Feasibility study on the use of recycling materials for prototyping purposes: a comparative study based on the mechanical resistance

Victor M. López
Department of Mechanical and Mining Engineering
University of Jaén
23071 Jaén, Spain

Diego Carou
Department of Design in Engineering
University of Vigo
Ourense, Spain
diecapor@uvigo.es

Fabio A. Cruz S.
ERPI, F-54000
Université de Lorraine
Nancy, France

***Abstract*—Nowadays, sustainability is one of the major objectives for manufacturing. The use of recycled materials can be a suitable strategy when economic, environmental and technical feasibility are verified. 3D printing is still a novel manufacturing process and the research on the topic is still limited, particularly when referring to sustainability issues. This paper attempts to evaluate the suitability of the substitution of virgin polylactic acid (PLA) by recycled PLA. To do that, it includes an experimental plan divided into three phases including .. to evaluate the technical feasibility based on mechanical resistance. The results showed that recycled PLA may be used due to the, though slightly lower, similar mechanical resistance than that of the virgin material. This reduction is limited to 13 % in the worst configuration (vertical). Besides, it was identified how the infill density and the orientation used for printing played a major role on the mechanical resistance, when others such as the infill pattern, printing speed and layer height had non-significant influence.**

***Index Terms*—keyword 1; keyword 2**

I. Introduction

Additive manufacturing (also called 3D printing) is becoming a key technology for cross domains applications. The principle of manufacturing objects layer-by-layer enables a higher flexibility degree in the product design phase. The set of several technologies are pushing forward the advantages such as customization of objects with complex geometries and a great deal of detail, combination of different materials, reduction of the need for assembly and high utilizations rate of raw materials [2]. Thus, this field is receiving great attention by the industrial companies and the general public.

3D printing has developed significantly over time. A great development is expected in sectors such as product consumption, medical products and aerospace components [3]. The rapid prototyping market reached $7.3 billion US dollars in 2018 according to Wohlers (Rodriguez-Hernández et al., 2020), which also forecasts the market to reach 23.9 and 35.6 billion dollars by 2022 and 2024, respectively [Forbes2020]. The industry has grown from $295 million to 5.1 billion over the past 25 years.

Nowadays, there is a need to find paths to reduce the ecological impact of manufacturing processes and activities [4]. Researchers are developing efforts to identify opportunities of 3D printing on the circular economy paradigm [5]. Moreover, due to the fact that plastic is one of the most used materials in the 3D printing industry [6], and given their non-biodegradable nature, it is one the most abundant type of waste produced and their impact is well document in the different ecosystems [7]. Thus, reducing the consumption of plastics and/or the use of the plastics already presented in the ecosystem is of great importance for the environment.

A major literature validates the rationale for prototyping phase in early design phases of product development coming from engineering, human computer interaction, design thinking or software development [8]. According the prototyping theory, different kind of prototypes are needed during the new product development phases (eg. prototype for desirability, for feasibility, and for viability) [9]. Based on that, a prototype is accomplished in terms of certain aims: (1) Model to Link, (2) Model to Test, (3) Model to Communicate, (4) Model to Decide, and (5) Model to Interact . The use of digital tools allows designers to create highly flexible prototypes that enable short learning cycles at an affordable cost. On the other hand, the use of 3D printing technology enables the materialization aspect. Even if the printed part is functional or non-functional, the printed part is found valuable in design decisions [10]. However, there is a gap in the literature in terms of sustainable manufacturing using 3D printing in the early design phases [3]. Although the technology offers high efficiency in the use of material, the great democratization of this technology could cause a rebound impact due to the increasing generation and disposal of huge amounts of waste or polluting emissions to fabricated virgin feedstock. Particularly, in the prototyping phases. Without a doubt, FFF's roots are linked to the rapid prototyping concept and in the last years it has been widely adopted by industry, academia and users to create functional objects for their designs. Therefore, one question that remains is to define the minimal conditions and mechanical properties in order to create prototypes in the early phases without compromising the mechanical properties, even for recycled feedstocks.

Studies on the technical acceptability of recycled materials as substitutes for conventional virgin materials are still limited for particular applications. It is important to note that in most cases, prototypes do not require excellent mechanical resistance but the minimum to be handled to inspect and measure. Thus, the type of material used and its amount can be further optimized when it comes to prototyping development.

The present study evaluates the mechanical properties of both conventional and recycled polylactic acid (PLA) materials. The objective of the study is the assessment of the suitability of the recycled PLA as replacement in prototyping, though its use may be further extended to other applications. To do that, this study is based on a comprehensive Design of Experiments (DoE) approach with three main phases in order to evaluate the influence of several printing parameters on the mechanical properties of the parts. In section 2, a literature review is presented in terms of critical parameters in 3D printing technology and an overview of the use of distributed recycling approach. Then, section 3 illustrates the methodology used in this study. In section 4, the results of the experimental approach is presented and we concluded by a discussion and perspectives.

II. Existing Theories & Previous Work

A. Main parameters on Fused Filament Fabrication

One of the most common processes in 3D printing is the Fused Filament Fabrication (FFF) (also known as fused deposition process modeling (FDM), which is a trademark). The process is based on material extrusion, so the material is heated above the melting point of the material and then deposited onto a platform [11]. In FFF/FDM, a variety of thermoplastic materials are commonly used, such as acrylonitrile butadiene styrene (ABS), polyvinylchloride (PVS), polycarbonate (PC), nylon, polifenilsulfona, high density polyethylene (HDPE), low density polyethylene (LDPE), polyethylene terephthalate (PET), high impact polystyrene (HIPS) and polylactic acid (PLA) [14].

