Nature Sustainability, pp. 1-8, 2024. DOI: 10.1038/s41893-024-01313-x

A vision for sustainable additive manufacturing

Serena Graziosi[1*], Jeremy Faludi[2], Tino Stanković[3], Yuri Borgianni[4], Nicholas Meisel[5], Sophie I. Hallstedt [6], David W. Rosen[7]

[1]Department of Mechanical Engineering, Politecnico di Milano, Milan, Italy, email: serena.graziosi@polimi.it

[2]Faculty of Industrial Design Engineering, Delft University of Technology, the Netherlands, email: J.Faludi@tudelft.nl

[3] Engineering Design and Computing Laboratory, Department of Mechanical and Process Engineering, ETH Zurich, Zurich, Switzerland, email: tinos@ethz.ch

[4] Faculty of Engineering, Free University of Bozen-Bolzano, Bolzano, Italy, email: Yuri.Borgianni@unibz.it

[5] School of Engineering Design and Innovation, The Pennsylvania State University, PA, USA, email: nam20@psu.edu

[6] Division of Product Development, Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden, email: sophie.hallstedt@chalmers.se

[7] Institute of High Performance Computing, Agency for Science, Technology and Research (A*STAR) 1 Fusionopolis Way, #16-16 Connexis, Singapore 138632, Republic of Singapore.
email: rosendw@ihpc.a-star.edu.sg

*Corresponding author: serena.graziosi@polimi.it

Preface

Radical technological innovations are emerging in response to environmental, economic, and geopolitical pressures. This affects how we design and manufacture new solutions. Additive manufacturing, one of the enabling technologies of the digital transition, can support more sustainable manufacturing processes if developed through a system-level approach. In this Perspective, we adopt such an approach: we propose to use established sustainable design methods to innovate additive manufacturing systems, and to consider how to make additive manufacturing an enabler of sustainable design in combination with conventional manufacturing. We then discuss how to implement our vision to enable additive manufacturing for sustainability.

Keywords: Sustainable Design, Design for Additive Manufacturing, Sustainable Development, Vision, Circular Economy, Additive Manufacturing

Global challenges imposed by climate change, biodiversity loss, and political turmoil are making the availability of raw materials and resources highly uncertain, calling for revising established practices from a sustainability point of view. In this respect, additive manufacturing (AM) is gaining significant attention as an alternative to conventional manufacturing (CM), such as casting, molding, forging, and extrusion. AM refers to a class of manufacturing processes that fabricate parts by repeatedly adding and processing materials layer-by-layer, known informally as “3D printing”. Although its original role was to fabricate prototypes during product development, AM is now used extensively for production parts, tooling, and an ever-increasing number of niche applications[1]. Thousands of AM-fabricated parts are flying on airplanes and spacecraft, and millions of AM metal parts have been implanted in people as spinal fixtures and joint replacements. The global AM market is estimated at US$15B in 2022 and is expected to grow at 20-21% annually for the next 10 years[2]. AM currently accounts for approximately 2% of all global manufacturing activity but is projected to comprise over 9% of manufacturing by 2032[2], with multiple and heterogeneous industrial sectors (e.g., food and construction) actively involved.

The wide variety of AM technologies and processable materials available promotes this widespread range of applications. Seven process categories and related identification acronyms have been identified in the ISO/ASTM 52900:2021 standard[3], based on the processing principle they implement, namely: binder jetting (BJT), direct energy deposition (DED), material extrusion (MEX), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL), vat photopolymerization (VPP). Thanks to these enabling processes and AM’s nature of stacking raw materials to fabricate complex geometries, industries’ capabilities are broadened to design performance-optimized, lightweight designs not previously feasible with conventional manufacturing processes. The enhanced design freedom enabled by AM is so vast that a dedicated research topic, i.e., Design for Additive Manufacturing (DfAM)[4], has been established. The concept of DfAM shows the multiple dimensions of complexity that can be exploited thanks to AM when designing shapes, materials, and functionalities to get numerous advantages in performance, personalization, and uniqueness[5]. But does this unlocked design and manufacturing freedom ensure material efficiency? Are our capabilities to design better products fully utilized? What about energy efficiency and material circularity?

