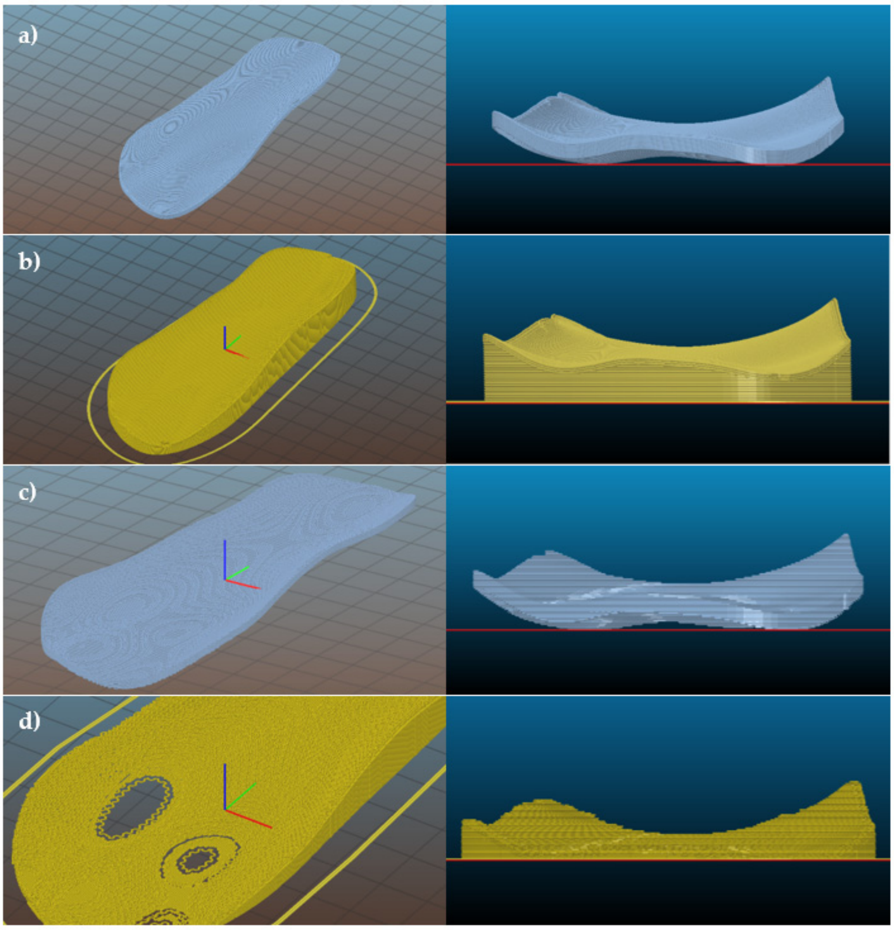

Figure 2. Printing paths resulting from the planar and non-planar slicing strategies for parts (shoe insoles), supporting molds or reusable tools, and conventional supports. Isometric (left column) and frontal (right column) views, in which the slices can be appreciated, are presented. (**a**) Non-planar slicing and printing paths for the shoe insole. (**b**) Reusable mold or support tool benefiting from a combination of planar and non-planar slicing and printing paths: planar paths are employed to create the main structure and two final layers deposited following non-planar paths are applied for achieving an improved surface quality. (**c**) Conventional planar slicing and printing paths for the shoe insole. (**d**) Conventional supports structure obtained using planar slicing and printing paths.

Due to its special interest in terms of minimized eco-impacts, as described in Section 3, the most innovative method A is illustrated in detail in Figure 4. The results from CAD models and non-planar printed prototypes, an example of a set of printed products using the same tool and the application of non-planar printing with alternative materials (i.e., flexible filament, "Filaflex"), are shown. To the authors' best knowledge, the employment of a reusable production tool, upon which non-planar printing processes as used for mass-production, is described in this study for the first time. As further discussed in the following section, such reusable tools may result in a significant trend towards minimizing environmental impacts in different AMTs, especially in FDM. On the one hand, the creation of supports, which in most cases are discarded as rubbish and involve time-consuming manual post-processes, is avoided. This leads to relevant savings of materials, time, and costs, which are clearly in connection with improved eco-impacts and eco-costs, as quantified and explained in Section 3. On the other hand, final surface quality is enhanced, as the typical pointy features, burrs, and barbs left on the products' surfaces after the removal of supports are avoided.

Figure 3. Prototypes for eco-impact assessment fabricated employing alternative printing strategies: methods A (**left images**), B (**central images**), and C (**right images**).

2.3. Methods and Software Employed for Studying Environmental Impacts

The fabrication of prototypes helps to systematically gather information regarding production time, materials consumption, costs, and eco-costs for the three printing strategies compared (methods A, B, C). Table 1 summarizes basic data for the calculation of environmental impacts and production costs. This information is subsequently employed to calculate production time, materials consumption, costs, and eco-costs for different series sizes (n > 1). The case study supposes that a professional sports practitioner may need several insoles along a season (e.g., one replacement per week), for which FDM may be competitive with other production techniques.