The mechanical properties are critical for engineering parts, particularly, for 3D printed because of the anisotropic behaviour which can influence up to about 47% in the ultimate tensile strength in function of the manufacturing parameters [15]. Using a systematic literature review, [16] identified certain key parameters influencing the printed parts including raster-to-raster air gap, raster angle, layer thickness, infill density and build orientation.

Nevertheless, it is highlighted that it might be uncertain if a set of optimal parameters for a machine/polymer/application combination can be transferred to other 3D printers due to the issue of intra-3D printer variability. The open source nature of the FFF development emphasizes the need for the development of a standard experimental protocols adequate with the features of personalization of the machines [17]. Therefore, it is important to identify the most important parameters among all of the available to carry out the process that may affect the response variable and their expected influence based on the scientific literature [18].

In general terms, it is found that for low values of layer height, as well as the thickness of the deposited or printed filament, the tensile strength of the material is improved. In addition, by orienting the printing direction towards the direction in which the tensile load will be applied during tensile strength, the property can be also maximized. The importance of the printing orientation was also identified by [19]. According to [20], a higher extrusion temperature and an optimized layer thickness, a triangular filling pattern and a higher filling level maximize the strength of the parts. Regarding the printing speed, it is identified that higher printing speed with higher layer thickness leads to lower part strength. Among others, [21] also identified the influence of the layer height on the mechanical resistance.

B. Materials and recycling

The development of new materials such as polymers, elastomers and composites in engineering plays a fundamental role in the advance sustainable manufacturing [22]. The use of biopolymers of natural and renewable origin, replacing synthetic polymers, is the cellulose, hemicellulose, lignin, starch, alginate, chitosan and derivatives derived from them represent the most abundant bio-based and renewable raw materials for different 3D printing technologies. In addition, these biopolymers of natural origin include lignocellulosic materials, seaweed materials and exoskeleton crustacean materials [23]. [23] reviews a wide range of biobased printing materials with the adequate printing/solidification approach and printed structures and potential applications.

Polylactic acid (PLA) is a type of natural biopolymer obtained from crops such as starch or sugar cane. It is a biodegradable biopolymer consisting of lactic acid molecules and it is one of the most used materials in 3D printing. In addition, PLA is a sustainable alternative that shows a range of crystallinity and mechanical properties between polystyrene and polyethylene terephthalate [13].

In the literature, the distributed recycling via additive manufacturing approach (DRAM) makes an emphasis in the technical steps to reuse plastic waste through the recycling chains for material extrusion based 3D printing [26]. Recycling (totally or blending of virgin/reused) of raw material is a method of special interest to contribute to manufacture in a sustainable way [27]. In the DRAM methodology, consumers have an economic incentive to recycle. This is because they can use their waste as feedstock for a wide range of consumer products that can be produced for a fraction of conventional costs of equivalent products. Moreover, 3D printing is especially suited because it allows producing parts with (almost) no waste and could reduce more than 40 % of the waste related to the used material, reusing 95 % of the unused material [28]. Currently, most of the cost of 3D printing is associated with the cost of the filament **ref?**. By recycling raw materials such as polylactic acid (PLA), the emissions of carbon dioxide can be reduced in the transport to landfills or shipping to customers offering environmental benefits [29]. The technical feasibility for recycling in laboratory conditions been proved for PLA

[30], ABS [31], PET [32] that recycled plastics have a similar performance to their virgin counterparts and they have even been applied in the manufacture of high value products in some sectors such as the automobile [27].

However, it is important to evaluate the properties of the recycled materials before substituting virgin for recycled materials. In this sense, [24] compared the elongation at break, load at break, flow index, Young's module and breaking stress of recycled ABS, high impact polystyrene (HIPS) and PLA. The PLA showed the highest elongation at break along with the ABS. In addition, the PLA had a higher breaking load and breaking stress, although a smaller Young's modulus. Other authors such as [33] identified the suitability of using recycled polypropylene instead of virgin polypropylene based on mechanical properties. Specifically, they found that the use of fillers (talc and glass fibre) improved the mechanical properties. [34] studied the influence of the percentage of recycled PLA used in the filament (i.e., 10 to 50 %) showing that the smaller the percentage the higher the ultimate tensile strength. [35] obtained higher values of tensile stress for recycled PLA when comparing to the virgin one.

As [36] pointed out, the use of recycled materials is still uncertain because of the potential changes in the material properties then recycling. [27] studied the cycles of printing that are able to withstand the PLA until it loses much of its properties. Thus, they showed that PLA withstands two printing cycles, since in a third cycle the mechanical properties and viscosity decreased considerably. The increase in crystallinity and melting enthalpy and the decrease of cold crystallization enthalpy are attributed to the 3D printing process, not to the extrusion recycling process. Table 1 shows the comparison of the properties between the virgin material and the same material subjected to another printing cycle, being possible to appreciate how properties such as the tensile strength and modulus are close for the two materials. Similarly, other authors such as [37] have proved how recycling PLA provides comparable mechanical properties as the virgin material only after a second recycling process.

The recycling of PLA has certain limitations because of reducing molecular weight with its reuse, resulting in degradation and decrease of mechanical properties. For instance, the addition of polidopamine (PDA) on the surface allows improving these properties. Viscosity is also reduced with each printing cycle but, it could be corrected by adding virgin plastic [13]. When recycling, there is a decrease in the properties of the material as a result of the presence of carbonyl groups and superficial pitting due to thermomechanical degradation during the process of new melting process occurring during 3D printing [27].

It is found that this valuable literature is focused on the evaluation and optimization of printed parts that seeks the best trade-offs among parameters for a final product. On the other hand, the aim of the study is to analyze the influence of major critical factors affecting the mechanical properties in FFF, evaluating their impact on the mechanical properties in 3D printing, particularly for both virgin and recycled PLA.