AM can foster manufacturing flexibility and adaptability due to its ability to switch among different production batches rapidly. The desire is to optimize raw material usage in manufacturing, in-service resource consumption such as vehicle fuel use, or socio-technical effects like repair and remanufacturing. However, does this flexibility and resource optimization, combined with the capability to realize almost any shape or geometry, promote more sustainable design and manufacturing practices? Under what circumstances does AM drive sustainability today, where does it worsen it, and how can we design it to be more universally sustainable?

AM is still considered a niche manufacturing technology with a niche market, but the previous data demonstrated that this scenario would change in the coming years. Its current impact on sustainability, whether positive or negative, will no longer be limited. We must act before technology becomes established because then a change will become more challenging. This action must build upon the different initiatives and governmental instruments, such as the United Nations’ Sustainable Development Goals and the European Green Deal, pushing organizations to reconsider their practices. Implementation issues, such as limited data availability and the difficulty of analyzing complex, systemic problems, still limit the adoption of these instruments in product development processes involving CM. How does that situation fit within the context of AM? Can we design AM technologies to meet requirements from these instruments more straightforwardly?

This Perspective will examine and answer these questions. It will also discuss sustainability challenges attributed to AM, new opportunities, and actions to integrate a sustainability perspective into AM. It will end with a vision for future product development via sustainable AM offered through a system view of a sustainable design and manufacturing scenario.

Integrating Sustainability into AM

To make AM more sustainable, it is necessary to integrate sustainable design strategies into practices for: AM machine design, processes, development of raw materials, and selection of supply chains. A system approach should be pursued. Before going into these topics, we must explain the current state of AM compared to CM and where AM should go to embrace sustainability.

The current state of AM

To promote the sustainability essence of AM, it is quite common nowadays to claim[6] "*AM is green because it eliminates 1) manufacturing waste and 2) transportation of parts in supply chains"*.

Though eliminating manufacturing waste is based on existing evidence, significant nuance is needed before claiming it. Many traditional manufacturing processes, such as injection molding, casting, and extrusion, already produce minimal waste at scale. Their part designs are thoroughly optimized for manufacturing. AM manufacturing waste depends on many circumstances and factors, especially the chosen printers and materials. Polymer PBF can generate up to 44% material waste, with a likely range of yields from 56-80%[7]. Much AM printing powder is wasted due to the sensitivity to the oxidation of the underlying materials[8,9]. Some photopolymer resin-based printers likewise produce significant liquid resin waste[10]. That waste is compounded by sacrificial support material, which is also wasted. Failed prints are similarly wasted, though numbers on average failure rates are challenging to find because companies have strong incentives not to reveal them. Despite significant efforts invested in reducing material waste, such as developing optimization approaches to design AM parts that do not require support structures[11], extensive waste material reduction seldom occurs.

AM can sometimes reduce material waste, significantly improving impacts, but it is strongly context-dependent. It is usually true when compared to machining complex shapes or to CM processes requiring tooling for small production runs (e.g., vacuum casting). It is valuable for parts characterized by high-embodied-energy metals, as in aerospace[12], or low production volumes where the impacts of tooling would be significant. CM of complex lightweight titanium parts can, for example, generate up to 80-90% scrap[9,13]. This titanium scrap is contaminated with oxygen and iron impurities, making it difficult to recycle as a high-grade material[13]. AM reduces the environmental impact by minimizing scrap and saving material during fabrication[9]. For example, titanium's high embodied energy makes the reduction of any material waste promising. However, although comparing AM advantages to the machining of complex geometry is popular, it offers a limited view. Most investments in AM are to scale up production volumes[14]. Low-volume production is not the expected future scenario. It is also unfruitful to think that since AM could have environmental advantages for low-volume manufacturing, switching all manufacturing to low-volume mass customization would be reasonable. This solution would only increase CM impacts because production volumes are reduced. It will not mitigate negative AM impacts.

