ADDITIVE MANUFACTURING AND DISTRIBUTED RECYCLING: WASTE AS RAW MATERIAL IN THE DESIGN AND MANUFACTURE OF UTILITARIAN OBJECTS

MANUFATURA ADITIVA E RECICLAGEM DISTRIBUÍDA: O LIXO COMO MATÉRIA PRIMA NO DESIGN E FABRICAÇÃO DE OBJETOS UTILITÁRIOS

FABRICACIÓN ADITIVA Y RECICLAJE DISTRIBUIDO: LOS RESIDUOS COMO MATERIA PRIMA EN EL DISEÑO Y FABRICACIÓN DE OBJETOS UTILITARIOS

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ABSTRACT

The first decades of the 21st century witnessed two major developments: the insertion of China into the global supply market and the popularization of the Internet. The most diverse segments of industry were affected by an avalanche of offers and falling prices of new machines and products, among them the Additive Manufacturing technologies. This technology allows production on a smaller scale and at lower values than traditional methods of producing artifacts. This connection, combined with the reuse of waste from local production, can revolutionize supply chains and circularity in the development and distribution of objects. This work demonstrates the development of an additive manufacturing system aligned to distributed recycling considering its impacts, advantages, disadvantages, and application possibilities in the Brazilian scenario, in terms of sustainability and circularity of the processes.

KEYWORDS

Additive manufacturing, recycling, Design, design for additive manufacturing, sustainability.

RESUMO

As primeiras décadas do século XXI testemunharam dois grandes acontecimentos: a inserção da China no mercado de fornecimento global e a popularização da Internet. Os mais diversos segmentos da indústria foram afetados por uma avalanche de ofertas e queda de preços de novas máquinas e produtos, entre eles as tecnologias de Manufatura Aditiva. Essa tecnologia permite a produção em menor escala e com valores mais baixos do que os métodos tradicionais de produção de artefatos. Essa conexão, aliada ao reaproveitamento de resíduos da produção local, pode revolucionar as cadeias de suprimentos e a circularidade no desenvolvimento e na distribuição de objetos. Este trabalho demonstra o desenvolvimento de um sistema de manufatura aditiva alinhado à reciclagem distribuída considerando seus impactos, vantagens, desvantagens e possibilidades de aplicação no cenário brasileiro, em termos de sustentabilidade e circularidade dos processos.

PALAVRAS-CHAVE

Manufatura aditiva; reciclagem; Design; Design para manufatura aditiva; sustentabilidade.

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RESUMEN

Las primeras décadas del siglo XXI fueron testigo de dos grandes acontecimientos: la inserción de China en el mercado mundial de suministros y la popularización de Internet. Los más diversos segmentos de la industria se vieron afectados por una avalancha de ofertas y precios a la baja de nuevas máquinas y productos, entre ellos las tecnologías de fabricación aditiva. Esta tecnología permite la producción a menor escala y a valores más bajos que los métodos tradicionales de producción de artefactos. Esta conexión, combinada con la reutilización de residuos de la producción local, puede revolucionar las cadenas de suministro y la circularidad en el desarrollo y distribución de objetos. Este trabajo demuestra el desarrollo de un sistema de fabricación aditiva alineado al reciclaje distribuido considerando sus impactos, ventajas, desventajas y posibilidades de aplicación en el escenario brasileño, en términos de sostenibilidad y circularidad de los procesos.

PALABRAS CLAVE

Fabricación aditiva; reciclaje; Diseño; Diseño para fabricación aditiva; sostenibilidad.

1. INTRODUCTION

The democratization of technology, which includes the production of design, has a challenge for the coming years: to get closer to the real needs of its user, aiming to adapt to some specific purpose or use. The assimilation of this technology by society brings a new way of producing knowledge, and thus breaks the academic and mass production hierarchization, aiming at the application of new ideas and using again the tools, instruments, and artifacts, originated from the strong correlation with the notions of adequacy, use of natural resources, and their socio-cultural and economic appropriation.

According to McDonough and Braungart (2002), in the contemporary world, we not only have at our disposal several resources for the development of countless techniques, but we are also aware of the growing demand for the adoption of the current model of society that is economically and socially more sustainable. It is necessary, for example, to reduce the generation of non-biodegradable waste, reduce energy costs and implement the rational exploitation of natural resources. For Veiga (2010), the concept of sustainability is inseparable from the relationship between economy and ecology. Thus, the methods of use of natural resources must be balanced with the impacts that their use entails.

