

Multi-material distributed recycling via Fused granular fabrication: rHDPE and rPET case of study

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Abstract

The high volume of plastic waste and the extremely low recycling rate has created a serious challenge worldwide. Local distributed recycling coupled to additive manufacturing (DRAM) offers a solution by economically incentivizing local recycling. A new DRAM technology capable of processing large quantities of plastic waste quickly is fused granular fabrication (FGF), where solid shredded plastic waste can be reused directly as 3D printing feedstock. This study presents an experimental assessment of multi-material recycling printability, using two of the most common thermoplastics in the beverage industry polyethylene terephthalate (PET) and high-density polyethylene (HDPE) and the feasibility of mixing PET and HDPE to be used as a feedstock material for large-scale 3-D printing. After the material collection, shredding, and cleaning its characterization, and optimization of parameters for 3D printing was performed. Results showed the feasibility of printing a large object from rPET/rHDPE flakes reducing the production cost up to 88%.

Acronyms

Acronym	Definition
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
DRAM	Distributed recycling via additive manufacturing
DSC	Differential scanning calorimetry
FDM	Fused deposition modeling
FFF	Fused filament fabrication
FGF	Fused granular fabrication
FPF	Fused particle fabrication
FTIR	Fourier-transform infrared spectroscopy
HDPE	High-density polyethylene
MFI	Melt flow index
PC	Polycarbonate
PET	Poly(ethylene terephthalate)
PLA	Poly(lactic acid)
PP	Polypropylene
PSO	Particle swarm optimization
PS	Polystyrene
SEBS	Poly (styrene-block-ethene-co-butene-block-styrene)
Tg	Glass temperature
pBC	Printed Bottle-Cap
rHDPE	Recycled High-density Polyethylene
rPET90//rHDPE10	Recycled Bottle-Cap (Cristaline bottle shredded without separation)
rPET	Recycled Poly(ethylene) terephthalate
vPET	Virgin or commercial Poly(ethylene terephthalate)

1 Introduction

- ¹ The disposal of plastic waste is one of the most challenging current environmental concerns
² given its systemic complexity ([Evode et al., 2021](#)). The mass of micro- / meso- plastics in the
³ oceans are expected to exceed the mass of the global stock of fish by 2050 ([MacArthur, 2017](#)).
⁴ More critically, the global plastic annual production is expected to reach 1100 metric tons
⁵ by the same year ([Geyer, 2020](#)). The societal awareness on plastic recycling have received
⁶ substantial attention by scientific, policymaker and general public ([Soares et al., 2021](#)). Un-
⁷ fortunately, the statistical analysis on the centralized recycling process proves that it has
⁸ been largely ineffective ([Siltaloppi and Jähi, 2021](#)) as only 9% of the plastic that has been
⁹ produced has been recycled from the total stock produced since 1950 ([Geyer et al., 2017](#)).
¹⁰ Therefore, it remains an open challenge to identify alternatives to valorize discarded plastic

11 material.

12 Distributed recycling and additive manufacturing (DRAM), is an innovative technical ap-
13 proach to recycle plastic wastes (Cruz Sanchez et al., 2020; Dertinger et al., 2020). DRAM
14 was first practiced with recyclebots, which are waste plastic extruders that made filament
15 for conventional fused filament-based 3-D printers (Baechler et al., 2013; Woern et al., 2018;
16 Zhong and Pearce, 2018). Past research demonstrated that using distributed recycling fits
17 into the circular economy paradigm (Despeisse et al., 2017; Ford and Despeisse, 2016); where
18 consumers directly recycle their own waste into consumer products from open source designs,
19 from toys for children (Petersen et al., 2017) to adaptive aids for those with arthritis (Gallup
20 et al., 2018). Distributed manufacturing is now in wide use (Pearce and Qian, 2022). In
21 this way DRAM-based recycling is done in a closed loop supply chain network (Santander et
22 al., 2020). This type of recycling aims to reduce the environmental impact by the reduction
23 of the transportation from the waste source to recycling facilities (Kreiger et al., 2014). In
24 that sense, it aims to propose innovative closed-loop strategies using waste materials as raw
25 resources (Romani et al., 2021).

26 Fused filament fabrication (FFF, which is also known as Fused Deposition Modelling –FDM©–
27) is the most-widespread and established extrusion-based AM technology due to the open
28 source proliferation from the self-replicating rapid prototyper (RepRap) project (Bowyer,
29 2014; Jones et al., 2011; Sells et al., 2009). This is due to its simplicity, versatility, low-
30 cost, and ability in the construction of geometrically complex objects in the industrial and
31 prosumer domains (Romani et al., 2021). Indeed, the open-source 3-D approach for 3-D
32 printers has enabled the technology to evolve in a radical manner for manufacturing and
33 prototyping adding value to the recycled material (Cruz Sanchez et al., 2020). There are
34 large efforts to find sustainable feedstocks for 3-D printing Pakkanen et al. (2017a). Several
35 studies in the literature have increase the spectrum of recycled filament materials such as
36 PLA (Anderson, 2017; Cruz Sanchez et al., 2017), ABS (Mohammed et al., 2017b, 2017a),
37 PET (Vaucher et al., 2022; Zander et al., 2018), HDPE (Baechler et al., 2013; Chong et al.,
38 2017; Mohammed et al., 2017b) PC (Gaikwad et al., 2018). In fact, using a comparative life

39 cycle assessment in a low density population case study of Michigan (USA), Kreiger et al.
40 (2014) argued that about of 100 billion MJ of energy per year could be saved in a distributed
41 approach, for the 984 million pounds of HDPE that are recycled in the U.S. There is thus
42 considerable evidence that DRAM can reduce the energy consumption and greenhouse gases
43 of the manufacturing processes.

44 Most DRAM studies have been using mono-material for the fabrication of feedstock for
45 FFF. There are, however, several examples of mixed materials including wood waste and
46 recycled plastic (Löschke et al., 2019; Pringle et al., 2018) and textile fibers and recycled
47 plastic (Carrete et al., 2021). Recently, Zander et al. (2019) reported the manufacturing
48 of composite filament from recycled PET/PP and PS/PP blending through compatibilizer
49 copolymer such as SEBS. Their results revealed the technical printability of polypropylene
50 blend composite filaments from a thermo-mechanical characterization perspective. Increasing
51 the performance window of blending materials by compatibilization which could be a relevant
52 path for recycling plastics in a local level and isolated areas contexts (e.g. during humanitarian
53 crises (Savonen et al., 2018 ; Corsini et al., 2022 ; Lipsky et al., 2019), supply chain disruptions
54 (Attaran, 2020; Choong et al., 2020 ; Novak and Loy, 2020; Salmi et al., 2020) and/or isolated
55 off-grid situations using solar-powered 3-D printers (Gwamuri et al., 2016 ; King et al., 2014;
56 Mohammed et al., 2018; Wong, 2015)). Likewise, Vaucher et al. (2022) studied the evaluation
57 of the microstructure, mechanical performance, and printing quality of filaments made from
58 rPET and rHDPE varying the wt% of HDPE material from 0 to 10%. They confirmed the
59 increase in the Young's modulus from 1.7 GPa of the pure PET to 2.1 GPa for all the HDPE
60 concentrations. Additionally, the maximum stress of the bends were augmented with high
61 HDPE concentrations. Values were lower than virgin PET filament, yet similar to commercial
62 recycle ones. The addition of rHDPE at higher levels, however, helped to meet the brittle-
63 ductile transition in 15% despite the low interfacial tension of both polymers, allowing the
64 printing of quality parts.