This reasoning concerning material waste also involves other considerations. Let us assume that AM can reliably and consistently reduce waste. That is not particularly relevant to its overall environmental impacts compared to other manufacturing methods because most of its impacts come from energy use[10]. Most polymer printers' energy impact alone exceeds the total impact of injection molding ABS plastic, sometimes by an order of magnitude[10]. This consideration is elaborated at maximum theoretical throughput, i.e., printing a full print bed with 100% yield for 24 hours/day for each printer's entire lifetime, versus injection molding at a mass production scale and considering the environmental impacts per part produced[10]. Results are similar for metal[9]. For most parts, AM uses more energy per kilogram of material processed than casting, molding, forging, or extrusion[15]. A considerable variation has also been seen between process categories (e.g., MEX vs. PBF vs. VPP), same category but different printer brands, and same printer but different materials[10]. Of course, different materials and processes provide different part strengths and other functional qualities. That significant variation means much room for environmentally improving machine design and operations.

Besides, the carbon footprint of AM is 2 to 20 times higher per kilogram of material processed than CM methods at scale due to its high electricity use[15]. If metal PBF and DED processes completely replaced conventional hot isostatic powder-based pressing processes in manufacturing steel parts, they would use over ten times the energy[8]. These laser-based AM systems are still characterized by relatively low efficiency, with only 9–23% of the laser beam energy melting steel powders and 3.6–7% for aluminum powders[16]. Additionally, the powder feedstock is tremendously energy-intensive to produce. The high carbon footprint is also due to other printer components, such as motors and control electronics. Compared to the overall energy operating a PBF machine, only about 0.8% of the total energy is allocated for powder melting[17]. The comparison of AM to casting, extrusion, rolling, and others[15], becomes relevant for ramping up AM fabrication beyond small-batch production while improving environmental impacts. Therefore, we need to improve the efficiency of AM processes and AM raw materials production[9,10]. Besides, we need more studies comparing AM and CM impacts "*per part produced*". They are fundamental to making more informed sustainability decisions. Measuring the impact "*per part produced*" instead of the impact "*per kilogram of material processed"* allows a much fairer comparison among technologies. However, the translation from impact per kilogram to impact per part is not straightforward, as multiple CM processes may be involved for one AM process. Also, AM and CM might have multiple pre-processing or post-processing operations, an important consideration that is captured by the "*per part produced*" metric. Wasted material is not included in the "*per kilogram of material processed*".

The second part of the claim, that AM is green because it eliminates transportation of parts in supply chains, also deserves clarification. AM is commonly considered to reduce transportation dramatically, which is potentially a strategic sustainability driver. However, in most cases, raw materials must still be shipped. AM only reduces the need to transport different parts made of the same materials. Even if AM eliminated material transport, it would not substantially improve most products' life cycle impacts. Life Cycle Assessments (LCAs) have shown for decades that transport accounts for a small portion of the lifetime impacts of most typical products[18]. It is a common misconception that transportation has a large share of the environmental impacts of products because transport accounts for a significant percentage of global greenhouse gas emissions[19]. The global impacts of transport are mostly from transporting people, not shipping goods. Parts' weight reduction enabled by AM benefits transportation costs and environmental impacts. But this does not make AM products sustainable by default if impacts from other life cycle stages are not lessened.

However, other benefits can be underlined. Since materials are usually commodities while manufacturing is a value add, local printing keeps more money in local economies, potentially benefiting economic goals. Local manufacturers might also be more easily monitored and certified for good labor practices. Companies should start reflecting on the most sustainable strategy to pursue, i.e., producing internally and managing the transportation of components or externalizing the production but working on guaranteeing suppliers' certification. A systemic perspective, alongside sustainability models, is needed to promote AM sustainability in multiple ways and support companies in making informed decisions.

Where AM should go

A fair and reliable assessment of when AM is better or worse than CM and how AM could be improved is significantly context-dependent. The baseline impacts of some AM processes are so high that despite the increased sustainable design opportunities present in lightweight design, process consolidation, and material saving, their environmental impact is still much more significant than CM processes and materials. Weight reduction can significantly decrease the use phase impacts of aircraft because lifetime fuel usage is most of the total lifetime impact. However, it does not provide comparable savings for automotive or marine vehicles[20]. Besides, even if AM significantly reduces material waste versus many CM processes, its current high energy use usually overwhelms the benefit.

To deal with these issues, comprehensive and context-based life-cycle perspectives are needed. So far, LCAs of AM have often been fragmented and unsystematic. Clarifying where AM is and is not sustainable is an excellent opportunity for research and practice if the following aspects are considered.