The eco-costs system was introduced at the beginning of the 21st century and has been made operational thanks to general databases, such as the one from the Delft University of Technology (DUT) used here [16,17]. This eco-cost method or system is based on calculating the sum of the marginal costs of preventing toxic emissions related to human health, as well as ecosystems, emissions that cause global warming, and the depletion of natural resources. The practical use of eco-costs relies on comparing, in standardized economic terms (€), the sustainability of various types of products with the same functionality. It provides a simple alternative to more systematic life-cycle analysis, which is especially suitable for preliminary assessments and conceptual studies. The eco-costs of raw materials employed, included in Table 1, and further used in this work, are obtained from the IDEMAT dataset from DUT and available at www.ecocostsvalue.com. The IDEMAT dataset is a set of life cycle inventories (LCIs) of more than 1000 materials, services, production processes, and end-of-life scenarios.

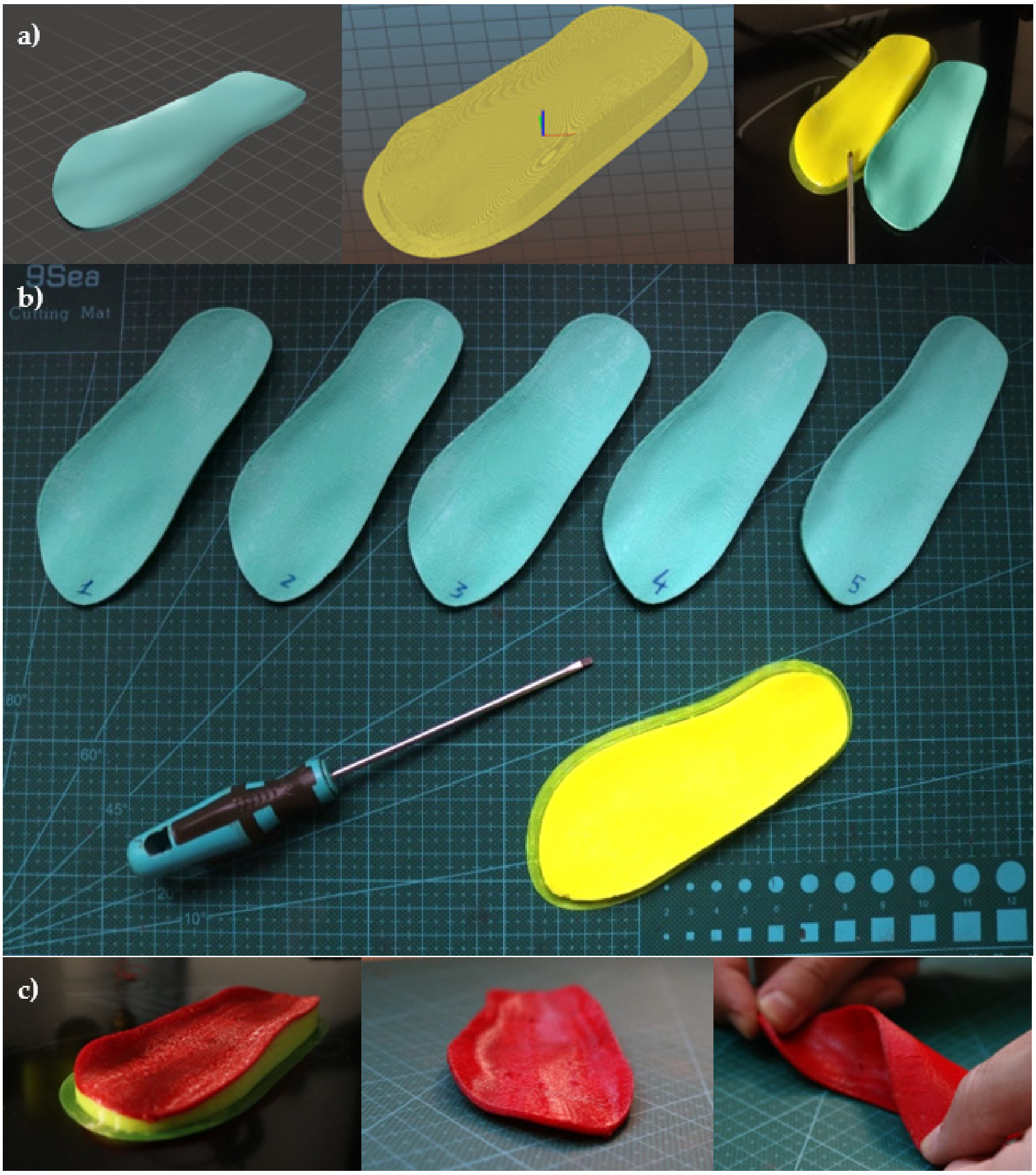

Figure 4. Details of innovative printing configuration or method A, which relies on a non-planar printed production tool or mold employed as supporting structure for sequential non-planar printing of a series of shoe insoles for comfortable sports practice. (**a**) Results from CAD models and non-planar printed prototypes. (**b**) Example of a set of printed products using the same tool. (**c**) Non-planar printing with alternative materials (i.e., flexible filament).