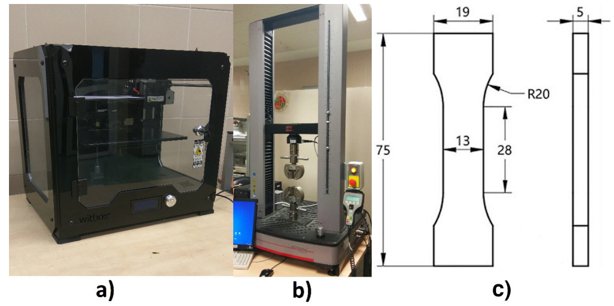


Fig. 1: Equipment used in the study: a) 3D printer, b) Universal testing machine an c) mechanical sample.

Thus, based on the results, it is expected to gain a better understanding on the suitability of using recycled materials in 3D printing and how to properly select the printing conditions to guarantee sufficient mechanical resistance. In order to do that, an experimental plan comprising three phases will be developed. This is a complementary approach to the established literature on FFF.

III. Methods

A. Materials and equipment

The printing materials used in the study were virgin and recycled PLA characterized by data listed in Table S1. Both materials were commercial ones, the recycled PLA contained 10 % of virgin PLA in the blend.

The 3D printer used to manufacture the specimens was a BQ's Witbox, shown in Fig. 1a. The software used to generate the printing code was the Ultimaker Cura 3.2.1. To perform the destructive test, the machine used was the MTS Criterion 43 universal testing machine (MTS, 2020) (Fig 1b) with a maximum load of 50 kN, being the maximum load supported by the LPS 104 cell of 10 kN. The clamping system was the Instron 2716-015 system with a maximum supported load of 30 kN. The selected strain rate was 0.5 mm/min.

In this study, the mechanical specimens were manufactured according to the dimensions proposed by [38] in which the length of the specimen was 75 mm. The dimensions of the specimen are the ones depicted in Fig. Fig 1c.

B. Methodology

Fractional designs are useful for reducing the number of tests reducing time and money [39], being used as screening designs. Hence, the experimental plan included three different phases (Figure 2) to carry out a comprehensive study with a limited number of tests not compromising the reliability of the results using fractional designs. The main goal of *Phase I* is to identify and discard factors depending on their influence on the response variable. The response variable chosen was the maximum load attained during the testing of the specimen [41]. In this phase, the design included only a specimen printed in the horizontal orientation for each of the combinations, not evaluating the influence of the orientation. The use of random order allowed guaranteeing that the hypothesis that

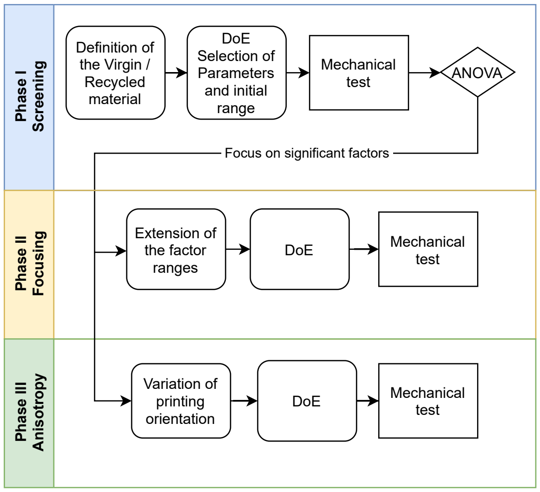


Fig. 2: Summary of the three phases of the experimental plan.

TABLE I: Results of the Phase 1.

Material	LH	IP	ID	PS	Load.max
Virgin	0.15	Tri-hex	60	40	2.206
Virgin	0.3	Tri-hex	60	80	2.163
Virgin	0.15	Grid	60	80	2.240
Virgin	0.3	Grid	100	80	3.598
Virgin	0.3	Tri-hex	100	40	3.620
Virgin	0.15	Tri-hex	100	80	3.811
Virgin	0.15	Grid	100	40	3.793
Virgin	0.3	Grid	60	40	2.160
Recycled	0.15	Tri-hex	60	40	2.163
Recycled	0.3	Tri-hex	60	80	2.163
Recycled	0.3	Grid	60	40	2.152
Recycled	0.15	Tri-hex	100	80	3.379
Recycled	0.3	Tri-hex	100	40	3.370
Recycled	0.15	Grid	60	80	2.051
Recycled	0.15	Grid	100	40	3.525
Recycled	0.3	Grid	100	80	3.488

Note:
Layer height (LH), Infill pattern (IP), Infill density (ID), Printing speed (PS)

the errors are independently distributed random variables was fulfilled [39]. Based on the literature research presented in section 2, the critical parameters for the study are the (1) layer height and (2) infill pattern. In addition, taking into account the goal of sustainable manufacturing (i.e., trying to optimize the consumption of material), but also productivity (i.e., trying to minimize printing times), (3) infill density and (4) printing speed were considered [43]. These four factors (layer height, infill pattern, infill density and printing speed) were selected using two levels for each of them with large ranges. In consequence, the factors and their levels used were: layer height (0.15 and 0.3 mm), infill pattern (tri-hexagonal and grid) , infill density (60 and 100 %) and printing speed (40 and 80 mm/s). The printing temperature chosen was 210 °C, which was the recommended for PLA material. This phase ends with an analysis of variance (ANOVA) in order to identify the influential factors on the response variable.

Then, the main goal of *Phase II* is to study in more detail the influence of the most influential factors according to the *Phase I*. In other words, the intent is to make a focus on how the response variable evolves finding minimal and maximal values. For that reason, in this phase an extension of the factor levels was established. On the other hand, the criteria selection of levels for the other three factors aimed at minimizing the printing time.

