FINDING A MIDDLE GROUND: LOCAL MAKERSPACES AS A DRIVER FOR THE CIRCULAR ECONOMY IN ADDITIVE MANUFACTURING

E. Hudson[+], I. Fidan*, M. Alshaikh Ali[+], V. Naikwadi[+], M. Mahmudov[+], S. Gudavasov[+]

[+]Department of Mechanical Engineering

*Department of Manufacturing and Engineering Technology

Tennessee Technological University, Cookeville, TN, 38505

Abstract

Additive manufacturing (AM) has been one of the driving forces behind the recent push for greater sustainability in the manufacturing sector, one of the main defining features of the industry 4.0 revolution. However, even though AM is more environmentally friendly than traditional machining, it is far from a waste-free process, although it does make the goal of achieving a circular economy for supply chains in manufacturing more achievable. The complexity of reworking large-scale supply chains to include recycled material sources, along with the desire for more point of use supply of daily goods, points towards community makerspaces as a middle ground solution for achieving a full circular economy in manufacturing. The goal of this paper is to outline the challenges present in the current industry setup and offer a proposal for why makerspaces could be used to push for more sustainable manufacturing.

Introduction

AM is one of the driving forces enabling sustainable manufacturing in the recent industry 4.0 revolution. Being a layer-by-layer process with material only used where needed, AM has a distinct advantage over traditional subtractive manufacturing methods in being significantly more material efficient [1], [2]. Along with this, AM allows for greater flexibility and fewer limitations in design, enabling novel part geometries which use material more efficiently, achieving significantly lighter weight without compromising on durability [3], [4]. That said, AM is far from a waste-free process, and is arguably contributing to one of the more worrying sources of industrial waste present today, as outlined below.

The most popular AM process is Fused Deposition Modeling (FDM) – also known as Fused Filament Fabrication (FFF) – in which a thermoplastic filament is heated and extruded through a nozzle, controlled by an xyz gantry, to achieve the desired part shape. While the thermoplastic materials used for this process are in theory 100% recyclable, recent studies have shown that the overwhelming majority of these plastics end up in landfills or incinerated [5], [6], [7].

One of the main problems with achieving a higher rate of recycling, not only with plastics but with any industrial material, is the complexity involved in altering the supply chains used by larger industries [8]. While large-scale manufacturing has benefits in being more affordable and repeatable at scale, to achieve a more sustainable and circular economy a smaller, more localized system of community production facilities may be a better alternative.

The following sections of this paper will discuss the background leading to the current state of industry today, outline the challenges presented in transitioning the current setup towards a circular economy, and propose a novel framework for localized recycling and remanufacturing of daily-use plastic goods, along with some improvements that can be made to existing technology and practices to improve the long-term viability of this setup.

Background

Beginning with the industrial revolution at the start of the 20th century, manufacturing in the modern era has moved away from the idea of the local artisan towards centralizing and scaling specialized manufacturing of goods. Arguably beginning with the first industrial assembly line devised by the Ford Motor Company, this setup presents multiple benefits for a growing economy. The larger scale of industry reduces and simplifies logistic concerns, while more specialized and automated manufacturing affords higher repeatability and quality in the final product, driving down prices and fostering innovation in multiple fields. While this move has done much to improve the quality of life for much of the global population, it has multiple drawbacks that have recently seen more focus.

The recent push towards more sustainable and environmentally conscious living has drawn more attention to the large amounts of waste associated with the consumer-based economy. While many of the products used in everyday life can be recycled, overall they are not. However, although the desire exists for an increase of recycled products in the global economy, the complexity of large-scale manufacturing presents a challenge to this framework [9], as outlined in the next section.

Another aspect of this recent focus on consumer waste and sustainable living is greater thought and appreciation being given to the everyday goods that people use. Along with rising prices due to inflation, this has led to a fostering of a “Do It Yourself” (DIY) culture in much of the world, with consumers having a desire to have a more active role in the production and design of the products they use [10]. AM has helped to enable this trend, allowing for at-home “prosumers” (producer consumers) to begin leading the drive away from large-scale manufacturing and consumable goods towards more customized and longer-lasting products, whether through better design or the ability to repair products [11].

