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White Paper

Recyclability of Additive Manufacturing Materials/Products

Opportunities to improve circularity and sustainability in additive manufacturing

Abstract

This paper will define a general framework for recyclability assessment of manufactured goods, including additive manufacturing (AM) materials and products according to international rules and regulatory requirements. Firstly, the global definition of recyclability of plastics products developed by the Association of Plastics Recyclers and Plastics Recyclers Europe is presented. Subsequently, existing challenges and possible solutions related to the recyclability of AM products are discussed. Lastly, other related requirements for the success of the recyclability of AM products are pointed out.

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Additive Manufacturing (AM) Technology

According to ISO/ASTM 52900, additive manufacturing also known as 3D printing, is a method of creating a three-dimensional (3D) article layer-by-layer using computer-aided 3D model design technology. 3D printing, instead of the traditional, subtractive manufacturing method, relies on moulds, dies or other tooling, and the final article must be cut from large blocks of materials. On the other hand, articles only require materials for the part by using 3D printing. As such, 3D printing can create articles with little or no material wastage and more importantly, 3D printing can create articles with much more complex structure as compared to traditional manufacturing method.

In the recent years, 3D printing has been adopted for industrial manufacturing of many functional parts and/or articles in various sectors including automotive, aerospace, dental, healthcare, architecture, jewellery, personal protective equipment, an d other consumer products. Several types of 3D printing processes currently available commercially or at the early development stage, which typically varies in the way they form plastic and metal 3D articles (or objects)[1]. The three most common 3D printing processes are described below.

- **Material Extrusion (MEX)** – such as Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), where the "plastic filament" is molten at high temperature and deposited on the build platform (print bed) of the 3D printer to form the article layer-by-layer. The most used plastic filaments (or spools) are mainly made from polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) with other alternatives such as silicone, clay, and other high-temperature polymers.

- **Vet Photopolymerisation (VPP)** – such as Stereolithography (SLA), Digital Light Processing (DLP), Liquid Crystal Display (LCD), Masked stereolithography apparatus (MSLA), and a few more processes. In general, these processes require "liquid photosensitive resin", which is usually contained in a tank (or vat) and selectively cured (or solidified) by a laser or light or heat beam within the 3D printer's tank, layer by layer (either from top to bottom, as refer as "top-down printing" or the opposite way, "bottom-up printing") until 3D article is completely built.

- **Powder Bed Fusion (PBF)** – this 3D printing process uses "powdered materials" (which can be metal powder, plastic powder, or even ceramic powder) as consumables. However, powder-based 3D printers are frequently used for metal 3D printing in various industrial applications. Three main types of powder-based 3D printing processes are: (i) Selective Laser Sintering (SLS) where a laser beam is used to sinter powdered material (ceramic, plastic, or metal), bonding the small grains of powdered material together to form a solid article; (ii) Selective Laser Melting (SLM) which is similar to SLS. The difference is that in SLM, the powdered material is molten (not sintered) to fuse the particles of powder to form the solid article; and (iii) Electron Beam Melting (EBM) which applies the same principle as SLM process i.e., a powdered material (often metal or metal alloys for EBM) is molten and solidified into 3D article by high energy generated from electron beam.

These 3D printing processes are suitable for different types and forms of materials, forming 3D articles or objects with different surface finishes, durability, manufacturing speed and cost. As such, many different types of 3D printing materials including plastic, ceramic, metal, and metal alloys, have been developed for each type of 3D printing process.

Circular Economy for Additive Manufacturing

In the past decades, the traditional model, "linear economy", has been implemented in businesses and manufacturing of all industries. A linear economy follows the "take-make-dispose", where resources or raw materials are extracted from nature, then converted into products and discarded as waste after consumption by consumers. This economic system prioritises profit over sustainability – the value is created by producing and selling as many products as possible, without concern for their ecological consequences. As such, materials or resources are generally not utilised to their maximum values in this linear economy system, and it always moves in one direction (open-ended) as indicated by its name – from raw material to waste.

This "linear economy" has various negative impacts not only on the loss of valuable materials and natural resources, but also many environmental damages, for example: (i) the lands that are being degraded; (ii) the ocean and water bodies that are being polluted by plastic wastes; (iii) the massive amount of waste that is being generated, daily; (vi) the biodiversity that is being lost; and many more which are driving the global challenges of climate change, global warming as well as biodiversity loss[2].

- **"Reduce"** is the first principle of circular economy – which requires minimising the use of raw material and the consumption of other natural resources (e.g., energy and water) as low as possible in the production process.

- **"Reuse"** is the second principle of circular economy – which requires the producers to produce durable and reusable products, to prolong the service life of products as well as maximise reuse of products and their parts.

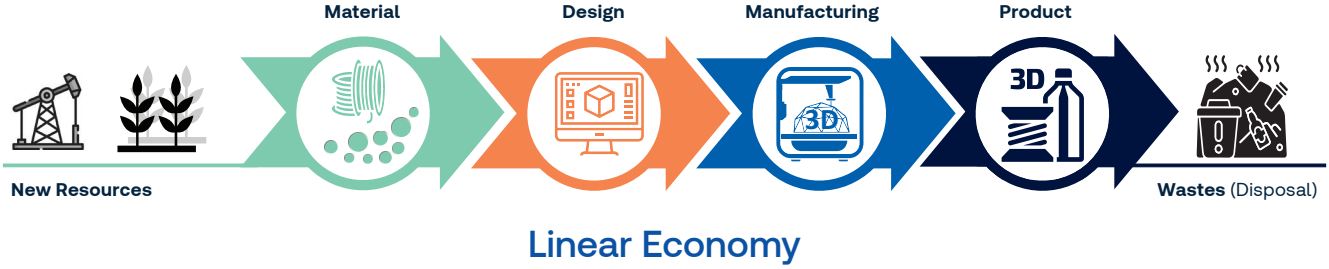
- **"Recycle"** is the third principle of circular economy – whereby the used products are required to be turned into usable resources after being discarded and sent back as raw materials into the production process, to maximise the value of materials as well as reduce the generation of waste.