Finally, the *Phase III* aimed at evaluating the influence of the anisotropy of the specimens depending on the printing orientation, which may notably affect the mechanical resistance of the specimen. In this phase, the main focus is to analyse the influence of the building orientation. Because of the anisotropy, the UNE 116005:2012 (UNE, 2012) standard requires printing specimens in three different orientations: edgewise (E), horizontal (H) and vertical (V), testing five samples in each orientation. This phase included the printing of 15 specimens of each virgin and recycled PLA.

IV. Findings

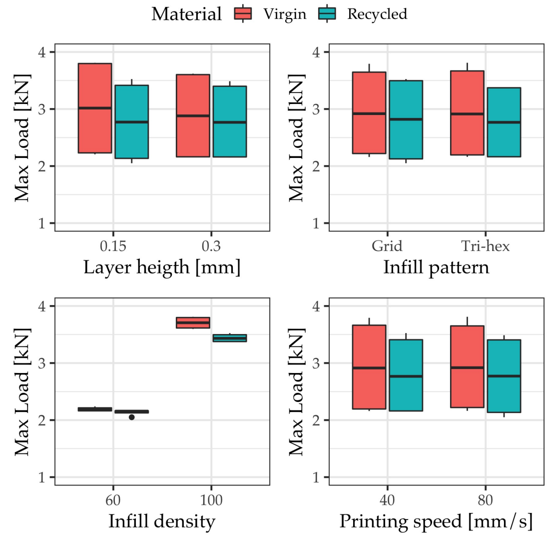
A. Phase I: Screening phase

Table **??** summarizes the experimental strategy with the results of the maximum load attained during this screening phase. A total of 16 samples were tested.

In general, shortly after attaining the maximum load, the fracture of the specimen occurred. However, the nature of the fracture was not homogeneous as shown in Fig 3a. Thus, in most cases, the specimens showed a fragile behavior and the fracture, either horizontally or with a lower inclination angle, was clean. However, for the recycled material, the specimens presented a ductile behavior and, properly, the fracture did not occur after the maximum load was attained, canceling the tests minutes after the maximum load was attained. The breakage in these cases occurred at a 45° angle and, in the cases of the RE-2 specimen, two parallel fracture lines can be clearly seen. The printing conditions did not allow us to observe a clear relation to the fracture of the specimens. This behavior may relate to that explained by [19]. The authors identified two different types of fracture: in-layer and interlayer. In general, the fracture occurs at the interface of two layers when printing in vertical position, even when varying the printing orientation up to 45º from the vertical position. In-layer fracture is more likely when the specimen is printed using an edgewise position (or, inclined up to 45º from that position). In this second case, the printing direction is the same as the tensile stress direction, which also happens when the horizontal orientation is used. In these cases, the material layer is not intact after the fracture. As a result, it is likely that both modes (in-layer and inter-layer fractures) coexist in this study, which may explain the heterogeneity of the different fractures.

An analysis of variance (ANOVA) was performed using R software in order to identify the influential factors on the response variable. As criterion, critical factors for the response variable were those with p-values lower than 0.05 [44]. Shapiro-Wilk normality tests allowed verifying the normality of the residuals. The figure **??** illustrates the boxplots of the

(a) Tensile sample of the Phase 1



(b) Boxplots to identify significant factors based on DoE

Fig. 3: Phase 1: screening tests to identify significant factors based on DoE

TABLE II: ANOVA results at 95% significance level

	Df	Sum Sq	Mean Sq	F value	Pr(F)
LH	1	0.0	0.013	1.340	0.27388873386647
IP	1	0.0	0.001	0.107	0.749885762008385
ID	1	8.0	7.963	824.810	6.10015416870348e-11*
PS	1	0.0	0.001	0.062	0.808001353429214
Material	1	0.1	0.106	10.957	0.00787655131772907
Residuals	10	0.1	0.010		

results considering each factors. Also, The Table I lists the results of the ANOVAs carried out for the experimental results.

From the results of the table I and figure **??**, it can be clearly identified how the infill density was the most statistically significant factor for the maximum load (p-valor lower than 0.001). Likewise, the type of material is also a significant factor for the response variable but in a less proportion, being non-significant the rest of the factors. When evaluating the contribution of each of the factors to the variability explained by the model, there were calculated values of 97.3 % and 1.3 % for infill density and type of material, respectively. Thus, when manufacturing new parts or specimens, infill density is a key factor for guaranteeing adequate mechanical properties of the specimens.

B. Phase II: Focusing

The main goal of phase II is the evaluation of the infill density by the fact that it was observed as a significant factor in the previous phase. Therefore, five levels of the infill density were chosen ranging from 40 to 100 % to evaluate the evolution of the maximum load for both virgin and recycled PLA. The specific levels selected were 40, 55, 70, 85 and 100 %. Regarding the selection of the other factors of the printing process, the main criteria was the reduction of time printing as stated in the methodology section. Therefore, the experimental conditions were layer height of 0.3 mm, infill pattern tri-hexagonal and printing speed of 80 mm/s with an estimated printing time of 20 min. A total of 10 samples were manufactured.

Fig. 4: Specimens after tensile test in phase II.

Figure 4 shows the fracture of the specimens tested in phase II. Regarding the fracture, the results were similar as those of the phase I (i.e., more ductile behavior for the recycled PLA specimens). The interest element in this phase is presented in Figure 5 where the maximum load versus infill density for both virgin and recycled PLA are illustrated.