Table 1. Some basic data needed for the calculation of production costs and environmental impacts. * According to Iberdrola's "Plan Estable 2020" [18]. ** Data obtained from the IDEMAT app [17].

Magnitude	Value
3D printer power consumption	600 W
kWh price *	0.1147 €/kWh
Polylactic acid (PLA) density	1.24 g/cm^3
Spool PLA price	17.9 €/kg
Polyethylene terephthalate glycol-modified (PETG) density	1.29 g/cm^3
Spool PETG price	20 €/kg
kg CO_2/kg material (PLA) **	2.78
kg CO_2/kg material (PETG) **	2.94
Eco-cost in €/kg material (PLA) **	0.4 €/kg
Eco-cost in €/kg material (PETG) **	0.42 €/kg

Additionally, for the evaluation of production time, materials consumption, costs, and eco-costs for the three printing methods, it is necessary to define and quantify some magnitudes, which are summarized in Table 2 and employed in the mathematical expressions described further on. The rationale behind the mathematical expressions from Tables 3 and 4 is based on a calculation of production time and materials employed. These quantities depend on geometry, printing method, and eventual use of supporting structures or rapid tools and are directly related to the consumption of electricity and polymers, whose eco-impacts and eco-costs are already known from the data included in Table 1.

Filament length is straightforwardly calculated from the sliced geometry and printing trajectories and can be monitored during printing. Knowing the filament length, diameter, and density, polymer mass is determined. Production costs depend on the quantity of materials used and their value and on power consumed, printing time, and €/kWh. The quantity of CO_2 equivalent is also linked to materials used and power consumed, as happens with eco-costs. The combined use of the data from Table 1 and the mathematical expressions, summarized in Table 3 (production time, materials consumption, and production costs) and Table 4 (environmental impacts and related eco-costs), helped to calculate values for any production number "n", which led to the results figures in Section 3.

The mathematical expressions from Table 3 helped to quantify material and electricity consumptions and evolved from a previous study by our team [13] but were adapted from laser stereolithography to fused deposition modeling. In short, the production time was related to the printing times for molds, supports, and parts and to preparation times and depends on the size of the production batch (n). The printing of prototypes helped us to quantify these values. Printed mass was quantified considering the density of polymers employed for printing parts and tools, considering the length of printing paths, and hypothesizing that the filament section is circular. Production costs, for comparative purposes, considered the cost of materials employed and the cost of energy consumed, obtained by multiplying machine power and production time. Machine amortization and personnel costs were not considered for this study. In addition, the quantity of CO_2 equivalent was calculated using the models from Table 4 by taking into account the consumption of polymers for printing (masses of parts, production tools, and supports) and the amount of energy required for 3D printing. This amount of CO_2 equivalent was converted into eco-costs following the mentioned methodology, which provides a straightforward €-based standardization useful for analyzing production and sustainability in an integral way.

Table 2. Symbols of parameters and related units used in the mathematical expressions, for assessing production time, materials consumption, costs, and environmental impacts.

Symbol	Parameter and Unit
A	Mold printing time (min)
B	Non-planar insole (NPL) printing time (min)
C	Preparation time for method A (min)
D	Support structure printing time for method B (min)
C′	Preparation time for method B (min)
E	Printing time for method C (support structure and planar insole (PL)) (min)
C″	Preparation time for method C (min)
ρ_{PETG}	PETG density (g/cm^3)
ρ_{PLA}	PLA density (g/cm^3)
Φ	Filament diameter (mm)
π	Number Pi
La =	PETG filament length for mold (mm)
Lb =	PLA filament length for NPL insole (methods A and B) (mm)
Lc =	Filament length for support structure for method B (mm)
Ld =	Filament length for method C (mm)
W	3D printer power consumption (W)
P	Energy cost (€/kWh)
M_{PETG}	PETG filament mass for method A (g)
M_{PLA}	PLA filament mass for method A (g)
n	Number of copies
Q	PETG cost (€/kg)
R	PLA cost (€/kg)

Table 3. Expressions used for the assessment of relevant production magnitudes (time, material consumption, costs) for a series of "n" units.