Problems with Recycling in Large-Scale Manufacturing

While in general the materials used in large-scale manufacturing can be easily recycled with minimal effect on properties [12], [13], these materials are mostly not recycled, instead being disposed of in landfills. Even though the use of recycled materials could potentially help stabilize the price and availability challenges present in conventional supply streams [11], there are multiple challenges presented in increasing their adoption.

While recycled materials are generally more affordable compared to virgin material, there isn't currently a readily available market for companies seeking to use these materials, especially when looking at the market for FFF filaments [14]. Along with this, the complexity of the supply chains used for manufacturing don't allow for the easy insertion of recycled sources of material. Large-scale production demands large and consistent material streams, and the usage of varying additives and colorants in plastic production hinders the development of these streams for reused material [14], [15]. And even if recycled material was able to be implemented into the current manufacturing industry, transportation of both these materials and the produced products is one of the largest contributors towards pollution and waste in many industries, as depicted in figure 1, a problem caused not by the use of non-renewable materials but by the centralization of many manufacturing industries [9]. This points towards localized or home manufacturing of many products where possible, a proposal which will be further analyzed in the following sections.

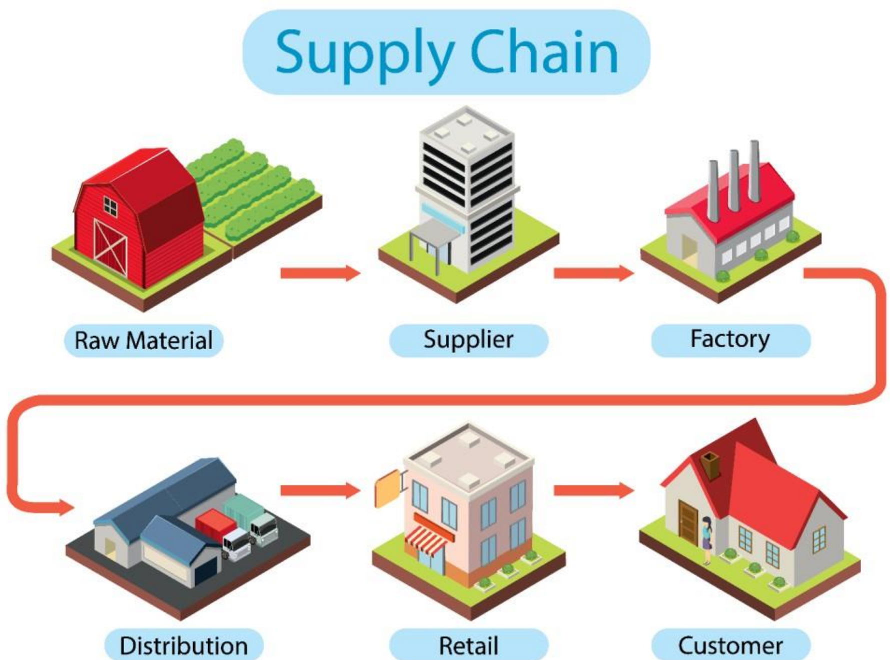

Figure 1. Generic supply chain for a manufacturing industry [16]. The supply of raw materials for a manufacturing process is a finely tuned system with many variables to control, so switching over to recycled material sources is far more complicated than it would seem

<u>Benefits and Drawbacks of At-Home AM Use</u>

Given the simplicity of FFF printing and the large community surrounding this technology, at home use has become one of the more popular use cases of AM. Contrary to popular belief, a background in engineering or design is not required to take advantage of this technology, with little skill or knowledge required to operate the more user-friendly machines now available [15]. Along with this, the affordability of these machines and the materials used already affords high cost savings when used to produce everyday household items, with one study showing over 90% savings and a return on investment as short as one year for a selection of common items [10].

Combined with the wide availability of already designed models for many of the desired products, a personal AM machine would quickly pay for itself for many potential owners.