From the analysis of the Figure 5, it is possible to appreciate that there are two clearly different regions. Therefore, in the A region, comprised between infill densities from 40 to 85 %, the slope of the curve grows slowly with a linear trend. Thus,

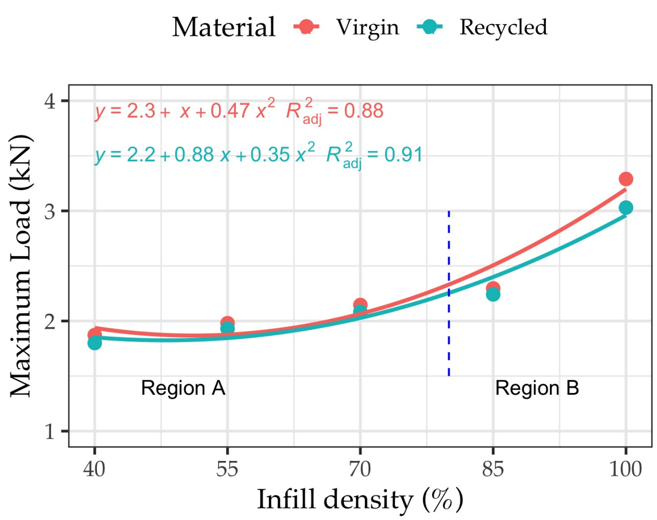


Fig. 5: Maximum load versus infill density for both virgin and recycled PLA.

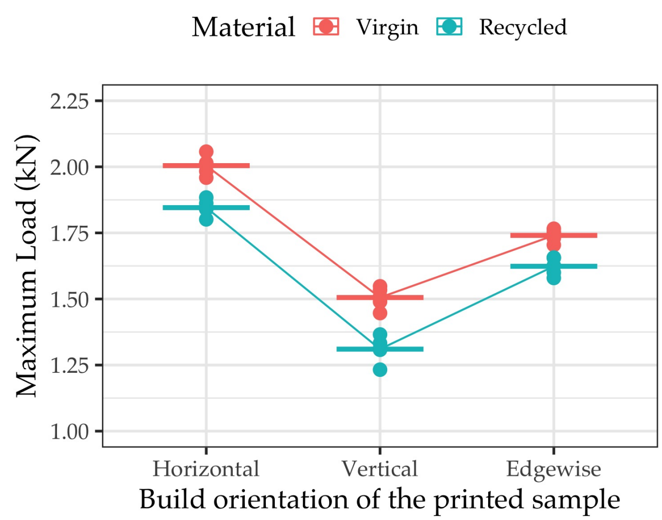


Fig. 6: Average of the load obtain for each build orientation.

an increase of the infill density did not provide an proportional increase in the mechanical properties. due to the fact that the maximum load remained almost constant. However, in the B region, the slope of the curve grows largely. Consequently, with a small increase of infill density, the maximum load notably grows. Regarding the type of material, it is clear that virgin PLA outperforms recycled PLA, but a reduced difference between them. These results are in agreement with studies on the comparison of the performance of recycled and virgin PLA [30] where there was found a difference of about 10% of the mechanical properties in the first recycling cycles. However, the difference notably increased as the infill density approached 100 %. The obtained results agree well with those presented by Wang et al. [45]. In their study, the authors studied infill density of 20, 40, 60, 80 and 100% and the evolution of the tensile strength is similar to the one shown in Figure 5.

Based on the results, it appears that a reduction from 100% to 40% of infill density implies a relatively reduction in 41.7% of the maximal load supported for both type of materials. This is an interesting result that enables to creation of prototypes with less materials, without compromising the mechanical solidity. Although the number of measured points is reduced, it is possible to model the relation between the maximum load (y) versus the infill density (x) for the two regions and tested materials by means of polynomial regression that are plotted in the figure. The models may help to anticipate the mechanical resistance of a part based on the selection of the infill density. Based on the developed models, it is possible to highlight that recycled PLA is a suitable substitute for virgin PLA guaranteeing similar mechanical resistance. Moreover, by developing models for the mechanical properties, it is possible to minimize the material consumption for both virgin and recycled materials satisfying the mechanical resistance requirements. Thus, by accurately knowing the influence of the printing conditions on the mechanical resistance, it is possible to advance towards sustainable manufacturing.

C. Phase III: Study on the printing orientation

In this final phase, the main goal is to test the influence of building orientation according the established standards by the UNE 116005:2012 (UNE, 2012). Five specimens for each of the orientations (edgewise, horizontal and vertical) for both virgin and recycled PLA were manufactured. The selected printing conditions were infill density of 50%, printing speed of 80 mm/s, tri-hexagonal infill pattern and layer height of 0.3 mm, with the objective of limiting the use of material and the time required for printing.

Fig S3 and S4 show the images of the tested specimens observing the same type of fracture as in the first two phases. It is interesting to evaluate the reduction in the maximum load depending on the type of material and orientation in which the specimens were printed.

The Figure 6 details the maximum load and the means values for the five specimens at each orientation. From the results, it is clear that the horizontal orientation is the one that provided the higher mechanical resistance, followed by the edgewise orientation. Likewise, the virgin samples performed better than the recycled samples.

The vertical orientation provided the worse results due to the deposition of the layers perpendicular to the tensile direction. These results are in good agreement with those by [46] and

[45]. For the recycled material, there is a slight decrease in the maximum load obtained from 6.71 to 13% depending on the orientation with respect to the virgin values. Particularly, the biggest reduction of the load happens in the vertical orientation with the 13 %. However, the other two orientations are more adequate for substituting the virgin material for the recycled material with a limited reduction in mechanical resistance (6.71 to 7.93 %).

V. Discussion and limits of the results

One of the systemic problems of plastic waste relies on dependency of the indiscriminate disposal of plastics which carries multiple risks because many plastic products contain additives that modify their physico-mechanical properties making it difficult the recycling/reuse [47]. The use of 3D printing technology for prototyping activities are not excepted of this societal issue. The main purpose of this article is to see to what extent the influence of printing parameters affects the tensile resistance of the printed parts. While a large literature is focused on optimization of the parameters for obtain functional printed objects using the 100% of the printed material, the approach opted here is to observe the influence of this factor of a large range factors considered as critical in the using a range. This type approach is important because it enables designers and users to use printing setups that are envisioned as prototypes objects, to be secure about the quality of printed products regarding not using.