Variable (Unit)	Method	Mathematical Expression
Production time T_i (min)	A	$T_A = A + n \cdot (B + C)$
	B	$T_B = n \cdot (B + D + C')$
	C	$T_C = n \cdot (E + C'')$
Material consumption M_i (g)	A	$M_A = (\pi \cdot (\Phi^2/4) \cdot (\rho_{PETG} \cdot La + \rho_{PLA} \cdot n \cdot Lb))/1000$
	B	$M_B = (\pi \cdot (\Phi^2/4) \cdot \rho_{PLA} \cdot n \cdot (Lb + Lc))/1000$
	C	$M_C = (\pi \cdot (\Phi^2/4) \cdot \rho_{PLA} \cdot n \cdot Ld)/1000$
Production costs C_i (€)	A	$C_A = W \cdot T_A \cdot P \cdot (60/3.6 \times 10^6) + ((M_{PETG} \cdot Q + M_{PLA} \cdot R)/1000)$
	B	$C_B = W \cdot T_B \cdot P \cdot (60/3.6 \times 10^6) + (M_B \cdot R/1000)$
	C	$C_C = W \cdot T_C \cdot P \cdot (60/3.6 \times 10^6) + (M_C \cdot R/1000)$

Table 4. Expressions used for the assessment of relevant environmental magnitudes, including impacts in terms of CO_2 generation and related eco-costs, for a series of "n" units. Values for PLA and PETG, as from Table 1, taken from IDEMAT app [17].

Variable (Unit)	Method	Mathematical Expression
Electricity consumption ELC_i (kWh)	A	$ELC_A = W \cdot T_A \cdot (60/3.6 \times 10^6)$
	B	$ELC_B = W \cdot T_B \cdot (60/3.6 \times 10^6)$
	C	$ELC_C = W \cdot T_C \cdot (60/3.6 \times 10^6)$
CO_2 equivalent $kgCO2_i$ (kg)	A	$kgCO2_A = (M_{PETG} \cdot 2.94 + M_{PLA} \cdot 2.78)/1000 + ELC_A \cdot 0.41$
	B	$kgCO2_B = (M_B \cdot 2.78)/1000 + ELC_B \cdot 0.41$
	C	$kgCO2_C = (M_C \cdot 2.78)/1000 + ELC_C \cdot 0.41$
Eco-costs EC (€)	A	$EC_A = (M_{PETG} \cdot 0.42 + M_{PLA} \cdot 0.4)/1000 + ELC_A \cdot 0.41 \cdot 23.34/1000$
	B	$EC_B = M_B \cdot 0.4/1000 + ELC_B \cdot 0.41 \cdot 23.34/1000$
	C	$EC_C = M_C \cdot 0.4/1000 + ELC_C \cdot 0.41 \cdot 23.34/1000$

3. Results

3.1. Main Results of the Study

The three described FDM methods enabled the manufacturing of the designed insoles, as shown in the images from Figures 3 and 4. However, in terms of surface quality, direct visual inspection puts forward the benefits of non-planar 3D printing processes (methods A and B) over conventional planar printing, in which the extruder follows 2D trajectories. The surface quality of method A overcomes that of method B, due to the lack of punctual supports, which normally leave burrs and barbs upon the printed surfaces after their removal. In addition, a very interesting result is the viability of sequential non-planar 3D printing (method A) repeatedly using a single supporting geometry or mold. This use of FDM as "rapid tooling" technology, for the production of reusable molds and supporting geometries, evolves from previous research by our team [19], but is here validated for non-planar printing for the first time. After having printed more than 10 insoles upon the test mold, the outer surfaces of the supporting production tool were in perfect condition and no geometrical mismatches or flaws could be appreciated after repeated use. Authors estimate that these tools may well withstand production runs or batches of more than 50 units. This target would be already a relevant figure and contribute to its employment for large series production [20], taking into account that low-cost 3D printing, when used for production, is normally applied to short series. Figure 5, as a complement to Figures 3 and 4, presents a detailed view of the supporting tool after part detachment (Figure 5a). In addition, the surface aspect after printing and detachment (Figure 5b), both from the printing tool (left photo) and from conventional supports (right photo), is shown in detail.

Figure 5. (**a**) Detail of supporting tool or printing mold after part detachment. (**b**) Surface aspect after printing and detachment from printing tool (left photo) and from conventional supports (right photo). (**c**) Alternative application case using similar processes: shin guards obtained employing non-planar printing with filaments of different colors for lower and upper layers, to enhance visual appeal.

In addition, a set of shin guards obtained using similar procedures as described in Sections 2.1–2.3 (method A) are presented (Figure 5c) as another application example. This real-use simulation employs non-planar printing with filaments of different colors for lower and upper layers, to enhance visual appeal.

Apart from the manufacturing results, the information thus gathered serves as fundamental input for the assessment of production-related magnitudes, as previously mentioned in the materials and methods section. The information obtained by consulting the references and machine-materials data sheets (see Table 1) and the values monitored during the manufacturing lead to the data included in Table 5. Their subsequent processing applying the expressions from Tables 3 and 4 leads to Table 6, which gathers the results obtained depending on a variable batch size.