With continuous development and implementation of "circular economy" in various industries, its core "3R" principles have been further improved, i.e., increasing from 3R to 6R or even more "R" – such as Rethink, Repurpose, Repair, Refurbish, etc. However, the 3R ("Reduce-Reuse-Recycle") principle remains as the core principle of circular economy.

"Reduce" advantages of 3D printing

Compared with the traditional manufacturing method, 3D printing directly produces the objects of any shape layer-by-layer from the computer-aided graphics data without any participation of machining equipment and moulds. This process only requires materials for the part itself, and hence it reduces the use of raw material and lowers the material wastage as well as carbon footprint.

Moreover, the "design" together with the "engineering" principle can be combined through the digital-aided manufacturing technology of 3D printing to optimise relevant algorithms, which helps to improve the object performance and further reduce the use of raw materials[1]. The featured designs of 3D printing objects like "lattices" and "honeycomb" structures are the best example of the combined "design" and "engineering" principle to limit the amount of raw material required and reduce the product's weight, while the mechanical performance of the object



Linear Economy

Fig. A Linear Economy: Materials are extracted from natural resources, converted into products, consumed, and eventually discarded as wastes

still can be maintained (or even further improved). When this object is applied to products like cars and airplanes, it can significantly contribute to reduced "fuel consumption".

Potential "Reuse" and "Recycle" advantages of 3D printing

In recent years, 3D printing has provided an alternative manufacturing method for various applications and industries with its unique advantages, whereby "Reduced Materials consumption" is one of them – contributing to the first core principle of circular economy. With the popularisation and increased application of 3D printing, there are many efforts from the technology developers to continue developing 3D printing technologies and materials to further promote circular economy and reduce its impact on the environment – which is very well in line with the global sustainable development strategy.

With the present technology, 3D printing can be combined with 3D scanning and 3D modelling to repair the damaged part(s) of the product, which helps to prolong the service life of products and avoid discarding as waste – and hence contributing to the second core principle of circular economy i.e., "Reuse". In addition, some 3D printing technologies have been developed to directly re-print on the surface of the old product for the missing parts or damaged parts of the product.

Concurrently, 3D printing materials have also been developing in a more circular way. Many new printing materials, especially for plastic filament extrusion 3D printing (FDM) are made by recycling "thermoplastic wastes" from other industries or other waste streams. For example, rPET filaments made from recycled plastic bottles or waste from a virgin material

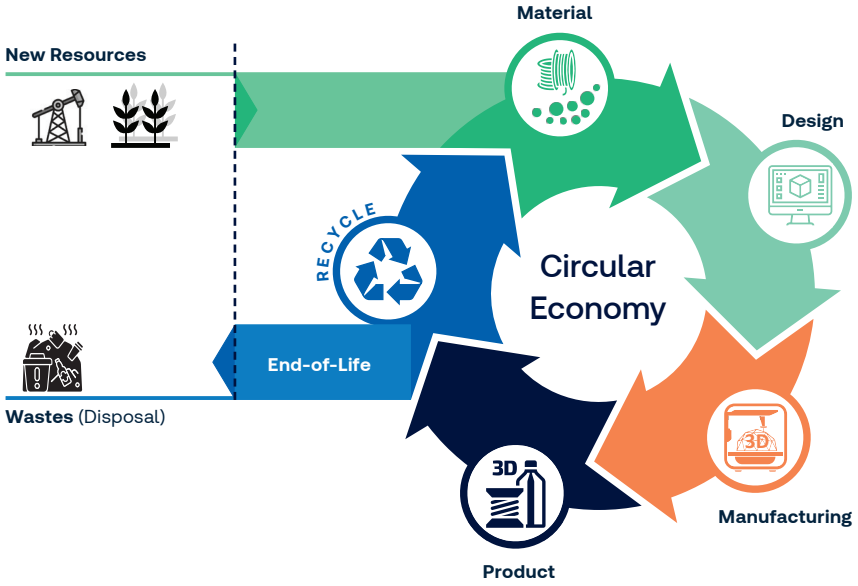


Fig. B Circular Economy: Closes material flow loop, circulating materials back into the supply chain or economy until the highest value of the materials is reached

manufacturing process, Recycled TPU (thermoplastic polyurethane) made from footwear waste, and more recycled 3D printing materials have been recently developing which are often being promoted as "Giving a second life to plastic waste". In addition, recycling technologies e.g., atomization have also been developed to recycle "metal and alloy scraps" from other industries into recycled metal and alloy powders for 3D printing materials. Recycling is a necessary component of a circular economy which keeps products, components, or materials circulating in the economy (but it should be considered only when the products or components cannot be reused or repaired anymore). Therefore, the further development of these circular (or recycled) 3D printing materials, especially from the 3D printing waste stream itself (i.e., 3D printed products or components after use or at their end-of-life, printing failures, support structures that cannot be repaired or reused or remanufactured) will contribute to the third core principle of circular economy i.e., "Recycle".