2. TECHNOLOGY AS AN ALLY

The end of the 20th century brought the world two amazing events: China becoming a key player in the global supply chain and the worldwide connection from the popularization of the internet. The industries, from the most diverse areas, were shaken by a great expansion of offers and falling prices of new machines and products, including 3D printing, or additive manufacturing (AM). Many local industries have collapsed and radically changed the way they produce. Another impact factor has been the power of the Internet that has enabled online trading and more niche methods of advertising and selling where the unit cost of production did not have to meet the pressures of scale and traditional logistics and distribution. Brought together by these two innovations came additive manufacturing that allows for production on a smaller scale and with much lower values than traditional methods of producing artifacts made of plastic (ANDERSON, 2013, DOS SANTOS et al., 2013; DOS SANTOS et al., 2019).

The democratization of manufacturing by making the technology available to individual entrepreneurs and the general public drives the mindset shift and behavioral changes needed to move toward more sustainable modes of production and consumption (ANDERSON, 2013; CHEN et al., 2015; KOHTALA & HYYSALO, 2015). The use of additive manufacturing within networks of hobbyist designers and producers serves as a pocket of knowledge and creativity platforms for both AM and the Circular Economy (CE) (DESPEISSE, et al., 2016).

2.1. Additive manufacturing, economy, and conscious consumption

PETERSON & PEARCE (2017) demonstrate that using AM locally results in substantial savings for each product produced compared to its counterpart produced by traditional methods and available in current trade channels. The study points to an average marginal cost reduction of 93.3% and 98.7% when compared to the lowest and highest retail values, respectively, considering manufacturing one product per week. Comparing the printed objects with the equivalent lower priced product, there was a payback time of 2.4 years. Compared to the higher priced objects, the payback time was only 5 months. The return on investment was 25% in year 3 and 108% in year 5 when the low-cost values were considered. Comparing the printing costs with the high-priced commercial prices resulted in an ROI of 552% in year 3 and 986% in year 5.

An important point in this manufacturing logic is the growing trend of conscious consumption, a growing contingent of responsible consumers are considering environmental concerns in their purchasing decisions. By providing a means to make products, consumers develop a high level of responsibility and become more selective in their consumption. In addition, distributed AM represents an environmental benefit, due to reduced material use, transportation, and packaging disposal.

However, currently the market for AM raw materials remains highly concentrated. While plastic for AM is processed into filaments by several small and large companies, the raw material (the pellets) is supplied by a select group of large polymer producers. This stems from the current reality where polymer production from petrochemical and bio-based feedstocks is capital intensive, leading to high barriers to entry (WITTER, 2015). In these types of markets, the minimum efficient scale for production remains large (CHANDLER, 1990). This raises the question of the technical feasibility of producing materials distributed on a smaller scale. This is especially the case for recycled materials, as they require large, centralized processes to convert mixed plastic waste into single polymers suitable for reuse. (DESPEISSE, et al., 2016, p. 6).

2.2. Additive Manufacturing and Recycling

Recent research has pointed to an increase in the attention given to technologies that can recycle waste plastics into AM, as well as the associated benefits. For example, a study by KREIGER et al. (2014) found that a distributed AM market supplied by distributed sources of recycled materials resulted in savings in embodied energy and carbon emissions compared to supply by a centralized recycling market when using single types of easily identifiable polymers (e.g., HDPE from beverage packaging).

By linking the environmental footprint of AM to the volume of material deposited, research suggests that energy efficient AM processes bring about cost savings by the technology operator that coincide with minimizing process energy and material consumption (BAUMERS et al., 2011). As discussed by LOVINS (1996) in the context of energy inputs, the alignment of cost efficiency with minimizing the environmental impact of the process forms an important enabler for minimizing resource consumption (DESPEISSE, et al., 2016)

This becomes feasible because, unlike conventional manufacturing technology, AM is a process capable of depositing complex product geometry in a single step of the manufacturing process. This means that processing and assembly activities can be limited, and very short supply chains are enabled, with an additional side effect of simplifying the measurement of resource consumption without having to consider long and complex supply chains (BAUMERS et al., 2013).