Table 5. Time and material consumption for creating a single insole using the different methods studied. * Preparation time includes heating and cooling of the heated bed for part removal and subsequent printing restarting, cleaning the extruder when changing from one material to another, and cleaning the build plate, among other minor cleaning and verification processes. (NPL: non-planar; PL: planar; h = hour; ′ = min.).

	Printing Time	Preparation Time *	Filament Length (mm)	Filament Volume (cm^3)	Filament Mass (g)
METHOD A					
Mold (PETG)	1 h 6′	5′	6908	16.62	21.43
Insole (NPL)	1 h 6′	3′	4361	10.49	13.01
METHOD B					
Support	40′	3′	2902	6.98	8.66
Insole (NPL)	1 h 6′	12′	4361	10.49	13.01
METHOD C					
Support + Insole (PL)	1 h 44′	14′	7582	18.24	22.61

Table 6. Quantitative assessment of time spent, material consumed, costs, and eco-costs depending on the number of units for the different production methods (NPL: non-planar; PL: planar).

n =		Batch Size (n)						
		1	**2**	**5**	**10**	**20**	**50**	**100**
Time SpentT_i (min)	Method A	140	214	436	806	1546	3766	7466
	Method B	121	242	605	1210	2420	6050	12100
	Method C	118	236	590	1180	2360	5900	11800
Material Spent M_i (g)	Method A	34.44	47.45	86.47	151.50	281.56	671.76	1322.09
	Method B	21.66	43.32	108.31	216.62	433.23	1083.08	2166.16
	Method C	22.61	45.23	113.07	226.13	452.26	1130.65	2261.30
Cost C_i (€)	Method A	2.06	3.03	5.95	10.82	20.55	49.73	98.37
	Method B	1.60	3.20	7.99	15.98	31.95	79.89	159.77
	Method C	1.58	3.17	7.92	15.85	31.70	79.24	158.48
Eco-cost EC_i (€)	Method A	2.09	3.07	6.03	10.95	20.81	50.36	99.61
	Method B	1.62	3.24	8.09	16.18	32.36	80.90	161.80
	Method C	1.61	3.21	8.03	16.05	32.10	80.26	160.51

To visually summarize the obtained results, Figures 6 and 7 graphically represent the information collected in Table 6, in which relevant production-related aspects for the different methods are systematically compared. In addition, a focus for the low production range (n < 5) is also provided to facilitate its reading, considering also that 3D printing is applied in many cases for very short production runs. In Figure 6, the quantitative assessment of time spent and material consumed, depending on the number of units for the different production methods, is presented. Figure 7, on the other hand, focuses on comparing production costs and eco-costs for the different methods and depending on the batch size or number of units "n" manufactured.

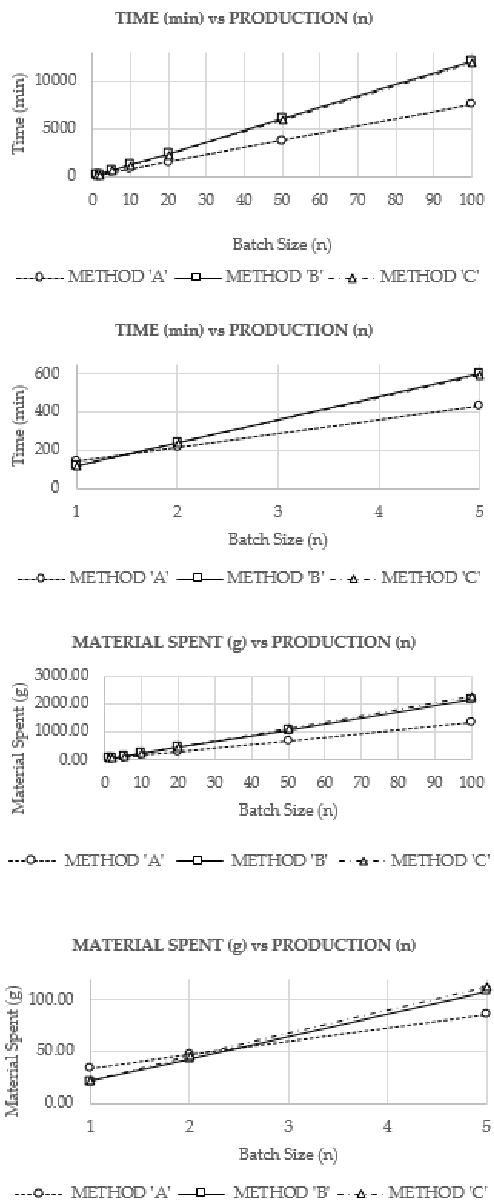

Figure 6. Quantitative assessment of time spent and material consumed depending on the number of units for the different production methods.