As such, alternative 3D printing materials are beginning to replace or substitute traditional 3D printing materials, and the trend has gained quick growth and market interest. This is mainly due to the customers' demand and many countries are now moving toward setting up regulations and standards for more sustainable production practices – and hence adopting these practices will be no longer an option, but rather the practice that businesses and industries must do. Recycling and the use of recycled materials in the new product are one of these practices adopted in various industries, including 3D printing. Although there are increasing technologies aimed at making it more eco-friendly, there are still many collective works to be done in this area. Based on the current situation that massive amount of plastic waste is sent to landfills and/or incineration, it is therefore of no use for "material" itself to be optimal for recycling if there are no proper collection, infrastructure, recycling technology as well as the necessary incentive (or commercial value) for it to be recycled. As such, this recyclability of the materials (including 3D printing materials and products) should not only consider 'what type of materials' are being used, but also 'how other components (colours, fillers, and other additives) affect the product recycling', and 'what is the effective likelihood of recycling (at scale) in different countries where the product is being sold'.

Recyclability of Additive Manufacturing Materials

Many organisations are now trying to establish the general standard framework and an index – so-called Recyclability – that will be used to "evaluate and analyse what the likelihood of each material or product can be recycled at the end-of-life". In short, this recyclability determines whether the material or product after its end-of-life can be circulated back to the economy in the existing collection, sorting and recycling infrastructures. In some European countries, laws and regulations have already been established to promote recyclable products, especially the product makes out of plastic. For example – Since 1 September 2020, a minimum standard for determining the recyclability of plastic packaging has been in force in Germany under the Packaging Act (VerpackG)[4].

Under the new upcoming European Union (EU) regulatory requirement such as the Eco-design for Sustainable Product Regulation (ESPR), the general rule for recyclability will be established for all manufactured products (within 2024 as a forecasted timeline)[5]. In the US, the green guides have been established by the Federal Trade Commission (FTC) with a set of guides to help marketers avoid making environmental marketing claims that are unfair or deceptive under Section 5 of the FTC Act, 15 U.S.C. § 45. Under the FTC Act, 16 CFR § 260.12(a) (Recyclable claims), it states that a company or a marketer can make an unqualified "recyclable" claim, as long as a substantial majority – which is defined as at least 60% – of the communities or the consumers where a product is marketed have access to recycling facilities that will accept the material. The lower the level of access to the appropriate recycling facilities, the more a company or a marketer should emphasise the limited availability of recycling for the product[6].

Since 3D printing materials and 3D printed products are currently being used in various sectors (such as automotive and aerospace industries, dental, healthcare, architecture, jewellery, personal protective equipment, and other consumer products), therefore 3D printing materials and 3D printed products will eventually be covered under these laws and regulations.

What is Recyclability? What does it mean if the product is called "Recyclable"?

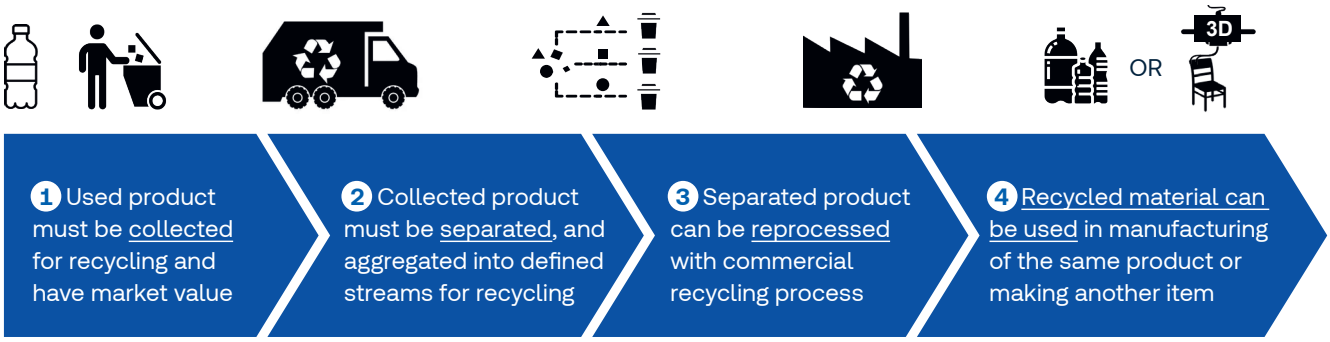
The answers to the above questions are surprisingly not as simple as you may think — and it is quite unfortunate that most people still do not truly understand what is recyclable and what is not. This could simply be because the Mobius loop – one of the most widely recognised recycling symbols – has been misused for the past decades. One of the best examples is that this generic Mobius loop was stamped onto the product made from a material that can be "technically" reprocessed, and it is always assumed that the product stamped with the Mobius loop logo can be recycled everywhere, although this assumption is wrong. Therefore, the product is not necessarily recycled even though the material used for making that product can technically be reprocessed.

In general, recyclability is defined as the "characteristic of a product that can be taken from the waste stream, and which can be then collected, processed and put back into use as a raw material or another new product"[4, 6]. Therefore, the recyclability of a product does not correspond solely to the physical property of the material used. Moreover, it should be noted that nothing is fixed in stone – Recyclability of the product (or associated component) evolves as the product design, the recycling infrastructure as well as the market or user demand also evolve.

Minimum requirements for Recyclability

In 2018, the industry association Plastics Recyclers Europe (PRE) together with the U.S.-based Association of Plastic Recyclers (APR) developed a "global definition governing the use of the term 'recyclable' as it relates to plastics packaging and other manufactured products." Several aspects beyond the technical recyclability of material itself must be considered. Therefore, for a product or associated component to be considered "recyclable", there are four minimum requirements that should be fulfilled[4].