At the same time, these technologies could serve as the basis for developing new sustainable value propositions. For example, companies can identify several new sustainable ways to capture value by adopting a lean manufacturing approach, while reducing inventories and over-manufacturing by managing the production of spare parts on demand, closer to the point of consumption (BOGERS et al., 2016). There are also opportunities to increase efficiency and create value using AM for end-of-life parts, generating reuse cycles for worn components. The changing relationship between manufacturers and customers presents opportunities to transform the Circular Economy business model with a service model that includes localized repairs. (DESPEISSE, et al., 2016, p. 11)

While the ecological benefits of distributed manufacturing with AM can be substantial, they can be enhanced using more sustainable materials. For example, distributed plastic recycling can be used to provide materials from local waste. The environmental life cycle analysis (LCA) conducted by BYARD, et al. (2019) on 3D printing filament manufacturing showed that the embodied energy of 3D printing filament could be reduced by 90% compared to traditional filament manufacturing. The results of this LCA study indicate that distributed HDPE recycling for rural regions is energetically favorable for both virgin resin use and conventional recycling processes. In the case study explored, embodied energy savings of 69 to 82 percent were found for distributed recycling compared to centralized recycling (BYARD, 2019). These results provide additional support for minimizing transportation distances for recycling to minimize environmental impact.

The concept of industrial metabolism, now widely known as industrial ecology (GRAEDEL, 2002), emerged in response to resource scarcity and the consequent rise in material cost. A key principle of industrial ecology considers sources and wastes of natural resources and promotes a regenerative use of resources where consumption should not exceed the rate of regeneration. Therefore, increasing manufacturing efficiency through process efficiency and recycling is key. Reducing material waste in the process and recycling are clear advantages with most AM technologies (DESPEISSE, et al., 2016).

3. MATERIALS AND METHODS

3.1. Research Trough Design

The present work followed established design research guidelines, specifically the "Research through Design" methodology. Research through design (RtD) is a method that utilizes design practice and design thinking, so that creativity and a critical eye present a product development process as a research model. In contrast to standard design practice, where efforts are focused on producing a commercially successful product, researchers engaged in RtD develop proposed objects to work on carefully posed questions (ZIMMERMAN et al., 2007).

The documentation of the design process has a preponderant role in this methodology. This practice leads to more accurate design decisions about the object because its classification allows for later appreciations and approaches, having the possibility to open new research paths. Design researchers, most of the time, adopt the double role of designers and researchers at different moments of the process. Thus, it is categorical that each step of development is recorded in the design procedure because it will serve as a starting point not only for the next steps of the investigation, but also as a repository for future developments (DALSGAARD; HALSKOV; 2012).

3.2. Design for Additive Manufacturing - DfAM

Additive manufacturing (AM) is a key pillar of the proposed process, Design for Additive Manufacturing (DfAM) becomes a fundamental piece as a means of developing the work. DfAM refers to the process of designing a 3D model or product specifically for the purpose of being manufactured using an additive manufacturing process. The basic principles of DfAM include understanding the capabilities and limitations of the specific technology being used. (TANG & ZHAO, 2016).

A successful DfAM involves several important steps that must be followed to ensure optimal results. First, it is critical to fully understand the features and limitations. This involves considering factors such as resolution, layer thickness, and material properties to align the design process appropriately. (LEARY, 2020)

The next step is to design the model with the process to be used in mind. This involves considering crucial aspects such as orientation, support structures, and wall thickness to optimize the manufacturability of the part. Next, the 3D model file needs to be prepared for printing. This includes exporting the file in the appropriate format and ensuring proper orientation and sizing to facilitate continuous printing.

To print the model, you need to define the appropriate settings and parameters. Adjustments to the layer height and fill percentage, as well as other technology-specific settings, are critical to achieve the desired print result.

Finally, post-processing plays an important role in refining the printed part. It involves cleaning and finishing the surface, removing support structures, and performing additional steps such as sanding and painting to improve the final appearance and functionality.

Remember that it is critical to properly document and store the final design, noting down the settings and parameters used during the printing process to ensure consistent replication of successful results in future productions.

3.3. Distributed Recycling Techniques

Using new technologies to reduce energy consumption in the AM process itself is becoming increasingly important. There are some technologies that can be used in distributed recycling through AM. Two of them present themselves as the most opportune.