One of the main results in this study relies on that infill density of 60% retains a 58.2% of the mechanical resistance. This is a relevant insight for prescriptions of minimal conditions where a printed part can be manufactured. Moreover, the use of recycled assets in the printing process, may be a relevant path, considering the current priorities of EU on circular economy and carbon neutral strategies ambitions. Also, there is a great development of applications using distributed recycling approach. For instance, Nur-A-Tomal et al [48] presented a valuable example of waste-to-wealth to use waste plastic toys retaining the original colour of waste plastic to fabricate new products. Certainly, the development of complete closed loop DRAM case studies based on material and location to demonstrate technical, ecological and economic feasibility [25].

There are certain limitations to this work in the perspective of materials and parameters tested. Certainly, the use of other materials is needed to evaluate if the influence of infill and recycled material are consequent with the results found. Moreover, other major factors are needed in order to consider the quality of a prototype. Clearly, in the prototypes where the main goal is the user acceptability, surface/text finishing, dimensional accuracy are key variables to include for the printed objects rather than mechanical resistance. Nevertheless, this is an ongoing research in which the main purpose is to promote the use. The validation statistical validation of the influence of minimal parameters.

VI. Conclusions

The present study includes a comprehensive experimental program to analyze the Fused Filament Fabrication process based on mechanical resistance using virgin PLA and recycled PLA. The paper aims at improving the sustainability of 3D printing process, assessing the technical feasibility of the substitution. The main conclusions of the study are the following. The printing conditions determined in a great manner the mechanical resistance of the specimens. Specifically, the most influential factor on the maximum load for both virgin and recycled PLA was the infill density.
The influence of the infill density on the maximum load allowed identifying two different regions: A, from 40 to 85 %, linear behavior with a slight slope and, B, from 85 to 100 %, the maximum load increases notably with a much higher slope. The fracture for the virgin material corresponded to that of a fragile material, while the fracture of the recycled material showed a more ductile behavior.

The selected orientation for printing the specimens is of great importance for the maximum load because of the anisotropy. In this sense, the horizontal orientation allowed attaining a higher maximum load, while the vertical orientation provided the lower value due to the fact that no layers were deposited in the tensile direction. Our results support the main argument on the substitution of virgin PLA for recycled PLA based on the mechanical resistance for prototyping purposes, advancing towards sustainable manufacturing. Is was found that using an infill density of 40%, there is a retention of the 58.2% of the mechanical resistance. Despite recycled PLA offers a slightly lower mechanical resistance, when possible, by properly selecting the printing conditions (mainly, by the infill density and orientation) it could be approximate to that of the virgin PLA. Particularly, when using edgewise and horizontal orientations it is possible to obtain maximum loads close to that of the virgin material (from 3 to 8 % lower).

VII. Acknowledgments

The authors would like to thank the “Mechanical and Energy Engineering” TEP 250 research group and to the Lorraine Fab Living Lab. This research is partially funded from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 869952.

References

[1] Y. Jin, Y. Wan, B. Zhang, and Z. Liu, “Modeling of the chemical finishing process for polylactic acid parts in fused deposition modeling and investigation of its tensile properties,” *J. Mater. Process. Technol.*, vol. 240, pp. 233–239, Feb. 2017, doi: 10.1016/j.jmatprotec.2016.10.003.

[2] K. Xiao, F. Zardawi, R. Van Noort, and J. M. Yates, “Developing a 3D colour image reproduction system for additive manufacturing of facial prostheses,” *Int. J. Adv. Manuf. Technol.*, vol. 70, no. 9–12, pp. 2043–2049, Feb. 2014, doi: 10.1007/s00170-013-5448-1.

[3] T. Peng, K. Kellens, R. Tang, C. Chen, and G. Chen, "Sustainability of additive manufacturing: An overview on its energy demand and environmental impact," *Addit. Manuf.*, vol. 21, no. June 2017, pp. 694–704, May 2018, doi: 10.1016/j.addma.2018.04.022.

[4] M. K. Niaki, S. A. Torabi, and F. Nonino, "Why manufacturers adopt additive manufacturing technologies: The role of sustainability," *J. Clean. Prod.*, vol. 222, pp. 381–392, Jun. 2019, doi: 10.1016/j.jclepro.2019.03.019.

[5] M. Despeisse *et al.*, "Unlocking value for a circular economy through 3D printing: A research agenda," *Technol. Forecast. Soc. Change*, vol. 115, pp. 75–84, Feb. 2017, doi: 10.1016/j.techfore.2016.09.021.

[6] C. M. González-Henríquez, M. A. Sarabia-Vallejos, and J. Rodriguez-Hernandez, "Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications," *Prog. Polym. Sci.*, vol. 94, pp. 57–116, Jul. 2019, doi: 10.1016/j.progpolymsci.2019.03.001.

[7] M. W. Ryberg, M. Z. Hauschild, F. Wang, S. Averous-Monnery, and A. Laurent, "Global environmental losses of plastics across their value chains," *Resour. Conserv. Recycl.*, vol. 151, p. 104459, Dec. 2019, doi: 10.1016/j.resconrec.2019.104459.

[8] C. W. Elverum, T. Welo, and S. Tronvoll, "Prototyping in New Product Development: Strategy Considerations," in *Procedia CIRP*, 2016, vol. 50, pp. 117–122, doi: 10.1016/j.procir.2016.05.010.