Four minimum requirements to be considered as "Recyclable"



1. The product or associated component must be made with a plastic that can be collected in large enough quantities at the end of its life for recycling, and still has market value and/or is supported by a legislatively mandated program.

2. The collected product must be sorted, separated, and properly aggregated into the defined streams that allow for high-quality recycling processes of the product.

3. The sorted product can be processed and reclaimed or recycled with proper technologies in the industrial recycling processes.

4. The recycled plastic becomes a raw material with acceptable quality/properties, and it can be used in manufacturing the same new product (so-called "Closed Loop" – for example, a used PET bottle becomes a new rPET bottle) or making another item that has market value (so-called "Open loop" – for example, a used PET bottle becomes rPET 3D printing filament).

For a product that is made from "innovated materials", it should be ensured that the product can be collected and sorted in sufficient quantities, and the product must be compatible with the existing industrial recycling processes. Otherwise, it should be ensured that the material will be available in sufficient quantities at its end-of-life to justify operating the new recycling process. Although the global definition of "recyclability" and these four minimum requirements have been established for a product or associated component that is made from "plastic", similar principles or considerations should be applied to a product or associated component that is made from other materials such as metals, as well.

General recyclability assessment framework

Recyclability is not a theoretical property of the product (or associated component). The recyclability of the product can be assessed to determine the ability of material or product to become a new secondary product (after its primary use phase) in the existing collection, sorting and recycling infrastructure. Therefore, recyclability is generally defined by two parameters, i.e. the compositional quality of the product and the real recycling options after usage.

When assessing the recyclability of a product (or associated component), the available content of recyclable material used in the product should first be taken as the minimum starting point for further assessments of other factors, including at least the following four factors: [4, 6]

1. The capability of collecting the product after the end of its life from the users.

2. The availability of sorting and recycling infrastructures that allow for high-quality recycling of used products.

3. The sortability of the products from other different types of waste/material and the separability of its components (where applicable).

4. Incompatibilities of the components or substances contained inside the product that might restrain the success of recycling process with currently used technology.

Theoretically, "100% recyclability" or "fully recyclable" should only mean that the product, after its use phase, can be fully collected, sorted from other wastes, separated its components (where applicable), and successfully recycled into high-quality recycled material which meets all (physical and chemical) requirements to become the new secondary product.

The following section describes the general 'Recyclability' assessment framework that can be applied to determine the recyclability of the product, sometimes also called "the object".