The first is the same as that used in most affordable AM processes. Called fused filament fabrication (FFF), it operates the raw material indirectly. These filaments are produced from virgin plastic resins or plastics discarded by society, i.e., a pre-processing of the plastic is required. In this technology, the discarded plastic must be ground up and made into filaments prior to printing the parts.

The second skips a step, and instead of making the filament for manufacturing, one can directly use virgin pellets (small spheres as the resins are marketed) - or flakes of discarded materials - in a process known as FGF - fused granular fabrication.

To deepen the understanding of the limits of each one, this work opted to work on both paths and evaluate their pros and cons to propose guidelines and possibilities of application for each one.

Thus, a distributed recycling and additive manufacturing (DRAM) cell was set up to train the team and define the implementation and production strategies. This cell also served as the basis for defining the project requirements and constraints, which enabled basic product development.

4. THE OBJECT

Today there is a high incidence of visually impaired people in the world population who do not wear glasses due to their high cost. The manufacturing of these products in the current molds is very complex, massified and centralized in industrial poles. For being a very evident object, worn on the face of the user, it has also become a fashion accessory, and thus has become an item of a very complex universe that involves not only material costs, but also high values linked to the intangible, such as desire. This makes eyeglass frames in most cases more expensive than the lenses.

Based on this fact, we realize that the development of the frames with locally discarded material, but keeping key design standards, brings a reduction of this cost and, thus, a greater access to such an important item. In addition, these frames, besides having a direct impact on the lives of people who need such orthosis, are the starting point for a new production logic to be established.

The frames were developed to be adapted to additive manufacturing techniques, the key technology of the cell. The logic used was that of Design for Additive Manufacturing. This logic, as already discussed,

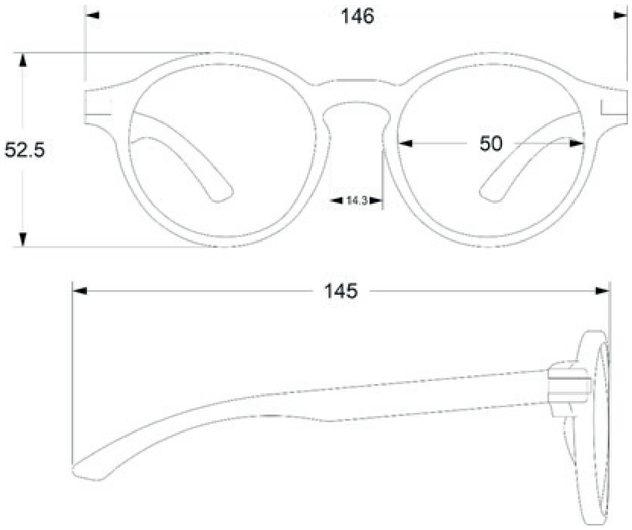

Figure 01: initial model based on market products.
Source: Authors.

optimizes the frame design to the techniques used in the cell, allowing a higher productivity, as well as a finishing quality, allowing the real use of the object without harmful consequences to the user.

An important point in the design of the frames was the search for the reduction of externally manufactured elements. The more elements produced internally, the greater the domain of the technique and the lower the production cost. In this way, the solution for the articulation between the stem and the frame itself was thought of in such a way as not to take any material other than plastic, and one that could be manufactured by means of AM. In this way, we arrived at a fitting solution that allows the opening and closing of the rods without the need for any externally produced elements such as hinges or hinges. This feature reduces the overall cost, manufacturing time, and facilitates maintenance, since the joint allows the replacement of any damaged part without the need for special tools or skills, and the product can be customized, changing colors and sizes for example.

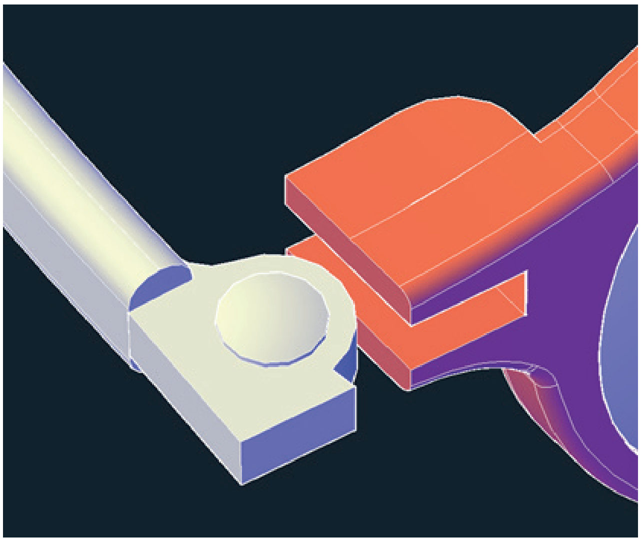

Figure 02: Fitting the rod.
Source: Authors.