65 While former studies have proven been successful in FFF, a new approach to DRAM is
66 fused granular fabrication (FGF) or fused particle fabrication (FPF), where the material-

67 extrusion AM systems print directly from pellets, granules, flakes, shred or grinder material
68 (Fontana et al., 2022; Woern et al., 2018). In the context of recycling, this could reduce the
69 number of melt/extrusion cycles that degrade the material needed in the filament fabrication
70 process (Cruz Sanchez et al., 2017). The FGF technique opens up the potential of use recycle
71 materials as well as print large-scale objects either with a conventional cartesian 3-D printer
72 (Woern et al., 2018), delta 3-D printer (Grassi et al., 2019) or hangprinter (Petsiuk et al.,
73 2022; Rattan et al., 2023). Research groups corroborate that plastic waste can be used
74 as feedstock materials for FGF/FPF. Alexandre et al. (2020) assessed the technical and
75 economical dimensions of virgin and shredded PLA printed in a self-modified FGF machine
76 and compared with FFF. The investigation showed that the use of FGF reduced printing cost,
77 time and its mechanical performance was comparable with the obtained using the traditional
78 FFF technique. Likewise, Woern et al. (2018) found comparable properties between PLA,
79 ABS, PP, and PET recycled and virgin materials. Later publications demonstrated the
80 technical and economic feasibility through the printing of complex objects validating the
81 possibility of recycle plastic with FGF in both conventional and common FFF materials
82 (Byard et al., 2019), but also recycle PC (Reich et al., 2019) and rPET (Little et al., 2020,).
83 Few researchers, however, have addressed the problem of the direct printing of recycled
84 multi-materials, which might be a key step forward needed to facilitate the ease of sorting
85 and recycling post-consumer plastic waste materials.

86 This study explores the potential of direct 3-D printing two immiscible polymers commonly
87 used in the beverage sector through a distributed recycling process for its easily implementa-
88 tion operation at the local level. To demonstrate the feasibility of the process, the bottle water
89 plastic most used in France of roughly 90% of PET (body of the bottle) and 10% of HDPE
90 (cap) now called *rPET90//rHDPE10*, is used as a test material. The experimental process of
91 collection, characterization, and printing of the recycled material is described and the results
92 are discussed in the context of widespread DRAM adoption at the community-based level.

93 2 Materials and Methods

94 The methodology presented in Figure 1 outlines the approach adopted to develop the study.
95 The three stages *Material obtention*, *Printing process* and *Evaluation* were thoroughly studied
96 in order to control the major processes steps and the technical characterization methods. In
97 the following subsections, each step is explained.

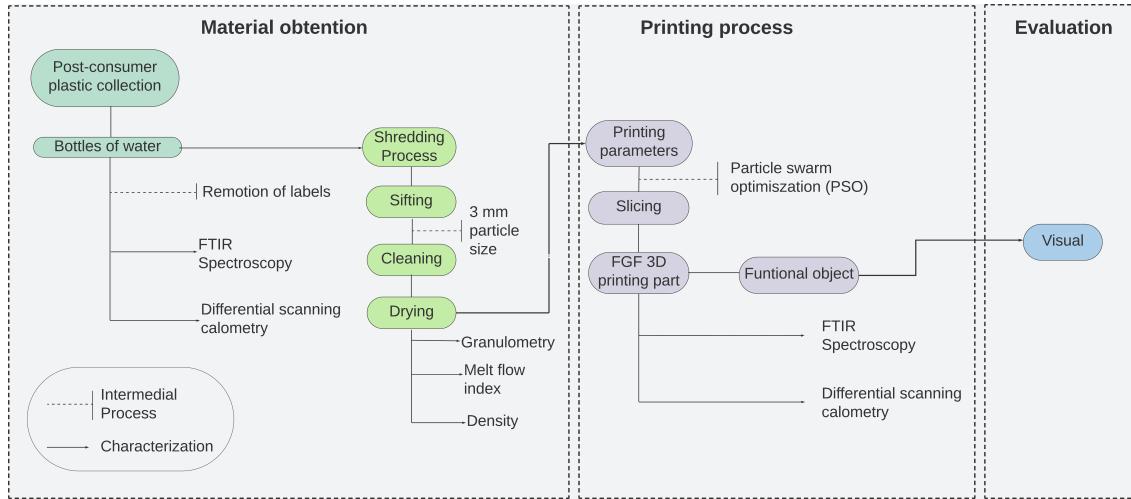


Figure 1: Global framework of the study

98 2.1 Raw material obtention

99 The goal of material stage is the collection and preparation of post-consumer plastic source. In
100 this study, bottles of water coming from the French brand Cristaline[®] was used as a feedstock.
101 The process steps used are shown in Figure 2 a/b. Post-consumer bottles were collected by
102 receptacles placed in partnership schools in Lorraine, France. To convert the complete water
103 bottles with its cap into 3DP feedstock material, the labels were removed before shredding
104 in a cutting mill Retsch MS300 using a 3 mm grid. After shredding, the obtained flakes were
105 sifted with a 1.5 mm, 3 mm, 5 mm sifters for further analysis. Next, flakes were cleaned
106 with hot water in an ultrasonic machine at 60°C for 1h to remove contaminants. Lastly, they
107 were dried in a conventional oven overnight at 80°C (Taghavi et al., 2018; Van de Voorde et
108 al., 2022) to avoid degradation of the material. Washing conditions were the same for all the

109 samples, therefore, the effect of contaminants was not considered. The resultant material is
110 shown in Fig 2.c.



Figure 2: Process steps to prepare the collected material

111 The material composition was calculated as a function of the mass of the bottles and caps
112 separately. The percent (%) of bottle-cap was found to be ~90% rPET (bottle) and ~10%
113 rHDPE (cap). The complete bottle was shredded without separation of both materials thus
114 this percentage is constant for all the samples.

115 2.2 Material preparation and characterization

116 2.2.1 Material particle size analysis -Granulometry-

117 In order to ensure the particle size suitable for printing, the characterization of the granulate
118 particles were developed using the open-source ImageJ software ([ImageJ, 2023](#)). The size
119 characteristics of the particles were evaluated between four different samples; vPET (used as
120 a reference) and the raw material sifted in three different sizes 1.5 mm, 3 mm and 5 mm.