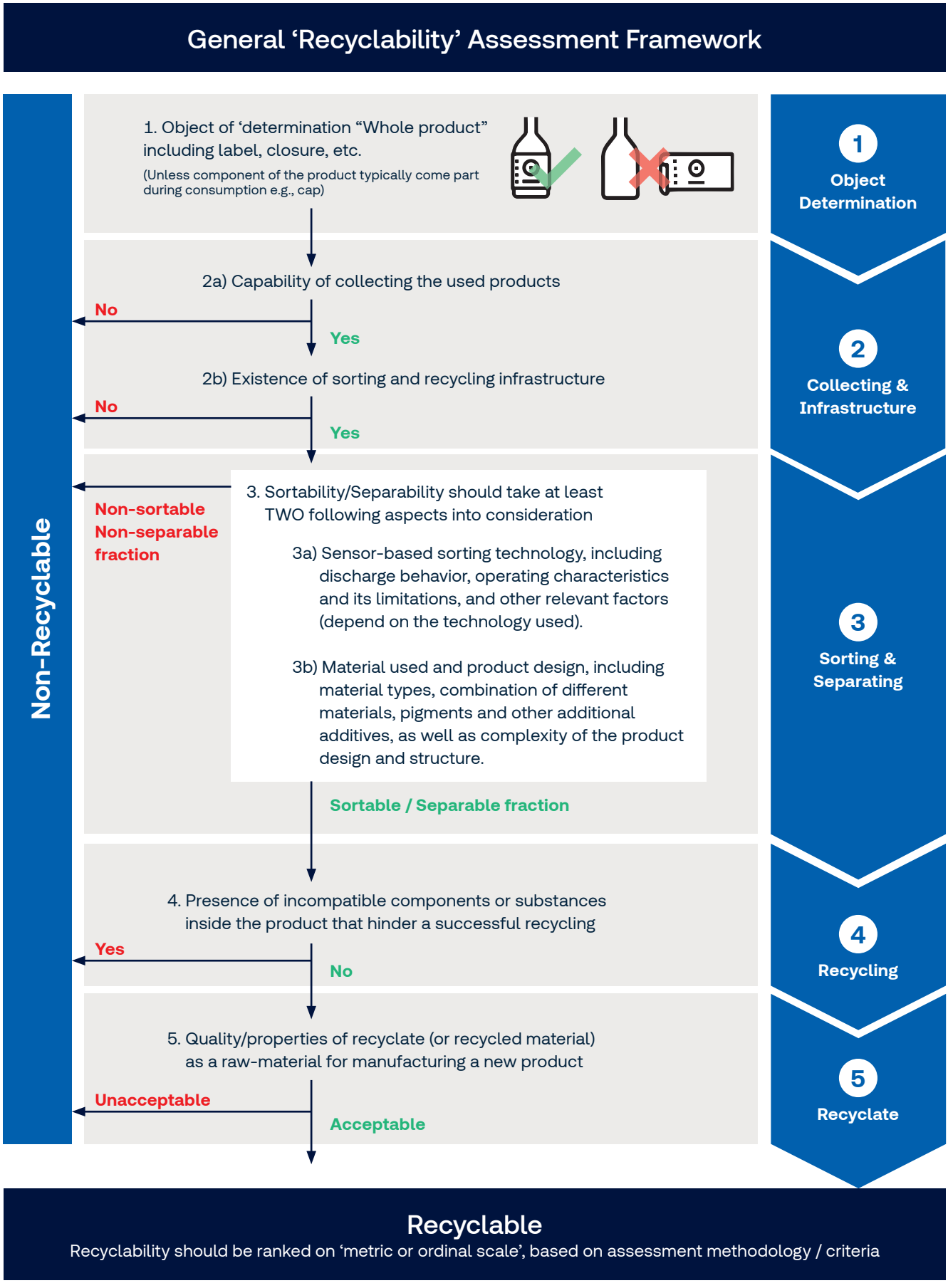


Fig. D General 'Recyclability' Assessment Framework

STEP 1:
Object of determination
The object for the determination of "recyclability" refers to the product as "a whole", including all related components such as marks, labels, lids, closures, etc. Determination of recyclability cannot be based on the selected individual producat components that can only be obtained through theoretical dismantling of the product. However, the recyclability of components of the products that typically come apart during consumption may be determined separately.

An example is the drinking water bottle with a labelling sticker and cap, whereby the cap is usually detached from the bottle during consumption, whereas the labelling sticker remains on the bottle – and hence 'cap' and 'bottle with labelling sticker' may be considered as two separated objects, but 'bottle' and 'labelling sticker' must be considered as one whole object.

STEP 2:
Availability of collecting, sorting, and recycling infrastructure
There must be 'publicly accessible' collection for post-consumer waste, and the infrastructure of sorting and high-quality recycling available wherever the product is being sold or used. Moreover, the product (after consumption) must fit with the waste stream, and most importantly, it must be compatible with the existing collecting, sorting, and recycling processes.

If one of these requirements is not possible, the product should not be considered "recyclable".

STEP 3:
Sortability and separability
Since different materials require different paths of recycling process, the success of recycling and the quality of recycled materials highly depend on the quality and purification of the defined waste streams through sorting (and separation, where applicable). With the recent technology, sensor-based sorting techniques are generally applied in waste management and recycling facilities, and are usually applicable for object sizes ranging between 10mm and 300mm. As such, "sortability", at scale, of the products or the objects by means of sensor-based sorting should be considered to determine recyclability.

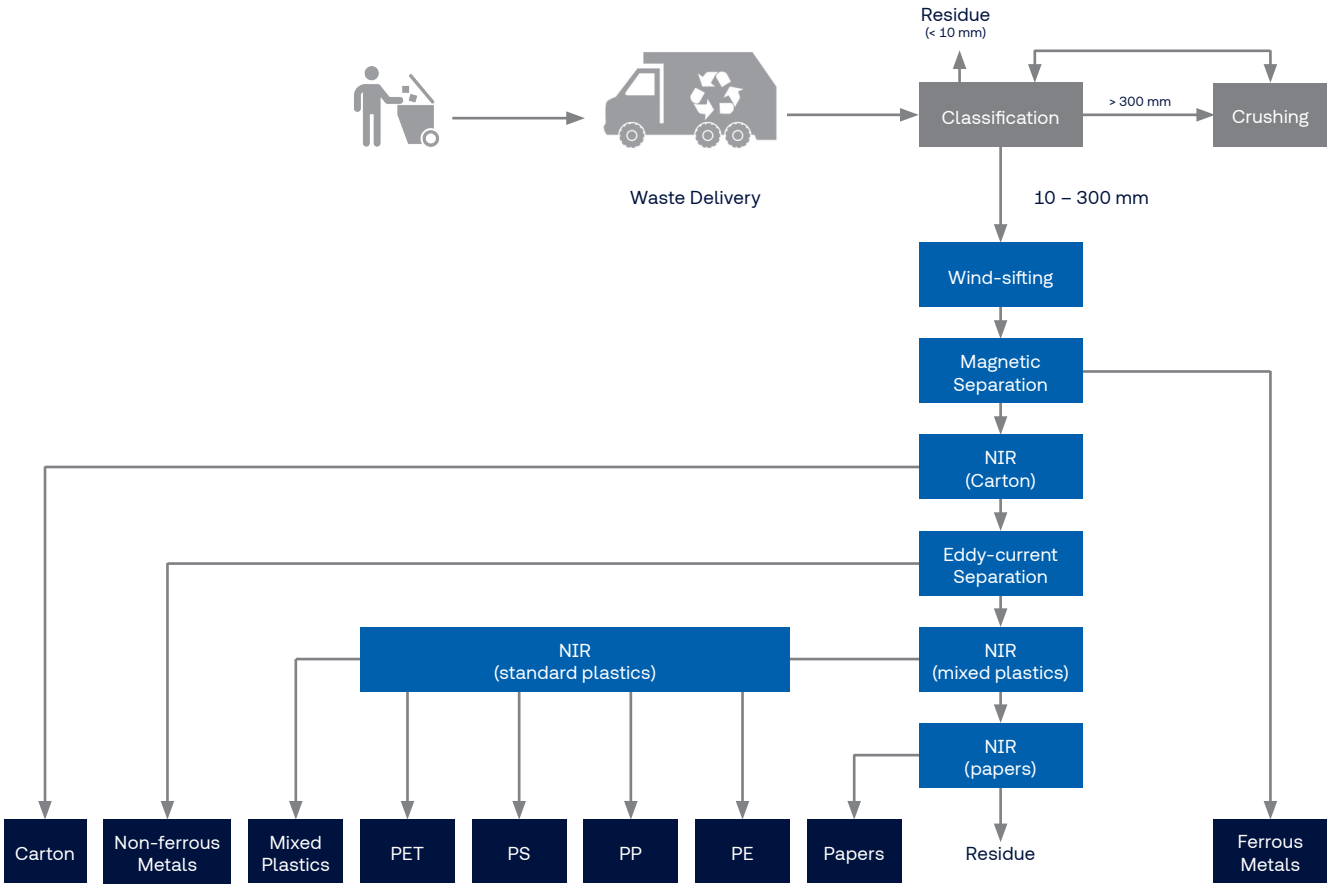


Fig. E Integrated sorting/separating systems commonly used in waste management infrastructure

Moreover, different materials also require different types of sorting technologies or systems:

- **Wind-Sifting** sorting system to separate lighter particles from heavier ones to ensure the purity of waste fractions for further sorting steps.