When analyzing Figures 6 and 7, it is important to mention that methods B and C may be contrasted by direct comparison of slopes, since the different graphed production functions for these methods pass through the origin of coordinates. The situation for method A is slightly different, as the employment of a 3D-printed production tool entails time, materials consumption, costs, and environmental impacts, even before the creation of the first insole or unit of the batch.

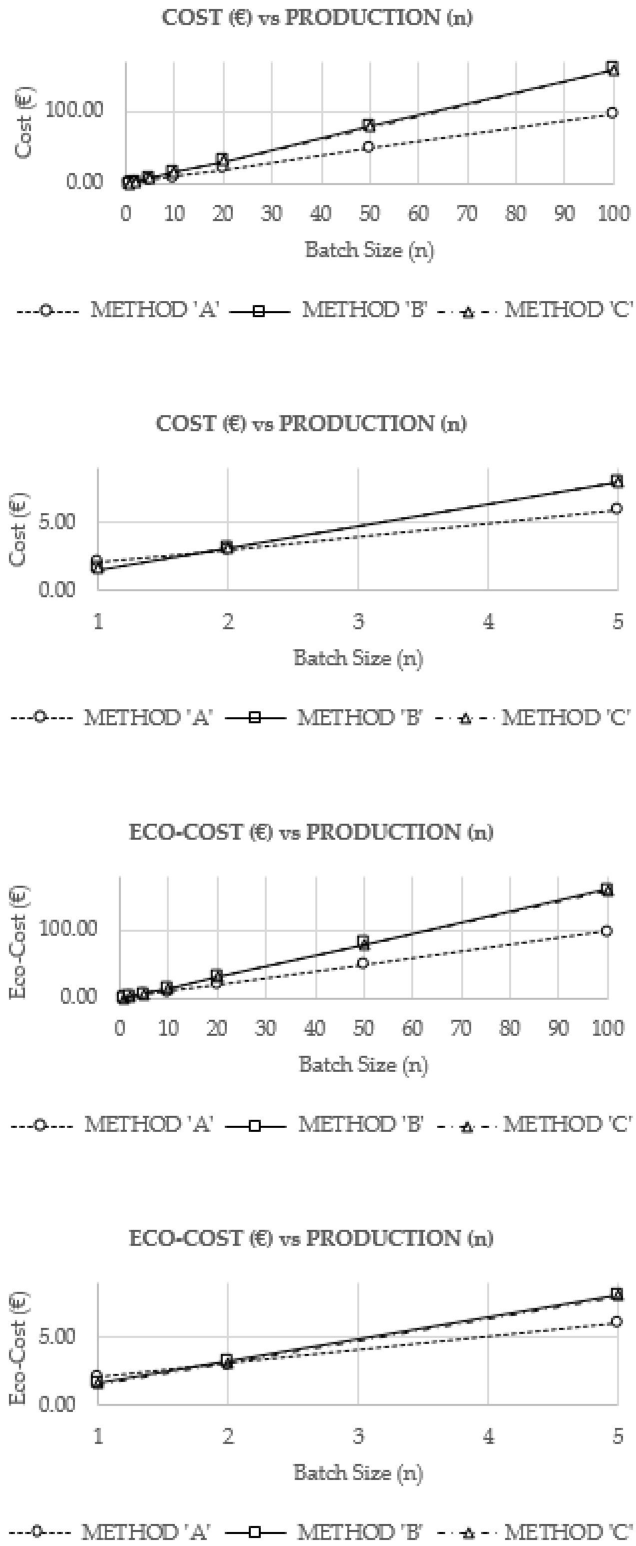

Figure 7. Quantitative assessment of production costs and eco-costs depending on the number of units for the different production methods. 1€ = 1.22 US$, as of 31 December 2020 (EU Central Bank).

Nevertheless, the impact of manufacturing the 3D-printed production tool is rapidly amortized: for batch sizes of 20 units, methods B and C are already around 50% more expensive than method A, in terms of time used, materials employed, incurred costs, and eco-costs. These differences reach values close to 60%–70%, in favor of method A, for batch sizes of 100 units. Even for a production of just two units, method A is the most competitive and the employment of the production tool or supporting mold is already justified, not only in terms of surface quality, but also regarding production and eco-costs.

3.2. Discussion and Future Proposals

To conclude the section, with a discussion of results, it necessary to stress that, according to the graphs previously provided, the larger the batch size, the more competitive method A (supporting mold + NPL insole) becomes. Its production benefits result is clear, for all the different variables studied, even for a batch size of two units. In addition, method B (NPL insole + supports) and method C (planar insole + supports) present almost the same behavior for all the evaluated aspects (overlapped curves). Thus, an advantage in terms of material, time, and costs savings for method B over method C cannot be established. Therefore, to select between B and C methods, it may be necessary to pay attention to other relevant features (aesthetics, achievable stiffness, fatigue endurance). In any case, it is necessary to highlight that common 3D printing cannot print upon an already created tool with a curved surface, so method A becomes the option of choice when sequential processes and the varied benefits of reutilizing a supporting tool or mold, instead of the traditional support structures, are desired.