¹²¹ **2.2.2 Fourier-transform infrared spectroscopy –FTIR-**

¹²² FTIR spectroscopy was carried out to determine the nature of the bottle and determine
¹²³ if there were impurities, plasticizers or additives that could be detected. The analysis were
¹²⁴ made on samples of rPET and rHDPE separately and then a printed sample of both materials
¹²⁵ to determine if there was possible to observe a chemical bonding. Every sample was measured
¹²⁶ in two different points, three times in each point then curves were normalized and analyzed
¹²⁷ with the Origin Pro 8. The Fourier transform infrared spectra have been recorded in the range
¹²⁸ of 4000 cm^{-1} to 375 cm^{-1} with resolution 4 cm^{-1} using Bruker IFS 66V spectrophotometer.

¹²⁹ **2.2.3 Differential scanning calorimetry –DSC-**

¹³⁰ Differential scanning calorimetry analysis were performed with a DSC-1 Mettler Toledo with
¹³¹ STArE software operating under nitrogen atmosphere at heating rate and cooling rate of
¹³² $10\text{ }^{\circ}\text{C/min}$. rPET, rHDPE and rPET90//rHDPE10 samples were investigated using three
¹³³ cycles: first heating from 20°C to $270\text{ }^{\circ}\text{C}$, cooling to $20\text{ }^{\circ}\text{C}$ and reheating to 270°C . The
¹³⁴ rHDPE sample was analyzed following similar cycles but with the maximum temperature set
¹³⁵ at 250°C and the blend with temperatures from -20 to 270°C . Glass transition temperature
¹³⁶ (T_g) of rPET was determined during the first heating cycle, while rPET90//rHDPE10 (T_g)
¹³⁷ during the second heating cycle along with the melting point of all materials. Crystallization
¹³⁸ temperature (T_c) of the each of the materials was determined during the cooling cycle. The
¹³⁹ degree of crystallinity (X_c) was calculated from the second cycle for recycled materials and
¹⁴⁰ first cycle for the blend as expressed in equation (1) ([Pan et al., 2020](#); [Taghavi et al., 2018](#)):

$$X_c(\%) = \frac{\Delta H_m}{w \cdot \Delta H_m^\circ} \quad (1)$$

¹⁴¹ Where, ΔH_m is the latent heat of melt, w is weight percentage of polymer in the blend,
¹⁴² and ΔH_m° is the reference heat of 100% crystalline PET (140 J/g) and HDPE (293 J/g),
¹⁴³ respectively, provided in the literature ([Kratofil et al., 2006](#); [Pan et al., 2020](#)).

₁₄₄ **2.2.4 Melt Flow Index –MFI-**

₁₄₅ The melt-flow index (MFI) of rPET90//rHDPE10 flakes was determined using a Instron
₁₄₆ CEAST MF20. The analysis was performed using three samples of ~5 g at 255 °C using
₁₄₇ a 2.16 kg weight according to ASTM D1238. The process was repeated three times. The
₁₄₈ average value of the three results was then reported with *gr/10 × min* unit.

₁₄₉ **2.2.5 Density**

₁₅₀ In order to calculate the material's density, first; the volume was found measuring the dimen-
₁₅₁ sions of a solid 50x50x50 mm cubic geometry fabricated injecting rPET90//rHDPE10 flakes
₁₅₂ into a square mould with a known volume using open-source desktop injection (Holipress,
₁₅₃ Holimaker, France) machine. Then the model was weighed, and the mass was obtained. Fi-
₁₅₄ nally, density was calculated as expressed in Equation 2. To ensure the accuracy the test
₁₅₅ was performed twice and the average value was reported in *g/cm³*.

$$\rho = V/m \quad \left[\frac{g}{cm^3} \right] \quad (2)$$

₁₅₆ Where, ρ is the density, V is the volume, and m the mass.

₁₅₇ Afterwards, experimental results were compared with the theoretical blend density which
₁₅₈ could be calculated by Equation 3.

$$\rho_{12} = \frac{1}{\frac{W_1}{\rho_1} + \frac{W_2}{\rho_2}} \quad \left[\frac{g}{cm^3} \right] \quad (3)$$

₁₅₉ Where, ρ_{12} is the density of the blend, W_1 and W_2 , the weight fractions of each polymer, ρ_1
₁₆₀ and ρ_2 , the theoretical density of each polymer for PET (1.38 *g/cm³*) and HDPE 0.93 to
₁₆₁ 0.97 *g/cm³* ([Jonathan GUIDIGO1 et al., 2017](#)).

₁₆₂ **2.3 Printing process**

₁₆₃ **2.3.1 Establishing optimal parameters**

₁₆₄ Establishing optimum combinations of parameters is essential for better quality and me-
₁₆₅ chanical properties of the printed parts ([Jaisingh Sheoran and Kumar, 2020](#)). According
₁₆₆ to Oberloier et al. ([2022a](#)), particle swarm optimization (PSO) is an effective and time-
₁₆₇ effective method for this purpose. The optimization of the 3-D printing parameters for the
₁₆₈ rPET90//rHDPE10 material in the GigabotX was performed using the open-source PSO Ex-
₁₆₉ perimenter platform (available in Linux), following the methodology developed by Oberloier
₁₇₀ et al. ([2022a](#)). Three process benchmark artifacts were printed; line, plane, and cube. They
₁₇₁ were modeled in CAD software Onshape CAD v1.150 and sliced using Prusaslicer v2.52.0.
₁₇₂ Figure 3 presents the geometry models and dimensions.

Geometry	Lenght (mm)	width (mm)	height (mm)
Line	200	2	1
Plane	100	100	1
Cube	40	40	40

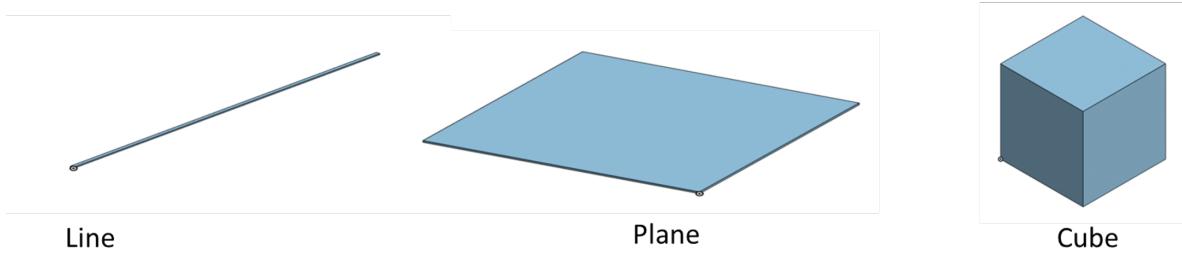


Figure 3: Dimensions and CAD models of the geometries used for parameters optimization.

₁₇₃ Four parameters were assessed: 1) the nozzle temperature, 2) bed temperature, 3) the printing
₁₇₄ speed and 4) extrusion multiplier ([Oberloier et al., 2022b](#)). The initial parameters for the line
₁₇₅ are presented in Table 1a while other parameters were obtained in preliminary experimental
₁₇₆ work shown in Table 1.b. Finally, the PSO tuning parameters were found in the previous
₁₇₇ PSO work ([Oberloier et al., 2022a](#)) Table 1.c.