However, there are some drawbacks to personal 3D printer use, one of the most prominent being the rate of use of the machine. Studies have shown that idle time for an AM machine, similar to for a traditional CNC machine, can be one of the largest wastes of energy and money, so near-constant usage of a machine is often the most effective method to gain the most benefit [15], [17], [18]. Along with this, while an entry-level FFF printer can be found for less than $200 [19], these more basic machines require more maintenance and care, and more reliable machines can easily run into the thousands of dollars [20], negating some of the cost benefits associated with this method. As well, even with eco-friendly materials such as Polylactic Acid (PLA), FFF printing has been shown to release Volatile Organic Compounds (VOC) into the surrounding atmosphere [21], so care must be taken to not introduce health hazards when investing in an AM machine for home use [22]. Along with this, while possibly easier than large-scale recycling, at home plastic recycling is far from a straightforward process [23], so a dedicated facility is still often required. An alternative to personal use is presented in the following section, one which still offers many of the benefits associated with personal AM production while allowing for safer and more efficient use of this setup.

A Proposal for Makerspaces as the Middle Ground

The recent cultural shift towards DIY production has also led to the rise of makerspaces on many college and public school campuses, as well as in some larger cities [24]. These often consist of a dedicated space for innovation and creativity, along with equipment such as FFF or other AM machines, along with traditional machining and electronics tools, to help enable the creation of these innovative designs. Given the typical setup of a makerspace, with machines available for use and dedicated staff to help with maintenance and troubleshooting, these spaces present a potential solution to some of the problems mentioned with introducing recycled materials into the manufacturing process.

The majority of makerspaces are often locally owned and operated, and as such are able to cater more to the needs of their specific communities. These facilities are also often able to afford larger scale AM machines, which are both more reliable and often more energy efficient due to economics of scale [25]. As well as this, when seeking to implement recycled materials into their supply sources, local facilities would not have to contend with transportation costs or supply chain issues due to being able to source waste material from their communities [21], greatly increasing the affordability and environmental impact of using recycled materials. Smaller-scale plastic recycling setups, the workflow of which is shown in figure 2, would be more affordable for a collaborative space compared to a single user [26], and a smaller production volume would help account for the inconsistencies present in different sources of waste plastic [14], allowing for easier and more consistent production of material. Lastly, community makerspaces with multiple regular users would more than likely bring the usage rate of the AM machines implemented closer to 100%, giving greater energy efficiency and a higher return on investment for these machines. Several other practices could be implemented into this framework to achieve more sustainable makerspace operation, as detailed below.