Products made by AM need very little, if any, finishing. This is especially true when using DfAM logics. One example is the way the frame and the stems are produced. Both are printed flat, parallel to the printer base. This avoids supports (support structures for printing), overhanging parts (which reduce the final quality of the part) and reduces printing time. Once ready, the parts are curved using heat on a template, also printed, ensuring the geometry required for the product's use. Finally, the printing parameters were defined for each technology to be used as well as for greater user comfort, ensuring the best surface quality, with the shortest possible printing time, material expenditure and energy consumption.

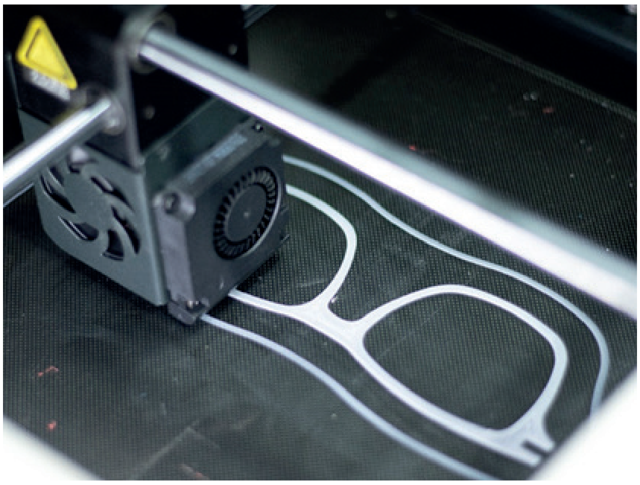

Figure 03 : FFF aditive manufacturing.
Source: Authors.

5. EXPERIMENTS

5.1. Fused Granular Fabrication (FGF)

The first step was to work with the Fused Granular Fabrication technique. The choice was since it has one less step in the processing of the material. Instead of grinding the material, making the filament, and then printing, this technique allows printing directly from the pieces obtained after grinding. To use this technique, it was necessary to adapt an Ender 3 printer (made in China and one of the most popular on the market) with a FGF extruder made in Spain by the company Mahor XYZ.

It began with the use of the polymer poly-lactic acid, or PLA, a biodegradable and recyclable plant-based plastic. PLA has characteristics that make printing easier, making it

Figure 04 : FGF technique.
Source: Authors.

Figure 05 : Sunglasses printed with recycled PLA by FGF.
Source: Authors.

more popular than other polymers. So old prints, backing material, and failed prints were shredded and dried. The shredded, also called flake, was put into the printer adapted the FGF technique and thus printing was possible.

One point that drew attention was the coloration. When several flakes of different manufacturers and colors are mixed, the flow is compromised due to the different pigmentation characteristics and additives contained in each one. Moreover, the final color ends up being a large mixture, tending towards gray. The use of flakes of the same color facilitates the repeatability of the extrusion parameters and, logically, causes the extrusion to have the same color (with small variations due to flakes of different prints and with small chromatic variations). This point was very important when defining the printing parameters. The variation of the material extrusion flow and the propensity to clog the nozzle, made it necessary to use a much thicker nozzle, going from the traditional 0.4mm nozzle to a 1.5mm one.

Figure 06 : Fitting detail printed with recycled material.
Source: Authors.

5.2. Fused Filament Fabrication (FFF)

The second technology used in the making of the frames was Fused Filament Fabrication. Different from the FGF technique, the FFF requires a filament manufactured within well-defined parameters. To this end, we used a filament manufacturing system manufactured in Brazil by the company Filmaq, composed of an extruder (with a 1.75mm matrix, the most common thickness in 3D printers on the market), a cooler/tractor and a spooling machine. An advantage of this technique is that it can be used with most printers on the market, without the need to adapt a different print head, as is the case with the FGF.

Figure 07 : Filament manufacturing process. Above: Filament manufacturing system. Below: From left to right: Introduction of virgin pellets and flakes; extrusion; filament ready for use.
Source: Authors.