Table 1: table 1

(a) Line optimization initial parameters

Variable	Min	Max	Guess	True/False	Description
T1	255	270	260	TRUE	Temperature Zone 1 on GigabotX
Tb	80	90	85	TRUE	Bed temperature
Ps	10	25	15	TRUE	Printing Speed
E	0.5	2	1	FALSE	Extrusion Multiplier

(b) Fixed parameters to perform printing parameters optimization based on PSO

Parameters	Value	Units
Layer height	0.5	mm
Width	2	mm
T2	230	°C
T3	220	°C
Cooling	0	%
Infill density	2	%

(c) Recommended parameters for PSO tuning

Variable	Value	Description
Kv	0.5	The emphasis given to the velocity component
Kp	1.0	The emphasis given to a particle's personal best position
Kg	2.0	The emphasis given to the swarm's group best position

178 2.3.2 Fused Granular Fabrication –FGF-

179 To print the raw material obtained, a 3-heat-zone modified open-source printer (Gigabot XL
 180 re:3D, Houston, TX, USA) was used as illustrated in Figure 4. The machine is a single screw
 181 extrusion-based 3-D printer capable of direct printing pellets, flakes or granules, with a nozzle
 182 size of 1.75 mm. For this study, a chair was printed to evaluate the ability for the material
 183 to 3-D print and the machine capacity to print large-objects such as a piece of furniture. The
 184 ideal parameters found for the cube geometry were used to print the final part.

185 3 Results and discussion

186 3.1 Material characterization

187 Both polymeric components of the bottle as well as the blend were characterized and analyzed
 188 to determine their properties using different methods as explained in the previous section.

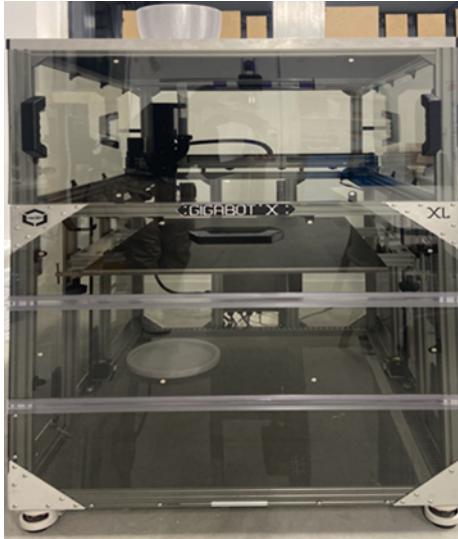


Figure 4: Fused granular fabrication printer Gigabot

¹⁸⁹ **3.1.1 Material particle size analysis (granulometry)**

¹⁹⁰ Previous studies demonstrated that particles with areas smaller than 22 mm^2 were optimal
¹⁹¹ for print without jamming or under-extrusion problems (Woern et al., 2018). From the
¹⁹² experiments conducted, however, particles with areas above 10 mm^2 clogged in the feeding
¹⁹³ system and auger screw of the machine. Therefore, granulometry analysis was performed
¹⁹⁴ using three different mesh sizes.

¹⁹⁵ Figure 5 shows the results obtained, where particles sifted at 5 mm had an average area
¹⁹⁶ similar to the reference. There are, however, particles with areas over 9 mm^2 which blocked
¹⁹⁷ in the feeding and extrusion section. Particles sifted to 1.5 mm showed a distribution with
¹⁹⁸ areas from 0 to proximately 3 mm^2 , this area was considered too low for printing. Small
¹⁹⁹ particles can completely melt in the first heat zone obstructing the consistent flow of other
²⁰⁰ particles and not allowing the pressure needed to extrude the melted particles lower in the
²⁰¹ screw. Although flakes of 3 mm show a more dispersed distribution and slightly lower area
²⁰² compared with the reference, those particles were found to be optimal for printing.

²⁰³ The final objects, however, still displayed under-extrusion issues. For this reason, a crammer
²⁰⁴ was implemented (Little et al., 2020) as presented in Figure 6; which physically pushes

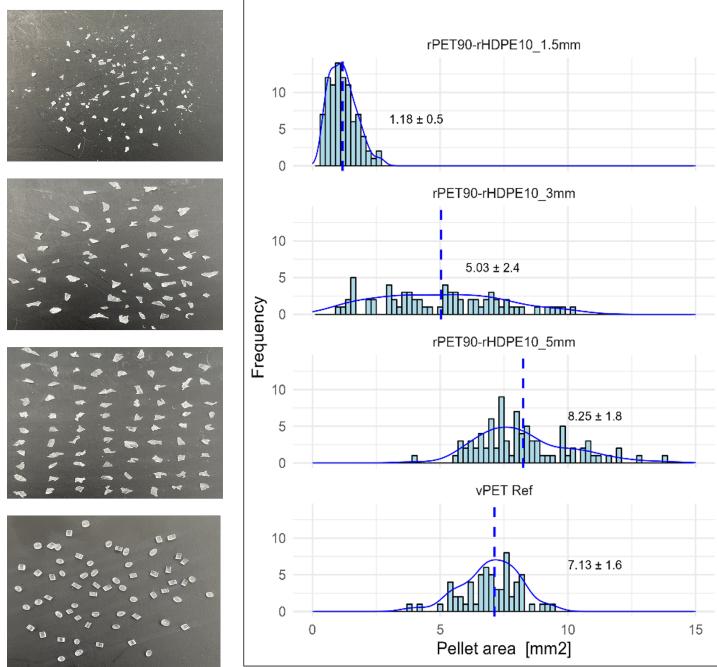


Figure 5: Granulometry analysis

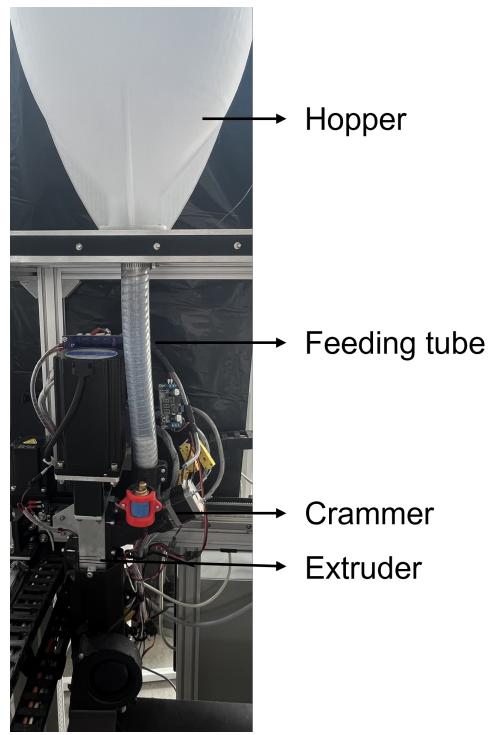


Figure 6: Gigabot feeding system

205 particles to the auger to convey them from feeding tube into the extruder. After the crammer
 206 implementation under-extrusion issues were significantly decreased. It was concluded that
 207 flakes with areas between 1.5 mm^2 to 10 mm^2 were optimum for print using a crammer able
 208 to aid the feeding system.