[9] J. Menold, K. Jablokow, and T. Simpson, "Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design," *Des. Stud.*, vol. 50, pp. 70–112, 2017, doi: 10.1016/j.destud.2017.03.001.

[10] C. W. Elverum, T. Welo, and S. Tronvoll, "Prototyping in New Product Development: Strategy Considerations," in *Procedia CIRP*, 2016, vol. 50, pp. 117–122, doi: 10.1016/j.procir.2016.05.010.

[11] P. Wolszczak, K. Lygas, M. Paszko, and R. A. Wach, "Heat distribution in material during fused deposition modelling," *Rapid Prototyp. J.*, vol. 24, no. 3, pp. 615–622, Apr. 2018, doi: 10.1108/RPJ-04-2017-0062.

[12] C. K. Chua, C. H. Wong, and W. Y. Yeong, "Standards, quality control, and measurement sciences in 3D printing and additive manufacturing." Academic Press, 2017.

[13] X. G. Zhao, K.-J. Hwang, D. Lee, T. Kim, and N. Kim, "Enhanced mechanical properties of self-polymerized polydopamine-coated recycled PLA filament used in 3D printing," *Appl. Surf. Sci.*, vol. 441, pp. 381–387, May 2018, doi: 10.1016/j.apsusc.2018.01.257.

[14] R. Singh, R. Kumar, and P. Singh, "Prospect of 3D Printing for Recycling of Plastic Product to Minimize Environmental Pollution," in *Ref. Modul. Mater. Sci. Mater. eng.*, Elsevier, 2018, pp. 1–14.

[15] J. J. Laureto and J. M. Pearce, "Anisotropic mechanical property variance between ASTM D638-14 type i and type iv fused filament fabricated specimens," *Polym. Test.*, vol. 68, no. March, pp. 294–301, 2018, doi: 10.1016/j.polymertesting.2018.04.029.

[16] D. Popescu, A. Zapciu, C. Amza, F. Baciu, and R. Marinescu, "FDM process parameters influence over the mechanical properties of polymer specimens: A review," *Polym. Test.*, vol. 69, pp. 157–166, 2018, doi: 10.1016/j.polymertesting.2018.05.020.

[17] F. A. Cruz Sanchez, H. Boudaoud, L. Muller, and M. Camargo, "Towards a standard experimental protocol for open source additive manufacturing," *Virtual Phys. Prototyp.*, vol. 9, no. 3, pp. 151–167, Jul. 2014, doi: 10.1080/17452759.2014.919553.

[18] A. Jaisingh Sheoran and H. Kumar, "Fused Deposition modeling process parameters optimization and effect on mechanical properties and part quality: Review and reflection on present research," in *Mater. Today proc.*, 2020, vol. 21, pp. 1659–1672, doi: 10.1016/j.matpr.2019.11.296.

[19] T. Yao, Z. Deng, K. Zhang, and S. Li, "A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations," *Compos. Part B Eng.*, vol. 163, pp. 393–402, 2019, doi: 10.1016/j.compositesb.2019.01.025.

[20] A. aldin Alafaghani and A. Qattawi, "Investigating the effect of fused deposition modeling processing parameters using Taguchi design of experiment method," *J. Manuf. Process.*, vol. 36, pp. 164–174, Dec. 2018, doi: 10.1016/j.jmapro.2018.09.025.

[21] M. Altan, M. Eryildiz, B. Gumus, and Y. Kahraman, "Effects of process parameters on the quality of PLA products fabricated by fused deposition modeling (FDM): Surface roughness and tensile strength," *Mater. Test.*, vol. 60, no. 5, pp. 471–477, May 2018, doi: 10.3139/120.111178.

[22] M. F. Ashby and K. Johnson, *Materials and design: the art and science of material selection in product design*. Butterworth-Heinemann, 2013.

[23] J. Liu, L. Sun, W. Xu, Q. Wang, S. Yu, and J. Sun, "Current advances and future perspectives of 3D printing natural-derived biopolymers," *Carbohydr. Polym.*, vol. 207, pp. 297–316, Mar. 2019, doi: 10.1016/j.carbpol.2018.11.077.

[24] R. Kumar, R. Singh, and I. Farina, "On the 3D printing of recycled ABS, PLA and HIPS thermoplastics for structural applications," *PSU Res. Rev.*, vol. 2, no. 2, pp. 115–137, Aug. 2018, doi: 10.1108/prr-07-2018-0018.

[25] F. A. Cruz Sanchez, H. Boudaoud, M. Camargo, and J. M. Pearce, "Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy," *J. Clean. Prod.*, vol. 264, p. 121602, Aug. 2020, doi: 10.1016/j.jclepro.2020.121602.

[26] H. A. Little, N. G. Tanikella, M. J. Reich, M. J. Fiedler, S. L. Snabes, and J. M. Pearce, "Towards Distributed Recycling with Additive Manufacturing of PET Flake Feedstocks," *Materials (Basel).*, vol. 13, no. 19, p. 4273, Sep. 2020, doi: 10.3390/ma13194273.

[27] P. Zhao, C. Rao, F. Gu, N. Sharmin, and J. Fu, "Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment," *J. Clean. Prod.*, vol. 197, pp. 1046–1055, Oct. 2018, doi: 10.1016/j.jclepro.2018.06.275.

[28] V. Petrovic, J. Vicente Haro Gonzalez, O. Jordá Ferrando, J. Delgado Gordillo, J. Ramón Blasco Puchades, and L. Portolés Griñan, "Additive layered manufacturing: sectors of industrial application shown through case studies," *Int. J. Prod. Res.*, vol. 49, no. 4, pp. 1061–1079, Feb. 2011, doi: 10.1080/00207540903479786.