Consequently, in general, method A is the method of choice in terms of environmental impacts. It benefits both from reduced printing times and minimal material usage, especially for large batch sizes. The fact that material reduction and manufacturing time lead to minimized environmental impacts are expected. However, we would like to stress that method A can be implemented thanks to the possibility of printing using curved deposition layers, as otherwise the support tool could not be reused without resorting to different printing jobs and starting again, with a layer-by-layer deposition, working upon the tool. Only through non-planar slicing and paths is it possible to create the thin curved surfaces by superposition of very few layers of material, which are continuously deposited upon already printed complex shapes and in a sequential or non-stop way.

Obtained results agree with other studies dealing with the evaluation of eco-impacts in FDM, which have highlighted the relevance of energy consumption during printing, which is directly linked to printing time [21]. The fact that method A helps to importantly reduce production time is directly linked with sustainable production. As regards the broader term of business sustainability, non-planar 3D printing can be considered part of Industry 4.0 technologies and has the potential to transform several business models, modify the supply chain, minimize material consumption, promote device personalization, and, in general, help to control production-related environmental impacts [22].

These non-planar or curved layer deposition strategies typically apply to complex-shaped and curved thin objects: protective garments, fashion accessories, housing of conventional products or toys, and enclosures for machines and vehicles, which may require good surface quality. In general, components with ruled surfaces for lightweight design and improved mechanical performance may be candidates for being printed using curved layer deposition procedures. Other medical devices and ergonomic appliances may benefit from similar production approaches and from the improved production costs and eco-costs achievable through non-planar 3D printing. Devices like protecting splints for safe sport practice, such as shin guards or face splints, immobilizing splints for repairing damaged articulations, among other laminar-shaped products with 3D surfaces, are adequate for non-planar production. Intrinsic benefits of non-planar 3D printing processes include improved surface quality and enhanced mechanical performance, but important progress towards sustainable production is also foreseeable, considering the results from the present study.

Summarizing, the presented non-planar 3D printing strategies prove highly interesting, in particular for method A, which demonstrates varied benefits including savings of time and materials and reduced costs and environmental impacts for the batch sizes usually achievable by FDM. As a consequence, sequential non-planar 3D printing (method

A) is considered a manufacturing strategy worthy of future studies, which will surely seek improvements in both software and hardware and may even develop a fully automated 3D printing production process.

Finally, it is necessary to highlight that the production costs and the eco-costs, environmental impacts quantified economically, are of the same order of magnitude, which demonstrates the relevance of performing these life-cycle-related analyses when planning the production of components by AMTs and, especially, when employing FDM.

Future research efforts will be devoted to creating a collection of non-planar 3D-printed medical devices with minimal eco-impacts and to extending these strategies to a wider set of manufacturing materials and additive technologies. Additional comparative studies with more traditional mass-production processes will be also undertaken, to study the batch sizes up to which FDM may be competitive with injection or compression molding processes, both in terms of production costs and environmental effects. We hope this research contributes to the sustainability of AMTs [23].

4. Conclusions

Non-planar 3D printing emerges as an interesting evolution of conventional 3D printing, in which the fused filament is deposited following truly three-dimensional paths, instead of the more common 2D trajectories. Non-planar 3D printing has been previously praised for the improved surface quality attainable, but its potential for improving the eco-efficiency of conventional 3D printing had not been analyzed in depth. This study demonstrated, through the complete development of a case study and the use of three different production methods, that non-planar 3D printing may constitute a turning point towards sustainable FDM production. The more relevant benefits are achieved thanks to the possibility, enabled by non-planar 3D printing, of manufacturing products upon reusable rapid tools. These support tools constitute an interesting alternative to the support meshes generally employed in additive manufacturing, which are normally a relevant source of waste and involve costly post-processes linked to their removal and cleaning of products' surfaces. Geometrical versatility, improved quality, and production sustainability go together in these innovative non-planar 3D printing strategies.