209 3.1.2 Chemical analysis from FTIR

210 Chemical structure information of the materials was obtained using FTIR spectroscopy, which
 211 provided analysis of the characteristic spectral bands of the polymers.

212 First, for the rPET (bottle) four characteristic bands can be observed Figure 7, one in
 213 1713cm^{-1} representing the $C = O$ double bond, the $C - O$ single bond ester at 1240cm^{-1} ,
 214 1093cm^{-1} band corresponding to the methylene group and vibrations of the ester bond and
 215 finally, a band 722cm^{-1} the CH₂ rocking bending vibration.

216 Similar results were obtained in the literature for PET coming from recycled water bottles,

217 soda bottles and food containers (Zander et al., 2018). For rHDPE (caps), four charac-
 218 teristic peaks were observed, the bond of C-H functional group in peaks 2915cm^{-1} and
 219 2847 cm^{-1} , main bending mode of the -CH₂ in 1465 cm^{-1} and CH₂ rocking bending vi-
 220 bration at 729 cm^{-1} . These results confirmed the chemical structures of starting materials.
 221 Additionally, other indicative resonances besides those associated with the polymer structures
 222 were not observed, concluding that additives or plasticizers in significative quantities were
 223 not present in either sample. The spectrum of the printed blend (rPET90//rHDPE10) had
 224 the same characteristic peaks as the bottle, confirming the PET dominant content. There
 225 are, however, observable differences between 1000 cm^{-1} and 720 cm^{-1} and in the bond of C-
 226 H (2915 cm^{-1} and 2847 cm^{-1} peaks), confirming the presence of HDPE (cap). The shifting
 227 observed can be attributed to interactions between both materials.

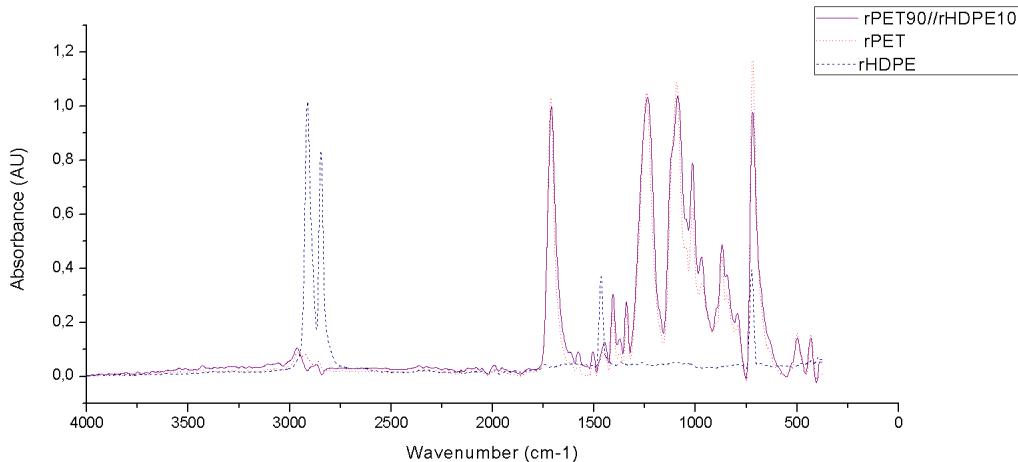


Figure 7: FTIR spectra of rPET, rHDPE and their blend

228 3.1.3 Thermal analysis DSC

229 The thermal properties of both recycled materials and their blend were characterized via
 230 DSC to have a starting point for the 3-D printing process parameter optimization.
 231 From the representative heating and cooling thermograms shown in Figure 8, two distinct
 232 endothermic peaks are observed in the printed blend sample that are associated with fusion

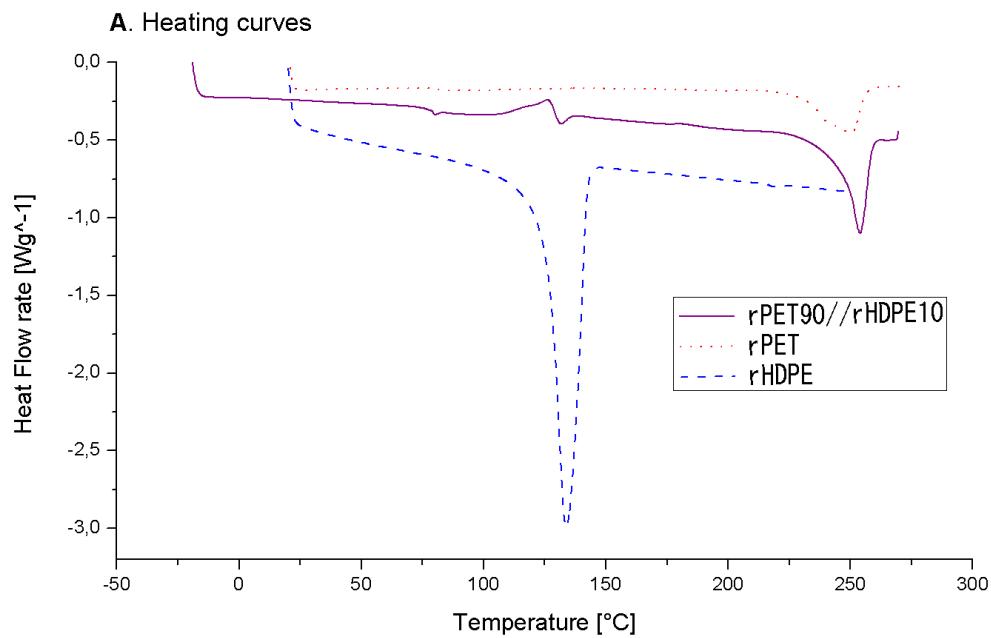
Table 2: Thermal analysis of rPET, rHDPE and their blend

Sample	Glass transition		Melting		Crystallization		% Crystallinity	
	Tg (°C)		Tm (°C)	ΔHm (J/g)	Tc (°C)	ΔHc (J/g)	ΔHcc (J/g)	Xc
rPET	82		249.9	31.6	196.7	34.8	-	22.6
rHDPE	-		133.8	172	118.7	158.5	-	58.7
rPET90//rHDPE10	77 / -		254/131.7	40.3/1.30	210.6/117.4	37.9/6.7	6.8	24.8 / 18.4