As in the case of FGF, it was decided to start with PLA. At first, using virgin pellets and, little by little, introducing ground flakes from old and/or failed prints, until 100% recycled material was used. Filament manufacturing is quite simple in theory; however, practice is different. There are many variables (temperature, cooling, pulling speed) and a key point is to get the extruded filament to have a constant diameter.

The next step was to introduce a material that has a more common disposal: ABS. This polymer was chosen since it is a plastic discarded a lot in Rio de Janeiro, the place where the work takes place, and with little outlet for collectors and cooperatives, having a very low purchase value: about 0.02 USD. However, ABS is widely used as a raw material for additive manufacturing.

Figure 08: Printing with recycled PLA filament and Glasses printed with filament made from recycled PLA.
Source: Authors.

Another point to observe about ABS is that it needs more temperature to be worked, however, it has fluidity characteristics that make it a little easier to extrude than PLA. This ease of work speeded up the development of the process, which also started with virgin pellets; however, knowing a little more about the equipment and the process, it was easier to introduce flakes.

To validate the logic as an imminently circular process, real elements were sought for an experimental cycle. Thus, a discarded part using ABS was used. A vacuum cleaner casing was collected in a disposal area, the markings relating to the type of plastic were checked, and then the casing was shredded. The flakes were sieved (to eliminate very large pieces) and dried in an electric oven. The humidity makes the extrusion process exceedingly difficult. After this stage, these flakes were taken to the filament manufacturing system and about 300g were extruded.

Some frames were printed with very promising results. A slight need to increase the flow was necessary due to a greater variation in the overall diameter of the filament (which fluctuated between 1.6mm and 1.8mm). In general, the quality and resistance of the pieces was very close to that of industrially produced filaments. The coloration was quite uniform when using flakes of the same object.

Figure 09: Preparing a discarded part for filament extrusion.
Source: Authors.

6. DISCUSSION

The FGF technology proved to be quite complex for making a small product such as an eyeglass frame. Many issues with the flow of the material arose, either from different additives and dyes, or from small dirt particles found in the recycled material. The use of a thicker nozzle facilitates the flow of the material, preventing clogging. However, the downside is that it leaves a very rough finish, as can be seen in Figure 02. In addition, the printing speed needs to be reduced, limiting the productivity of the machine. Another point is the cost of FGF technology. Despite cutting one step - filament manufacturing - printers on the market with FGF-ready heads are much more expensive than standard 3d printers (costing at least ten times more. It is possible to adapt a FGF print head to inexpensive printers in the market. However, this head costs more than the printer itself and requires expertise not only for the mechanical assembly work, but also for reconfiguring the printer's firmware.

In this regard, working with FFF technology proved to be more interesting in the case of eyeglass frames, but

Figure 10: Final model produced by FFF, with recycled ABS polymer.
Source: Authors.

not without some points to consider. The work of parameterizing all the variables and obtaining the ideal filament for printing was quite arduous. However, when the parameters were reached, the process was very smooth and with a good repeatability. The moisture is another point to be aware. The material needs to be let to dry before the use to have a better filament. The moisture causes a lot of bubbles, which drops the quality and, in some cases, made the material impossible to print.

With the product manufactured by FFF, it was possible to compare costs, as well as demonstrate its advances towards greater circularity, sustainability, and economic competitiveness. For example, the material used in the confection, ABS, has a low sale value to collectors (around 0.02 USD per kilo). The frame developed uses about 10g of this material and between the command to start printing and the finished product it takes about 50 minutes, spending about 0.32 kWh in the entire process. The unit cost, based on these data and the study done by PETERSEN & PEARCE (2017), is 0,20 USD. The selling price of similar frames is around 20,00 USD. Thus, the potential gross return on this frame would be about one thousand times greater than the direct resale of the plastic, and one hundred times greater than the unit cost of manufacturing. These numbers corroborate the commercial, circular, and low-impact potential of this process.

7. CONCLUSION

The research on polymer recycling for additive manufacturing in the Brazilian scenario is increasing importance. With high potential for economic return and circularity as a central element, distributed recycling solutions allow local manufacturing from nearby discards with low commercial value, which facilitates the readjustment of the supply chain and the inclusion of social groups as key actors such as collectors and cooperatives, thus supporting the local economy and the reduction of solid waste in the areas of operation.

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