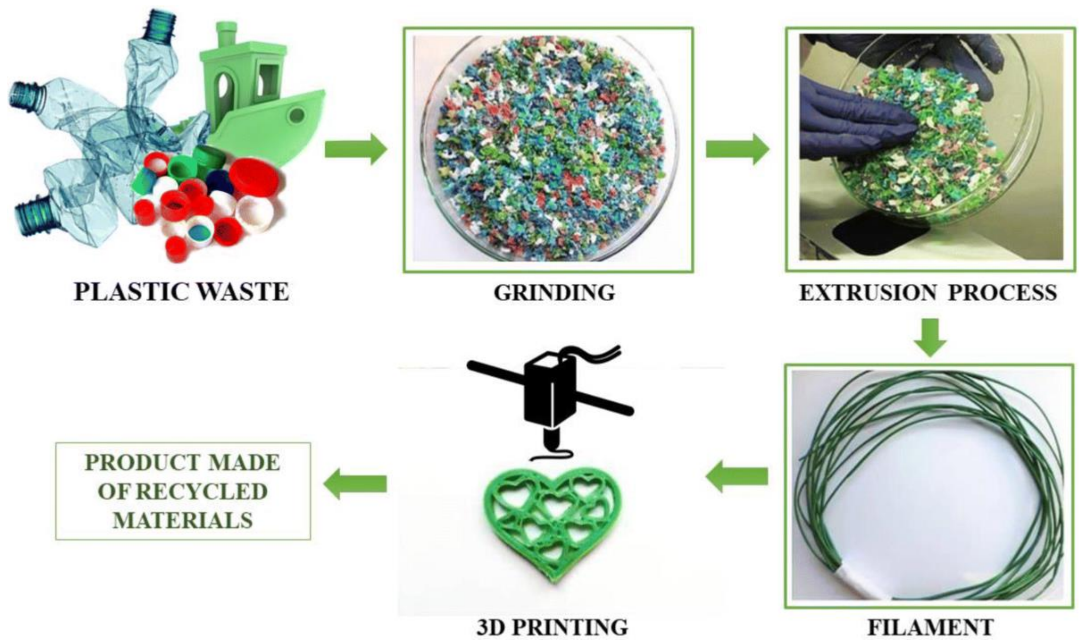

Figure 2. The typical process for recycling plastic for use in FFF machines [27]. Unlike with large scale manufacturing, much of this process can be done in a small setting, eliminating the costs associated with transportation of raw materials.

Suggested Improvements to the Current AM Industry, and Best Practices for More Sustainable Makerspaces

While the AM industry is focused greatly on open-source hardware and software and collaborative innovation, there are still many facets that are closed off and hard to find information on, the availability of which could allow for greater sustainability in AM. While much of the hardware for FFF machines is well-known and readily available for purchase [28], the specifics of the construction of individual machines are often closed off [15], hampering repair or upgrade efforts. As well, material compositions of both AM feedstock and other sources of waste plastic are rarely available, which can lead to difficulties in achieving full recycling of materials. Given that maintaining material quality and part strength are vital for the success of the sustainability movement [8], [29], knowledge of the composition of the materials being recycled is vital for being competitive in the manufacturing sector.

Further, several practices can be implemented in the operation of sustainable makerspaces to achieve more environmentally friendly operation. Process parameters have a high effect on the energy efficiency of AM processes [3], and given that electricity consumption accounts for up to 28% of the cost of an AM machine [30], proper operation of these machines can help reduce their energy usage and make them more affordable and environmentally friendly. As well as this, proper material selection can help ensure the sustainability of supply streams. Polyethylene Terephthalate (PET) plastic is already commonly used and understood in FFF printing, along with being one of the more abundant contributors to global plastic waste. This material is also one of the more eco-friendly to recycle when compared to other commonly used FFF filaments [31], so ensuring that it is the primary material used in a makerspace can help make it more efficient. Lastly, common practices such as designing long-lasting and/or easily repairable parts [11], while also reducing complexity of models to decrease print times [30] can help ensure the sustainability of AM use.

Conclusion

While traditional and large-scale manufacturing have done much to contribute to the modernization of the global economy, their drawbacks and the push for more sustainable manufacturing indicate that a new method of production may be more effective for many applications. Given the need for more local and generalized manufacturing, makerspaces offer an optimal solution for these problems in the opinion of the authors, while also allowing for easier usage of recycled materials to achieve a circular economy. Along with ensuring higher transparency in the AM industry, this setup has the potential to be a longer-term solution for achieving higher sustainability and efficiency in the manufacturing sector.

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References

[1] G. Manogharan, R. Wysk, O. Harrysson, and R. Aman, "AIMS – A Metal Additive-hybrid Manufacturing System: System Architecture and Attributes," *Procedia Manuf*, vol. 1, pp. 273–286, Jan. 2015, doi: 10.1016/J.PROMFG.2015.09.021.

[2] E. Hudson and I. Fidan, "The development of a framework to produce additively manufactured, low-cost aluminum via material extrusion process," *International Journal on Interactive Design and Manufacturing*, pp. 1–10, Apr. 2024, doi: 10.1007/S12008-024-01813-2.

[3] I. Fidan, V. Naikwadi, S. Alkunte, R. Mishra, and K. Tantawi, "Energy Efficiency in Additive Manufacturing: Condensed Review," Feb. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/technologies12020021.

[4] F. Alifui-Segbaya, I. F. Ituarte, S. Hasanov, A. Gupta, and I. Fidan, "Opportunities and Limitations of Additive Manufacturing," *Springer Handbooks*, vol. Part F1592, pp. 125–143, 2023, doi: 10.1007/978-3-031-20752-5_9.