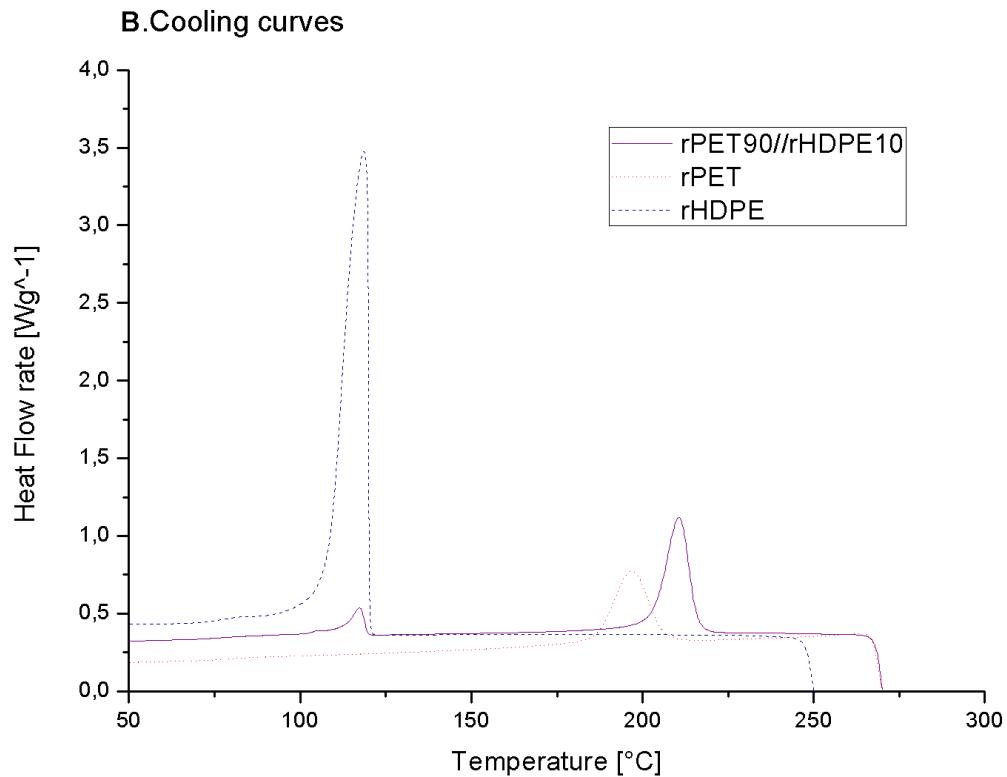
233 of the crystalline fractions of rHDPE and rPET, which confirms the immiscibility of both
 234 materials. Moreover, a significant reduction in the enthalpy of fusion and crystallization of
 235 the rHDPE in the blend is attributed to the low percentage of HDPE in the blend. The
 236 observation of cold crystallization peak in the blend but not in the individual polymers,
 237 however, can be attributed to an interaction between both polymers, where the rHDPE
 238 might act as a nucleating agent. Table 2. list the thermal properties for rPET, rHDPE and
 239 rPET90//rHDPE10. The melting point for rHDPE and rPET are 131.7 °C and 249.9 °C,
 240 respectively and are similar to those found in the literature ([Chen et al., 2015](#); [Lei et al., 2009](#);
 241 [Vaucher et al., 2022](#)). It is observed that the melting and crystallization temperature of rPET
 242 shifted to a higher value, while slightly decreasing for rHDPE. In addition, the crystallization
 243 of rPET was found be somewhat affected by the addition of rHDPE as it was increased 4%.
 244 It is likely that the addition of the rHDPE acted as germination point for crystallization
 245 ([Vaucher et al., 2022](#)). The slight changes in the rPET temperatures of fusion-crystallization
 246 and degree of crystallinity showed the interaction of both polymers.

247 3.1.4 Rheology MFI

248 The melt flow index of the flakes was determined, enabling a fast and practical screening of the
 249 viscosity of the material. Following the DSC results, the initial temperature to start the MFI
 250 test was 250°C, however the material did not flow reliably so the temperature was increased by
 251 5°C to enable the melt flow index of the rPET90//rHDPE10 to be determined. A temperature
 252 of 260°C was also tested, however, the material flowed rapidly and the measurement could
 253 not be reliably obtained. MFI tests were performed three times and the results of the
 254 rPET90//rHDPE10 was a medium MFI 39.4 ± 2.4 g/10min, which is roughly consistent



(a) Heating curves



(b) Cooling curve

Figure 8: DSC thermograms of recycled materials and blends

255 with values found in literature for rPET (Bustos Seibert et al., 2022; Langer et al., 2020;
256 Nofar and Oğuz, 2019). This result suggests that the low percentage addition of HDPE do
257 not highly impact the MFI value of rPET. As the material flowed at temperature of 255°C
258 in the MFI, it provided the input temperature for 3-D printer parameters optimization.

259 **3.1.5 Density**

260 The density allows the estimation of cost, material use, time consumed and weight of the
261 printing object in the slicer. This information is useful to find the accurate printing param-
262 eters with the PSO experimenter as fitness is calculated as a function of the dimensional
263 accuracy and weight of the printed object. Hence, density was useful to determine the weight
264 of the geometries.

265 From calculations made after weight and measuring the rPET90//rHDPE10 injected object,
266 the density of the material was found to be 1.13 g/cm^3 . The inclusion of HDPE in the
267 matrix polymer led to a slight decrease in its density, which is a common outcome when a
268 polymer is mixed with a lower density polymer. However, if we consider a PET/HDPE blend
269 with a mass ratio of 90/10, the calculated theoretical density is 1.32 g/cm^3 . The observed
270 decrease of 14% in the results could be attributed to factors such as experimental conditions
271 and manual measurements.

272 **3.2 Particle swarm optimization (PSO) Experimenter**

273 Geometries were 3-D printed changing the parameters as expressed in the PSO Experimenter
274 software. The fitness function is defined by the weighted sum of the dimensional measure-
275 ments (length, width, height, and weight) of the printed object, where fitness below 0.1 was
276 set as a desirable threshold. In the software five particles were established for one iteration,
277 thus in one iteration five different parameters combinations were printed. The first geometry
278 (line) was able to reach a fitness of < 0.1 after six iterations for a total of thirty lines printed.
279 The ideal parameters for this geometry are listed in column two of Table 3 and images of the
280 resulting geometries are illustrated in Figure 9 .