- **Magnetic Separation**, also known as magnetic segregation, to separate magnetically susceptible metals (so-called ferrous or ferromagnetic metals such as iron, chromium, nickel, and its alloys) from crushed scrap mixtures by means of magnetic force.

- **Eddy Current Separation (ECS)**, a process that uses a powerful magnetic field (that will induce electrical current to flow throughout the body of conductive objects) to separate "non-ferrous or non-ferromagnetic metals" e.g., aluminum from waste/scrap mixtures.

- Automated **Near-Infrared (NIR) sensors**, to separate different types of plastic (as well as paper) by using the wavelength signature of specific plastic to distinguish them from one another, and then the automated compressed air jets are typically used to eject the selected plastics from waste mixtures.

Since the 'separating mechanism', 'discharge behaviour', 'operating condition and limitation' of the above techniques are different, the sortability of the products made from different materials must be individually assessed according to the particular sorting technique[7].

Sortability and separability of the product should also take "materials used and product design" aspects into consideration (depending on sorting technology used), for example:

- Pigmented plastics (especially carbon black) should be avoided as it significantly affects the "sorting efficiency" of the NIR sorting facilities.

- Preferably mono-material is used for the entire product, or different materials used for other product components, which typically come apart after consumption (e.g., bottle caps) or can be easily separated during sorting/separating processes.

- Composites should be avoided as they might affect the overall recyclability of the product.

- Product structure, size or some other physical attributes should be compatible with the available sorting/separating facilities.

STEP 4:
Recycling incompatibilities
The product should be considered as recyclable if the entire product is made from recyclable material. For the product made from the combination of recyclable and non-recyclable materials, the product component(s) made of the non-recyclable material must be "separable" by the sorting and separating steps established in the existing recycling process. Otherwise, the entire product should not be considered as recyclable. The proportion of materials must therefore be taken into the determination of "recyclability" of the product. More importantly, it must be qualified and declared which portions of the product are recyclable, and which are not. Moreover, there must not be any ingredients or substances inside the product that hinders the ability of the recycling process. Otherwise, the entire product should not be considered as recyclable.

STEP 5:
Recyclate (or Recycled materials) properties
To fulfil the fourth minimum requirement for recyclability – i.e., recycled plastic becomes a raw material with acceptable quality, and it can be used in manufacturing a new product – both physical and chemical properties (such as material density, melt flow rate, tensile strength, impact strength and other properties) of the recyclate or recycled materials should be examined, ensuring that the recycled materials meet the requirements and relevant standards as a raw material for manufacturing the new product.

After the assessment, the recyclability of the product or the object should be ranked on the metric or ordinal scale, depending on the specific assessment methodology and criteria used. An example is the recyclability of the product could be ranked from 0% (for non-recyclable) to 100% (for fully recyclable).

Existing challenges for recycling 3D printing materials and potential solutions

The current 3D printers use a variety of materials, which can be plastic, metal/alloy, and even ceramic. For plastic, there are two primary plastic materials commonly used for 3D printing – i.e., thermosets and thermoplastics, depending on the 3D printing processes[1]:

- **Thermosets** – e.g., polyurethane, silicone, epoxy, etc. – are plastics commonly used for vat photopolymerisation (VPP) processes such as stereolithography (SLA). These plastics need "curing or crosslinking process" to be solidified into the 3D printed object – this also means that they cannot be recycled with the current mechanical recycling processes.

- **Thermoplastics** – e.g., acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyethylene terephthalate glycol (PETG), PA6/PA12 nylon, or polycarbonate (PC) – are commonly used by almost all Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) 3D printers because these plastics can be molten and become pliable or moldable when they are heated at around their melting temperature. Then they can be quickly hardened or solidified upon cooling (without any curing or crosslinking process). These plastics are also used by Powder Bed Fusion (PBF) processes such as Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF), especially PA6/PA12 nylon and polycarbonate. These plastics do not need to be cured or crosslinked; hence they can be re-melted and recycled multiple times.

Currently, there are two most common ways to recycle failed prints as well as 3D printed scarps made from thermoplastics, i.e., turning them into material that can be reused for 3D printing itself or turning them into recycled plastic for making another product in other manufacturing processes such as injection moulding. However, nearly all thermoplastic filaments used in FDM/FFF and thermoplastic powders used in SLS and MJF 3D printing are classified as Type 7 or "Other" by standards organisation ASTM International. This means these plastics are not typically accepted and processed by the current municipal programs.

As a result, these Type 7 classified plastics (after consumption or the end of their life) cannot simply be thrown into the recycling bin and expected to be recycled. Many individual efforts and collective actions will be required as a long-term solution to address this problem, by considering both environmental and economic aspects, for example:

- Protocols for reuse and recycling of this material category need to be standardised.

- Further research to reduce material usage and create repairable and recyclable products.

- Further develop sorting/recycling technologies that are compatible with various materials.

- Investment in new technologies to capture and process these materials "economically".