[5] "Think that your plastic is being recycled? Think again. | MIT Technology Review." Accessed: September 3, 2024. [Online]. Available: https://www.technologyreview.com/2023/10/12/1081129/plastic-recycling-climate-change-microplastics/.

[6] The Last Beach Cleanup, "The Real Truth About The US Plastics Recycling Rate," May 2020, Accessed: September 3, 2024. [Online]. Available: https://www.beyondplastics.org/reports/the-real-truth-about-the-us-plastics-recycling-rate

[7] E. M. Bennett and P. Alexandridis, “Informing the Public and Educating Students on Plastic Recycling,” *Recycling 2021, Vol. 6, Page 69*, vol. 6, no. 4, p. 69, Oct. 2021, doi: 10.3390/RECYCLING6040069.

[8] “A Sustainable Circular 3D Printing Model for Recycling Metal Scrap in the Automotive Industry.” [Online]. Available: http://mc.manuscriptcentral.com/jmtm

[9] C. Caceres-Mendoza, P. Santander-Tapia, F. A. Cruz Sanchez, N. Troussier, M. Camargo, and H. Boudaoud, “Life cycle assessment of filament production in distributed plastic recycling via additive manufacturing,” *Cleaner Waste Systems*, vol. 5, Aug. 2023, doi: 10.1016/j.clwas.2023.100100.

[10] E. E. Petersen and J. Pearce, “Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers,” *Technologies (Basel)*, vol. 5, no. 1, Mar. 2017, doi: 10.3390/technologies5010007.

[11] V. G. Muñoz, L. M. Muneta, R. Carrasco-Gallego, J. de J. Marquez, and D. Hidalgo-Carvajal, “Evaluation of the circularity of recycled pla filaments for 3D printers,” *Applied Sciences (Switzerland)*, vol. 10, no. 24, pp. 1–12, Dec. 2020, doi: 10.3390/app10248967.

[12] 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,” in *Procedia CIRP*, Elsevier B.V., 2019, pp. 143–146. doi: 10.1016/j.procir.2019.02.030.

[13] P. E. Carrion, A. Soltani-Tehrani, N. Phan, and N. Shamsaei, “Powder Recycling Effects on the Tensile and Fatigue Behavior of Additively Manufactured Ti-6Al-4V Parts,” *JOM*, vol. 71, no. 3, pp. 963–973, Mar. 2019, doi: 10.1007/s11837-018-3248-7.

[14] B. I. Oladapo, O. K. Bowoto, V. A. Adebiyi, and O. M. Ikumapayi, “Net zero on 3D printing filament recycling: A sustainable analysis,” Oct. 10, 2023, *Elsevier B.V.* doi: 10.1016/j.scitotenv.2023.165046.

[15] A. Faludi, J. Bayley, and C. Bhogal, “UC Berkeley Green Manufacturing and Sustainable Manufacturing Partnership Title Comparing Environmental Impacts of Additive Manufacturing vs. Traditional Machining via Life-Cycle Assessment Publication Date Comparing Environmental Impacts of Additive Manufacturing vs. Traditional Machining via Life-Cycle Assessment.” [Online]. Available: https://escholarship.org/uc/item/0gv882qk.

[16] “Free Vector | Diagram of supply chain management.” Accessed: September 3, 2024. [Online]. Available: https://www.freepik.com/free-vector/diagram-supply-chain-management_25537237.htm#query=supply%20chain%20management&position=5&from_view=keyword&track=ais_hybrid&uuid=714c609b-eec2-4e22-a6aa-2fbb0aa5a5f8.

[17] V. Vladinovskis, “Potential Power Management Efficiency Improvements in Desktop 3D Printers,” in *2022 IEEE 63rd Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2022 - Proceedings*,

Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/RTUCON56726.2022.9978882.

[18] V. KORKUT and H. YAVUZ, "Examining the Influential Parameters on Reducing both Energy and Time Requirements in Open-Source 3D Printers," *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, vol. 12, no. 1, pp. 403–411, Mar. 2022, doi: 10.21597/jist.903159.