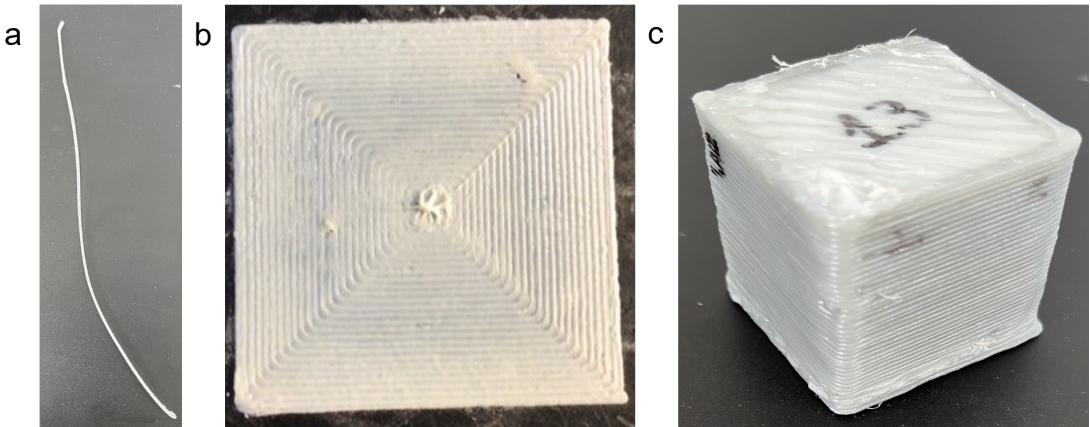


Figure 9: Images of the resulting geometries a) line, b) plane, c) cube

281 Afterwards, these parameters were used as initial guess for plane geometry, which reached
 282 the desired fitness in the first iteration. Likewise, cubes were printed using the plane ideal
 283 parameter as initial guess and optimal parameters, where found in the first iteration. Results
 284 showed a significant change in the printing speed, which lowers at higher geometry complexity.
 285 Moreover, the cube geometry required a higher extrusion multiplier to fill gaps and overcome
 286 under-extrusion problems. The optimization of the parameters for the three geometries took
 287 around 10h reducing the experimental time, compared with conventional methods. According
 288 to Oberloier et al. (2022a) this time of experimentation can be reduced 97%. Indeed, the
 289 efficacy of PSO in finding global optimum parameters is high, particularly when there is a
 290 large or complex design space (Saad et al., 2019; Selvam et al., 2020).

291 Additionally, PSO converge to optimum solutions with fewer iterations than DoE methods
 292 (Zhang et al., 2015) while mixing PSO with other meta-heuristic methods has shown higher
 293 ability of predict and optimize parameters (e.g. minimize surface roughness(Shirmohammadi
 294 et al., 2021), compressive strength and porosity of scaffolds (Asadi-Eydivand et al., 2016),
 295 mechanical properties(Raju et al., 2019)). However, the DoE methods are still widely used
 296 as they provide insight into the effects of individual design parameters and their interactions
 297 while the ability to find interaction between the variables is not possible using PSO. In the
 298 beginning of a set of optimization experiments, the complete understanding of the process
 299 technique as well as the function settings might be complex. The methodology used in this

300 study, however, was easy to implement and the software has the advantage of being free, open
301 source and user-friendly, lessening the initial difficulty. Thus, PSO demonstrated to be an
302 effective and high accuracy prediction technique able to find the initial optimum parameters
303 for rPET90//rHDPE10 material for FGF/FPF.

304 From the results it is observe that the optimal parameters may change depending of the object
305 printed and each parameter has its own variation. One hypothesis is that geometry might
306 play a role in parameter assignment and probably could be more visible in larger prints, yet
307 this hypothesis needs further investigation. There are several physical mechanisms at play
308 that would be expected to change optimal printing parameters based on the geometry and size
309 of the object. For example, the cooling time and temperature history of a voxel will depend
310 on the geometry of the printed object ([Cleeman et al., 2022](#)). Thus, to maintain the same
311 thermal history the printing parameters must change as the geometry changes. This same
312 effect of thermal history can also have more subtle impacts such as degree of crystallization
313 even for PLA ([Wijnen et al., 2018](#)).

314 In addition, some physical effects of materials extrusion are magnified with scale. The most
315 obvious is the impacts of thermal expansion and contraction. Small changes in contraction
316 as a part cools may cause acceptable distortions for small prints, but these are magnified
317 for large prints (e.g. causing deformation and in the worst cases delamination or loss of bed
318 adhesion)([Shah et al., 2019](#)). Although, Roschli et al. ([2019](#)) showed the obstacles and
319 possible solutions of the large-scale AM according to the way of the parts are designed the
320 incidence of the geometry in the printing parameters needs far more detailed future studies.
321 Specifically better models for mapping 3-D printing parameter optimizations of small printed
322 objects to large volume objects is needed.

323 3.3 Functional object print

324 The ideal parameters found for the cube geometry were used as final parameters for print the
325 case study product, except the print speed for the optimized line speed was used to decrease
326 the printing time and delamination. This change was performed as according to the PSO

Table 3: Ideal printing parameters for fused granule fabrication of waste PET and HDPE blend made from shredded whole plastic water bottles

Variable	Line value	Planes value	Cube value	Δ	Units
T1	258	263	264	6 \pm 3.2	°C
Tb	86	82	84	4 \pm 2	°C
Ps	21	14	10	11 \pm 5.6	mm/s
E	1.07	0.87	1.32	0.5 \pm 0.3	-

327 results the material is printable in a range of 10 to 20 mm/s. Additionally, the faster the
 328 printing the lesser the time of cooling between the layers thus avoiding possible delamination
 329 (Roschli et al., 2019), which is exacerbated for larger objects.

330 The Gigabot X successfully produced a piece of furniture from multi-material recycled water
 331 bottles that included mixing HDPE and PET as shown in Figure 10 a.

332 The printing quality is acceptable as a prototype, proven the machine capacity of printing
 333 large-scale functional objects where the chair was able to hold a child with a mass of 20 kg
 334 comfortably as shown in Figure 10 f. The material, in the other hand, needs further evaluation
 335 as the printed object showed weak bond strength between the adjacent layers (delamination
 336 Figure 10 b). This is probably due to the difference in chemical properties of both materials or
 337 immiscibility (Chu et al., 2022; William et al., 2021), high crystallinity (Verma et al., 2023)
 338 and the large volume of the object as delamination issues were more visible at the time of
 339 print the chair that in the parameters optimization process. Indeed, delamination presented
 340 in the printing of a larger object can be attributed to the rapid cooling of the layers before
 341 the material is once again deposited contrary of the cube printing where the small surface
 342 allowing the adhesion of layers before there are completely cooled. This can even be an issue
 343 for more popular 3-D printing materials like PLA from the print surface (Wijnen et al., 2018).
 344 The addition of agents that reduce the interphase tension between polymers might help to
 345 solve the delamination present and enhance the properties of the material (Dai et al., 1997;
 346 Inoya et al., 2012; Kramer et al., 1994) as interfacial bond can be enhanced by polymer
 347 modification (Gao et al., 2021) and viscosity decrement (Ko et al., 2019). Additionally,
 348 while printing warping problems were observed, (Figure 10 c) which are likely caused by the

349 high crystallization rates of HDPE ([Schirmeister et al., 2019](#)). The use of Magigoo adhesive
 350 (Thought3D Ltd., Paola, Malta) and the addition of a brim was tested in order to enable
 351 bed adhesion, yet this solutions did not completely solve the problem. A previous study
 352 showed that the use of a building plate made of thermoplastic elastomer SEBS allowed the
 353 adhesion of the plastic and enables facile detachments of the printing object without breaking
 354 or damaging ([Schirmeister et al., 2019](#)), suggesting a solution that needs further evaluation
 355 in future work. Another visible issue present in the close angles of the printed object was
 356 the shrinkage (Figure 10 d) which occurs during solidification and especially upon polymer
 357 crystallization. Moreover, as is well-know, PET has hygroscopic tendencies and easily absorbs
 358 atmosphere moisture making it difficult to extrude ([Bustos Seibert et al., 2022](#)) thus is likely
 359 to break down in the presence of water, lowering the quality of the print. Before the chair
 360 printing some samples showed brittle behavior and voids formation therefore, the material
 361 was constantly dried and the hopper was closed in order to avoid moisture coming from
 362 the environment helping to have a more printable material. Visually it can be observed
 363 some vibration and ringing problems (Figure 10 e) caused by the machine upgrading, both
 364 acceleration and jerk (maximum value of the instantaneous speed change) needs finer tuning.