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References

1. Medellin-Castillo, H.I.; Zaragoza-Siqueiros, J. Design and manufacturing strategies for fused deposition modelling in additive manufacturing: A review. *Chin. J. Mech. Eng.* **2019**, *32*, 1–12. [CrossRef]
2. Vyavahare, S.; Teraiya, S.; Panghal, D.; Kumar, S. Fused deposition modelling: A review. *Rapid Prototyp. J.* **2020**, *26*, 176–201. [CrossRef]

3. Micalizzi, S.; Díaz Lantada, A.; De Maria, C. Shape-memory actuators manufactured by dual extrusion multimaterial 3D printing of conductive and non-conductive filaments. *Smart Mater. Struct.* **2019**, *28*, 105025. [CrossRef]
4. Lifset, R. 3D printing and industrial ecology. *J. Ind. Ecol.* **2017**, *29*, 6–8. [CrossRef]
5. Ahlers, D. 3D Printing of Nonplanar Layers for Smooth Surface Generation. Master's Thesis, Universität Hamburg, Hamburg, Germany, 2018.
6. Ahlers, D.; Wasserfall, F.; Hendrich, N.; Zhang, J. 3D printing of nonplanar layers for smooth surface generation. In Proceedings of the IEEE 15th International Conference on Automation Science and Engineering (CASE), Vancouver, BC, Canada, 22–26 August 2019; pp. 1737–1743.
7. Sherwood Page, J. Systems and methods for improved 3D printing. U.S. Patent US10005126B2, 19 March 2014.
8. Chakraborty, D.; Aneesh Reddy, B.; Roy Choudhury, A. Extruder path generation for curved layer fused deposition modeling. *Comp. Aided Des.* **2008**, *40*, 235–243. [CrossRef]
9. Diegel, O.; Singamneni, S.; Huang, B.; Gibson, I. Curve layer fused deposition modeling in conductive polymer additive manufacturing. *Adv. Mater. Res.* **2011**, *199–200*, 1984–1987. [CrossRef]
10. Singamneni, S.; Roy Choudhury, A.; Diegel, O.; Huang, B. Modeling and evaluation of curved layer fused deposition modeling. *J. Mater. Process. Technol.* **2012**, *212*, 27–35. [CrossRef]
11. Chen, L.; Chung, M.-F.; Tian, Y.; Joneja, A.; Tang, K. Variable-depth curved layer fused deposition modeling of thin-shells. *Robot. Comp. Integr. Manuf.* **2019**, *57*, 422–434. [CrossRef]
12. Huang, B.; Singamneni, S. Curve layer fused deposition modeling with varying raster orientations. *Appl. Mech. Mater.* **2014**, *446–447*, 263–269.
13. Díaz Lantada, A.; de Blas Romero, A.; Sánchez Isasi, A.; Garrido Bellido, D. Design and performance assessment of innovative eco-efficient support structures for additive manufacturing by photo-polymerization. *J. Ind. Ecol.* **2017**, *21*, 179–190. [CrossRef]
14. Cheng, A. How Adidas Plans to Bring 3D Printing to the Masses. 22 May 2018. Available online: https://www.forbes.com/sites/andriacheng/2018/05/22/with-adidas-3d-printing-may-finally-see-its-mass-retail-potential/?sh=2a101d24a607 (accessed on 3 February 2021).
15. Thingiverse. Human Female/Lady Right and Left Feet Model by Znanzhu. 7 November 2016. Available online: https://www.thingiverse.com/thing:1876380 (accessed on 3 February 2021).
16. Vogtländer, J.G. The Model of the Eco-Cost/Value Ratio. Available online: www.ecocostsvalue.com (accessed on 30 November 2020).
17. IDEMAT App. Available online: http://idematapp.com/ (accessed on 30 November 2020).
18. Iberdrola. Plan Estable. 2020. Available online: https://www.iberdrola.es/ (accessed on 30 November 2020).
19. Munoz-Guijosa, J.M.; Zapata Martínez, R.; Martínez Cendrero, A.; Díaz Lantada, A. Rapid prototyping of personalized articular orthoses by lamination of composite fibers upon 3D-printed molds. *Materials* **2020**, *13*, 939. [CrossRef] [PubMed]
20. Dröder, K.; Heyn, J.K.; Gerbers, R.; Wonnenberg, B.; Dietrich, F. Partial additive manufacturing: Experiments and prospects with regard to large series production. *Procedia CIRP* **2016**, *55*, 122–127. [CrossRef]
21. Falaudi, J.; Hu, Z.; Alrashed, S.; Braunholz, C.; Kaul, S.; Kassaye, L. Does material choice drive sustainability of 3D printing? *Int. J. Mech. Mechatron. Eng.* **2015**, *9*, 216–223.
22. Godina, R.; Ribeiro, I.; Matos, F.T.; Ferreira, B.; Carvalho, H.; Peças, P. Impact Assessment of Additive Manufacturing on Sustainable Business Models in Industry 4.0 Context. *Sustainability* **2020**, *12*, 7066. [CrossRef]
23. Colorado, H.A.; Gutiérrez Velásquez, E.I.; Neves Monteiro, S. Sustainability of additive manufacturing: The circular economy of materials and environmental perspectives. *J. Mater. Res. Technol.* **2020**, *9*, 8221–8234. [CrossRef]