[29] P. Santander, F. A. Cruz Sanchez, H. Boudaoud, and M. Camargo, "Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach," *Resour. Conserv. Recycl.*, vol. 154, p. 104531, Mar. 2020, doi: 10.1016/j.resconrec.2019.104531.

[30] F. A. Cruz Sanchez, H. Boudaoud, S. Hoppe, and M. Camargo, "Polymer recycling in an open-source additive manufacturing context: Mechanical issues," *Addit. Manuf.*, vol. 17, pp. 87–105, Oct. 2017, doi: 10.1016/j.addma.2017.05.013.

[31] N. Vidakis, M. Petousis, A. Maniadi, E. Koudoumas, A. Vairis, and J. Kechagias, "Sustainable additive manufacturing: Mechanical response of acrylonitrile-butadiene-styrene over multiple recycling processes," *Sustain.*, vol. 12, no. 9, 2020, doi: 10.3390/SU12093568.

[32] N. E. Zander, M. Gillan, and R. H. Lambeth, "Recycled polyethylene terephthalate as a new FFF feedstock material," *Addit. Manuf.*, vol. 21, no. January, pp. 174–182, May 2018, doi: 10.1016/j.addma.2018.03.007.

[33] F. Gu, P. Hall, and N. J. Miles, "Performance evaluation for composites based on recycled polypropylene using principal component analysis and cluster analysis," *J. Clean. Prod.*, vol. 115, pp. 343–353, Mar. 2016, doi: 10.1016/j.jclepro.2015.12.062.

[34] Babagowda, R. S. Kadadevara Math, R. Goutham, and K. R. Srinivas Prasad, "Study of Effects on Mechanical Properties of PLA Filament which is blended with Recycled PLA Materials," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 310, no. 1, p. 012103, Feb. 2018, doi: 10.1088/1757-899X/310/1/012103.

[35] A. C. Pinho, A. M. Amaro, and A. P. Piedade, "3D printing goes greener: Study of the properties of post-consumer recycled polymers for the manufacturing of engineering components," *Waste Manag.*, vol. 118, pp. 426–434, 2020, doi: 10.1016/j.wasman.2020.09.003.

[36] L. Suárez and M. Domínguez, "Sustainability and environmental impact of fused deposition modelling (FDM) technologies," *Int. J. Adv. Manuf. Technol.*, vol. 106, no. 3–4, pp. 1267–1279, 2020, doi: 10.1007/s00170-019-04676-0.

[37] A. Lanzotti, M. Martorelli, S. Maietta, S. Gerbino, F. Penta, and A. Gloria, "A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA," *Procedia CIRP*, vol. 79, pp. 143–146, 2019, doi: 10.1016/j.procir.2019.02.030.

[38] W. Lin, H. Shen, G. Xu, L. Zhang, J. Fu, and X. Deng, "Single-layer temperature-adjusting transition method to improve the bond strength of 3D-printed PCL/PLA parts," *Compos. Part A Appl. Sci. Manuf.*, vol. 115, pp. 22–30, Dec. 2018, doi: 10.1016/j.compositesa.2018.09.008.

[39] D. C. Montgomery, *Design and Analysis of Experiments*. 2001.

[40] J. M. Chacón, M. A. Caminero, E. García-Plaza, and P. J. Núñez, "Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection," *Mater. Des.*, vol. 124, pp. 143–157, 2017, doi: 10.1016/j.matdes.2017.03.065.

[41] T. Letcher, B. Rankouhi, and S. Javadpour, "Experimental study of mechanical properties of additively manufactured abs plastic as a function of layer parameters," in *ASME int. Mech. Eng. Congr. Expo. proc.*, 2015, vol. 2A–2015, doi: 10.1115/IMECE2015-52634.

[42] R. Singh, H. Singh, I. Farina, F. Colangelo, and F. Fraternali, "On the additive manufacturing of an energy storage device from recycled material," *Compos. Part B Eng.*, vol. 156, pp. 259–265, Jan. 2019, doi: 10.1016/j.compositesb.2018.08.080.

[43] Md. Q. Tanveer, A. Haleem, and M. Suhaib, "Effect of variable infill density on mechanical behaviour of 3-D printed PLA specimen: an experimental investigation," *SN Appl. Sci.*, vol. 1, no. 12, pp. 1–12, Dec. 2019, doi: 10.1007/s42452-019-1744-1.

[44] M. Pérez, G. Medina-Sánchez, A. García-Collado, M. Gupta, and D. Carou, "Surface quality enhancement of fused deposition modeling (FDM) printed samples based on the selection of critical printing parameters," *Materials (Basel).*, vol. 11, no. 8, p. 1382, Aug. 2018, doi: 10.3390/ma11081382.

[45] S. Wang, Y. Ma, Z. Deng, S. Zhang, and J. Cai, "Effects of fused deposition modeling process parameters on tensile, dynamic mechanical properties of 3D printed polylactic acid materials," *Polym. Test.*, vol. 86, 2020, doi: 10.1016/j.polymertesting.2020.106483.

[46] D. Corapi, G. Morettini, G. Pascoletti, and C. Zitelli, "Characterization of a polylactic acid (PLA) produced by Fused Deposition Modeling (FDM) technology," in *Procedia struct. integr.*, 2019, vol. 24, pp. 289–295, doi: 10.1016/j.prostr.2020.02.026.

[47] S. Wagner and M. Schlummer, "Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures," vol. 158. Elsevier B.V., p. 104800, Jul-2020, doi: 10.1016/j.resconrec.2020.104800.

[48] M. S. Nur-A-Tomal, F. Pahlevani, and V. Sahajwalla, "Direct transformation of waste children's toys to high quality products using 3D printing: A waste-to-wealth and sustainable approach," *J. Clean. Prod.*, vol. 267, 2020, doi: 10.1016/j.jclepro.2020.122188.