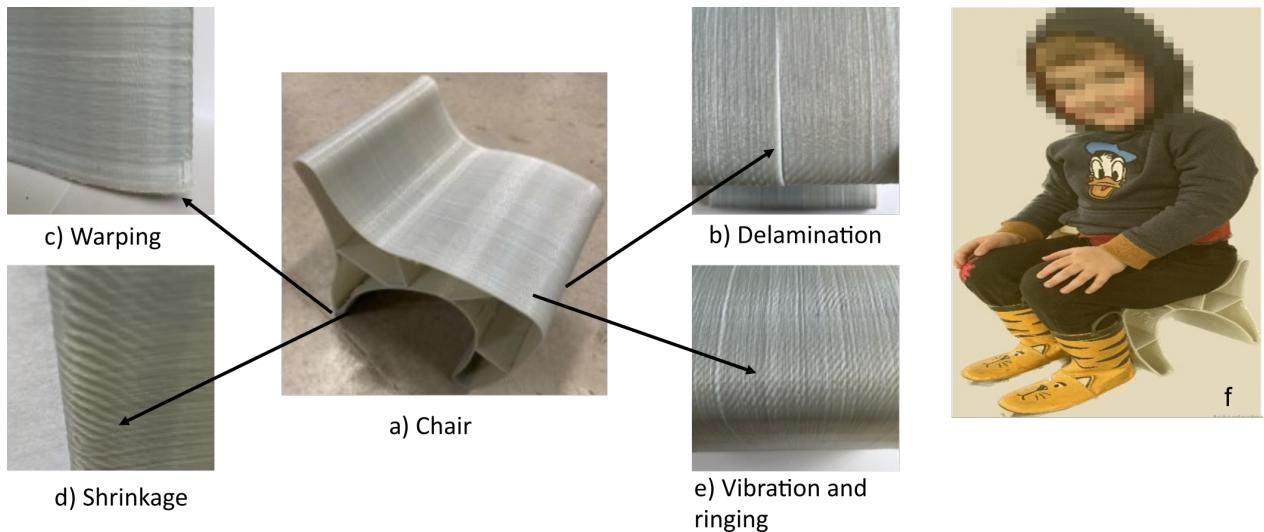


Figure 10: Finished children chair and printing issues

365 **3.3.1 Cost and environmental impact**

366 The printing time took 10 h and the printed object has a mass of 840 g. Due to the found
367 optimized speed being low, the printing rate (grams per hour) is low considering the machine
368 that pellet printers have a typical throughput of 220 g to 9 kg per hour. The printing time
369 could be improved by upgrading the extruder motor to a more powerful one. Besides, the
370 energy required for 10 hr of 3-D printing was found to be 6 kW-hr resulting in a production
371 cost of ~1.2 € in function of the electricity cost in France, without considering the material
372 cost as bottles were obtained from post-consumers waste. When labor costs are not included
373 the price was significative reduced (~88%) compared with those low cost found in the market.

374 The economics of fabricating the case study product remained competitive even if recycled
375 plastic pellets or shreds are used, which can be found on the market from 1-10 €/kg. However,
376 labor, maintenance and machine devaluation were not considered in the final price and are
377 needed in future work for a complete economic evaluation.

378 Regarding the environmental impact, although this study does not evaluate the entire life
379 cycle of the printed object, various scientific studies have already shown feasibility of dis-
380 tributed recycling ([Kerdlap et al., 2022](#); [Santander et al., 2020](#)), the comparation between
381 conventional and distributed manufacturing in terms of energy consumption and emissions
382 ([Kreiger and Pearce, 2013](#)), environmental performance of AM ([Colorado et al., 2020](#); [Garcia
383 et al., 2018](#)) and the appearance of DRAM as a source of raw material for diverse 3-D printers
384 coming from post-consumer plastic waste in the form of either filament ([Hart et al., 2018](#);
385 [Mikula et al., 2021](#); [Mohammed et al., 2017b](#); [Pakkanen et al., 2017b](#)) or granules ([Alexandre
386 et al., 2020](#)).

387 Additionally, Caceres-Mendoza et al. ([2023](#)) has developed a complete life of cycle assess-
388 ment of a DRAM system based on the production of PLA filament comparing virgin and
389 recycled materials. Their environmental results showed a reduction of the impacts of produc-
390 tion (climate change, fossil depletion, water depletion and potential eutrophication) of ~97%
391 compared to virgin filament. These results, however, are dependent on the energy supply

³⁹² and can vary depending on location.

³⁹³ 4 Conclusion and future work

³⁹⁴ This study analyzed the feasibility of using mixed post-consumer waste as feedstock material
³⁹⁵ for direct 3-D printing without compatibilization. The results showed the potential of mixing
³⁹⁶ solid waste plastics (PET/HDPE) for its use as feedstock material by printing a water bottle
³⁹⁷ with two incompatible polymers from the cap and body of the bottle. Additionally, the results
³⁹⁸ showed that a large-scale FGF 3-D printer was capable of producing a cost-effective functional
³⁹⁹ object from these mixed waste PET/HDPE plastics. Further research is needed in the analysis
⁴⁰⁰ of mechanical properties of the material as well as the possibilities of using compatibilizers
⁴⁰¹ capable of enhancing the interphase tension between plastics and lower their crystallinity,
⁴⁰² which might help improve performance and enhance material and 3-D printed part properties.
⁴⁰³ These factors increase in importance as the scale of the 3-D printed part increases. The
⁴⁰⁴ improvement of the material science of the approach can also offer an opportunity to improve
⁴⁰⁵ the quality of the printing printing time, lowering the energy consumption of the machine
⁴⁰⁶ and thus improving the economic viability of DRAM with mixed plastic waste.

⁴⁰⁷ In addition, future work could assess the different types of combinations or blends between
⁴⁰⁸ commodity plastics using or not compatibilizer towards its printability, bringing out the
⁴⁰⁹ possibility of selection/sorting process elimination. In the same way, the development of
⁴¹⁰ a methodology that allows the reproducibility of the process even in areas with limited
⁴¹¹ infrastructure opens up the potential of plastic revalorization using DRAM.

⁴¹² Declaration of competing

⁴¹³ The authors declare that they have no known competing financial interest or personal rela-
⁴¹⁴ tionships that could have appeared to influence the work reported in this paper. Acknowl-
⁴¹⁵ edgements

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