- Policies and regulatory compliance along the entire value chain to promote sustainable, responsible "production" and "consumption behaviours".

Therefore, the success of this endeavour depends on further development, standardised protocol, investment in new technologies, policy, and regulation, and most importantly the involvement of all stakeholders, including the consumers.

Product Stewardship Program (Collecting and Recycling)

Meanwhile, commercial solutions that are collaborative and scalable can also be established among stakeholders of Additive Manufacturing industry. The product stewardship program could be considered one of the promising solutions for the industry.

Product Stewardship – also known as Extended Producer Responsibility (EPR) – is the recently established environmental management strategy in which whoever designs, produces, sells, or uses the product should share responsibility for minimising negative impacts on human health and the environment at every stage of the product's lifecycle, including its end-of-life (i.e., post-consumer waste) management. Moreover, the most responsibility should lie with whoever

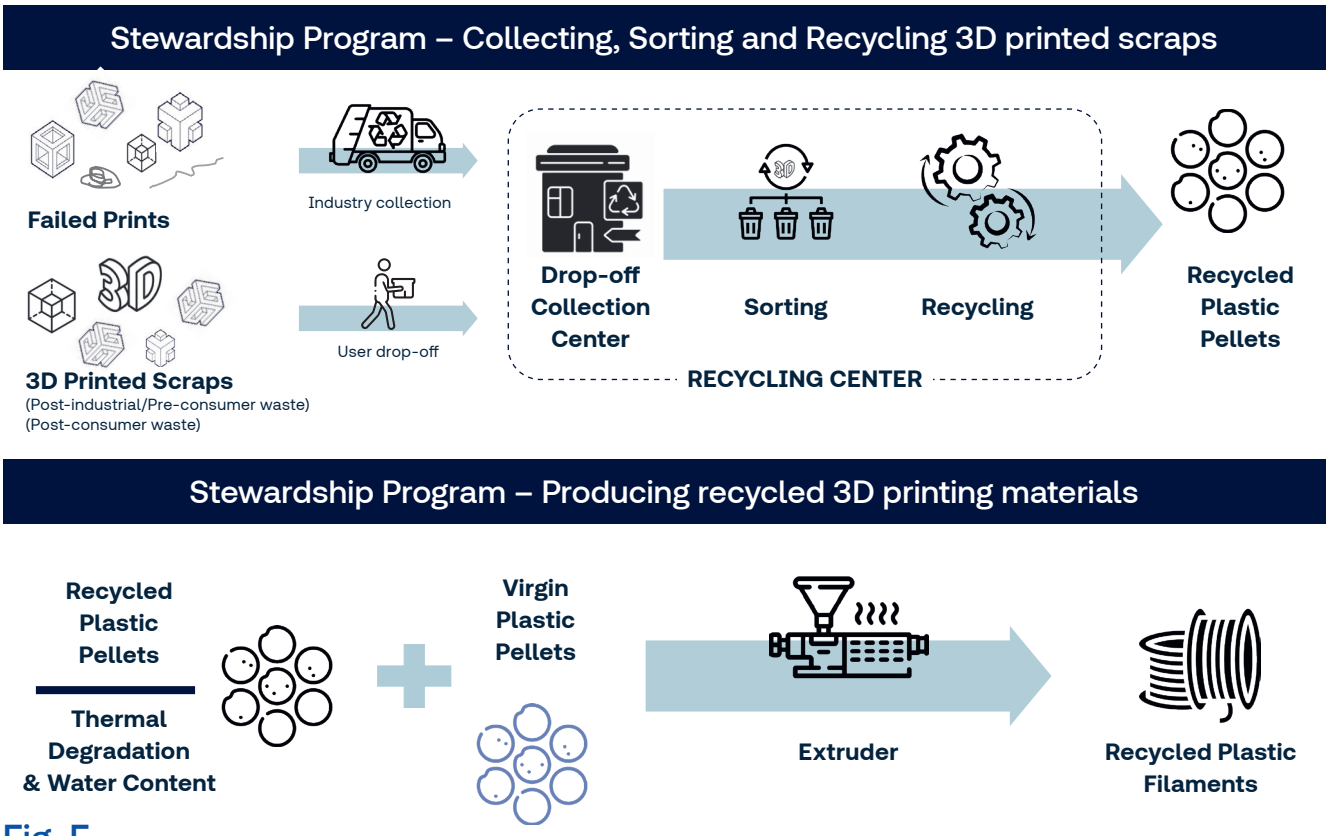


Fig. F Stewardship Collecting and Recycling Program

has the most ability to control the lifecycle environmental impacts of the product – which principally refers to "the producer of the product"[8].

As such, all stakeholders involved in the Additive Manufacturing industry, including designers, suppliers, producers, retailers, or even recyclers should locally create the Stewardship Collecting and Recycling Program – where "collecting, sorting, and recycling" facilities need to be established. The consumers should then take responsibility for returning or dropping off the 3D-printed scraps (or post-consumer waste) to the provided collection points or centres (based on the program structure). Moreover, the failed prints and other manufacturing wastes from the manufacturers (and, if applicable, other industrial waste streams made from the same plastic category) can also be delivered to the established recycling center where the collected wastes can then be effectively sorted and turned into high-quality "recycled plastic pellets" or other forms of the recycled plastic products such as "recycled plastic 3D printing filaments".