[19] "Ender-3 V2 Neo 3D Printer - Creality Official Store." Accessed: September 3, 2024. [Online]. Available: https://store.creality.com/products/ender-3-v2-neo-3d-printer?utm_source=googleshopping&gad_source=1&gclid=CjwKCAjwp4m0BhBAEiwAsdc4aLuUILxfvtuBLSSNrVNSMpMqEdGiRNWcrb7o3Vw8mA3899wlZ5-7shoCsU8QAvD_BwE.

[20] "Bambu Lab X1-Carbon 3D Printer | Bambu Lab US." Accessed: September 3, 2024. [Online]. Available: https://us.store.bambulab.com/collections/3d-printer/products/x1-carbon-3d-printer.

[21] M. N. Nadagouda, M. Ginn, and V. Rastogi, "A review of 3D printing techniques for environmental applications," Jun. 01, 2020, *Elsevier Ltd*. doi: 10.1016/j.coche.2020.08.002.

[22] S. Hasanov, A. Gupta, F. Alifui-Segbaya, and I. Fidan, "Environmental Health and Safety II," *Springer Handbooks*, vol. Part F1592, pp. 547–557, 2023, doi: 10.1007/978-3-031-20752-5_32.

[23] J. Officer and I. Fidan, "Development stages of a number of electromechanical systems to establish a green additive remanufacturing ecosystem," *International Journal on Interactive Design and Manufacturing*, pp. 1–9, Apr. 2024, doi: 10.1007/S12008-024-01845-8.

[24] I. Fidan, S. Canfield, V. Motevalli, G. Chitiyo, and M. Mohammadizadeh, "iMakerSpace Best Practices for Shaping the 21st Century Workforce," *Technologies (Basel)*, vol. 9, no. 2, Jun. 2021, doi: 10.3390/technologies9020032.

[25] N. Hopkins, L. Jiang, and H. Brooks, "Energy consumption of common desktop additive manufacturing technologies," *Clean Eng Technol*, vol. 2, Jun. 2021, doi: 10.1016/j.clet.2021.100068.

[26] "Full Recycling & 3D Printing Setup." Accessed: September 3, 2024. [Online]. Available: https://www.filabot.com/products/full-recycling-3d-printing-setup

[27] S. Selvaraj *et al.*, "COVID-19 Biomedical Plastics Wastes—Challenges and Strategies for Curbing the Environmental Disaster," *Sustainability 2022, Vol. 14, Page 6466*, vol. 14, no. 11, p. 6466, May 2022, doi: 10.3390/SU14116466.

[28] S. Kiranlal, V. M. Brathikan, B. Anandh, and S. Vikash, "A Review on Electrical and Electronics Part of 3D Printer," *IOP Conf Ser Mater Sci Eng*, vol. 1228, no. 1, p. 012007, Mar. 2022, doi: 10.1088/1757-899x/1228/1/012007.

[29] I. Fidan *et al.*, “Nano-Level Additive Manufacturing: Condensed Review of Processes, Materials, and Industrial Applications,” *Technologies 2024, Vol. 12, Page 117*, vol. 12, no. 7, p. 117, Jul. 2024, doi: 10.3390/TECHNOLOGIES12070117.

[30] J. Ajay, A. Singh, R. C. Song, C. Zhou, and W. Xu, “Don’t Forget Your Electricity Bills! An Empirical Study of Characterizing Energy Consumption of 3D Printers”, *APSys '16: Proceedings of the 7th ACM SIGOPS Asia-Pacific Workshop on Systems*, pp. 1-8, doi: 10.1145/2967360.2967377.

[31] R. Kumar, H. Sharma, C. Saran, T. S. Tripathy, K. S. Sangwan, and C. Herrmann, “A Comparative Study on the Life Cycle Assessment of a 3D Printed Product with PLA, ABS & PETG Materials,” *Procedia CIRP*, vol. 107, pp. 15–20, Jan. 2022, doi: 10.1016/J.PROCIR.2022.04.003.