General requirements and standards for 3D printing materials

High quality filaments – whether made from virgin plastic or recycled plastic – are essential for industrial 3D printing applications. Some relevant standards required for the plastics used in additive manufacturing processes are listed as follows:

Table 1 Standards for Additive Manufacturing – Materials[9]

Standards	Descriptions
ISO/ASTM 52903-1-20	Additive manufacturing – Material extrusion-based additive manufacturing of plastic material (Part 1: Feedstock materials)
ISO/ASTM 52903-2-20	Additive manufacturing – Material extrusion-based additive manufacturing of plastic material (Part 2: Process equipment)
ISO/ASTM 52925-22	Additive manufacturing of polymers – Feedstock materials – Qualification of materials for laser-based powder bed fusion of parts
F3091/ F3091M-14(2021)	Additive manufacturing – Standard specification for powder bed fusion of plastic materials

These standards clearly describe the essential characteristics and properties of the plastics used in the particular additive manufacturing processes. An example is ISO/ASTM 52903-1-20, which clearly describes a method for defining requirements for the "plastic materials" used in extrusion-based additive manufacturing processes. These materials include unfilled, filled, and reinforced plastics, to which a certain content of special additives (e.g., flame retardants, stabilisers) can also be added. This standard is intended for manufacturers of materials, feedstocks, filaments, or printed plastic parts and products through material extrusion-based additive manufacturing processes.

As such, maintaining the high quality of the recycled plastic 3D printing filaments becomes another challenge – because the quality and properties (both physical and chemical) of the recycled plastic are usually unstable, even though the quality and contamination of the input waste stream are effectively controlled by the proper collection program. This is because thermoplastics gradually lose their mechanical (such as viscosity, molecular weight, breaking strength, etc.) and chemical properties during the process of mechanical recycling. It was also reported that there could be "significant deteriorations" in most mechanical properties after three recycling cycles. Therefore, it is important to further develop effective recycling technologies that can maintain the mechanical properties of recycled plastic. On the other hand, the combination of recycled plastic with virgin materials can be another practical solution compromising between "maintaining quality" and "reducing plastic waste".

In summary, the success of the production of recycled plastic filaments depends on the consistency and quality of the input waste stream, the amount of virgin materials (if needed), the use of advanced recycling and production lines, and most importantly, compliance with the strict quality guidelines or standards for additive manufacturing materials.

Verification of 'Recycled Content' in recycled materials and products

Due to the technical challenges, it has become a general industrial practice that "recycled plastic" is usually mixed with virgin plastic to maintain the required (physical and chemical) properties of materials and remain as an alternative to 100% virgin material. However, it might be a complex and challenging task for the manufacturers to qualify or verify "the recycled content of their products" – this is because, under upcoming regulatory requirements, the manufacturers, suppliers, and even retailers are required to ensure that their environmental and sustainable claims of the products are substantiated under the relevant standards.

The following two standards are commonly used to verify the recycled plastic content in a product and traceability of the recycled plastic and the manufactures involved in processing that recycled plastic[10].

- ISO 14021 defines recycled contents as "the proportion, by mass, of recycled material in a product. Only pre-consumer and post-consumer material shall be considered as recycled content".
- EN 15343 specifies the procedures needed for the traceability of recycled plastics and defines the basis for the calculation procedure for the recycled content of a product.

"Recycled content in the product" should be determined when both recycled and virgin materials are used in the manufacturing process by ensuring traceability of the recycled material as it segregates throughout the value chain.

TÜV SÜD offers "Recycled Content Certification" service according to ISO 14021 and EN 15343 standards by conducting desk (document) and factory (onsite) verifications on the products upon receiving recycled content verification claims. The verification approach focuses on 'incoming materials control', 'manufacturing process control' and 'quality assurance control' to identify the existence and percentage of recycled material contents in the products.



Fig. G TÜV SÜD Recycled Content Certification

TÜV SÜD Verification approach

Document audit of the supply chain sites
- Control of input material
- Control of manufacturing process
- Control of quality assurance

Onsite audit of the supply chain sites
- Control of input material
- Control of manufacturing process
- Control of quality assurance

Optional: Recyclate characterization testing

This service is applicable to any plastic used in the product, for which the 'recycled content' claim is being made by a manufacturer, supplier or retailer. To demonstrate transparent use of recycled plastics in the product at every stage of the value chain, the origin of input material (i.e., waste) and the segregation of recycled material along the upstream supply chain will be verified to ensure the traceability of recycled material used in the product.

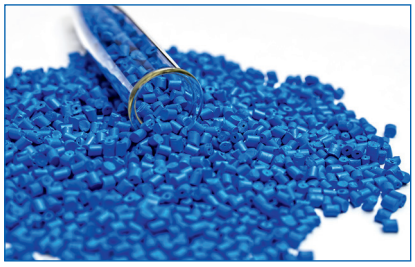
TÜV SÜD services

AM Materials and Production

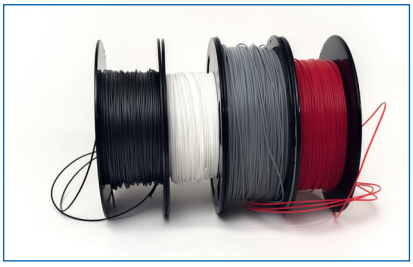
- **AM Material and Product Testing**
  (Physical and chemical properties, acc. ISO, ASTM standards)
- **iAM Production Site Certification**
  (Industrial grade AM centers, acc. ISO/ASTM 52900:2017)

Recycled Materials Content

- **Recycled Content Certification for recycled plastics (including 3D printing materials)**
  acc. ISO 14021 - Recycled Content
  EN 15432 - Recycled Plastic Traceability
- **Recycled Content Certification for Electronic-related Products**
- **Recycled Content Certification for Textile and Footwear Products**



Raw Material
(Recycled Pellets)



Consumables
(Filaments, Powders)



Finished Products
(3D printed products)

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