First, LCAs should choose fairer functional units. We recommend impacts "*per part produced*" for certain reference parts, rather than (or in addition to) "*per kilograms of material processed*". Second, include pre-process and post-process operations and the printer's construction. Third, include machine utilization scenarios. Energy use per part printed can vary by up to two orders of magnitude from maximizing temporal and spatial utilization for some printer types[11]. Some printers have high idle power and are left running between prints. Others can print many parts at once without using significantly more energy. This can apply to both metal and polymer printers[10,21]. Having fewer printers shared by many users can dramatically reduce impacts. Reducing batch volumes may not always lead to energy savings. Studies should also break down the energy use of AM processes to the component or subsystem level[17]. They could set priorities for the sustainable redesign of AM processes, comparing heating energy to material impacts, waste, mechanical or other systems, post-print annealing or machining, or other aspects of the process. Such studies can also compare consolidated parts, where several CM processes are replaced by one AM part with some post-processing, potentially resulting in lower total impacts.

An LCA excluding material production and end-of-life impacts could lead to missed opportunities for AM. While material impacts do not often dominate AM's total life cycle impacts, they are still significant and can be a lever towards exploring more sustainable AM materials. It could also mean making design compromises using materials with lower technical performance in favor of better sustainability impacts[9,22]. AM may enable the exploitation of new green materials simply because it is a different process.

LCAs should also be expanded to include context-dependent design decisions (i.e., how does part lightweighting influence the product's use phase?). We already discussed transportation aspects, but additional product life cycle phases should be considered. Part consolidation can be relevant for manufacturing operations and post-processing phases. Despite the high impact of AM per operation, their significant reduction could lead to a significant net benefit. Design could thus emerge as a fundamental mediating factor in AM's capability to support sustainable product development. While theoretical models of such tradeoffs have been performed[23], empirical research has not yet shown how often part consolidation replaces enough operations to pay back the extra energy per operation. Also, highly consolidated parts may be less repairable if they prevent disassembly and replacement. This has not yet been studied at scale to determine how frequently the cost outweighs the benefit.

Besides measuring impacts, AM processes, machines, and materials must be redesigned to improve impacts. One example is the Solar Sinter by Markus Kayser [24], which sinters sand into glass using a giant Fresnel lens, eliminating electric heating by passively focusing sunlight into a concentrated spot[24]. The print bed's motors and electronics are powered by solar photovoltaics, and the sand can be locally sourced. This is an extreme example, and no LCAs have yet been performed, but it suggests enormous improvements to AM processes and materials.

Another example is replacing melting of plastics with direct ink writing AM of bio-composite pastes that harden by drying[25]. Rael and San Fratello's binder jet printing of sawdust, grape skins, or salt has been measured to have 1/10th – 1/40th of the impacts per part printed as other polymer print technologies[26]. Though the strength of bio-composite pastes is much lower than standard polymers, redesigned parts could have five times the wall thickness, using five times as much material, while still having half the impact of most other AM parts. Such low-energy printing of upcycled biomaterials can include multiple materials with different strengths, stiffnesses, colors, or other properties[27]. Furthermore, AM can enable more expensive novel materials to become economically viable due to optimized designs using less material, especially if printing consolidates manufacturing steps and thus saves labor or other processing costs. Including a material's end-of-life impacts enables comparisons of new materials with better recyclability or compostability. Current multi-material printing renders even commonly recyclable polymers non-recyclable because they cannot be easily separated from each other, accumulating impurities. Recovering unprinted metal powder of mixed materials is also challenging[28], and recyclable multi-material prints require entirely new printers with different processes[29]. Multi-material prints can be easily recovered at end-of-life if all ingredients are compostable. Compost generally requires no sorting after removing non-compost trash. Some marginally compostable materials require higher temperature facilities to biodegrade, but these facilities also process easily compostable materials.

Sustainable design tools and methods could be applied to make such improvements more systematic. Some studies have already cut the environmental impacts of printing through these methods, though such progress needs further development to scale to industry[30].

Prioritizing sustainability as a performance requirement when developing printers and materials, even without special design methods, would drive significant progress. Examples could be designing metal alloys tolerant to impurities to enable more recycling[22] or architected materials with advanced mechanical properties[9] to prevent the need for high-performance materials. However, making sustainability a required design specification is the first step.

The second step is learning and using sustainable design tools and methods to help achieve those goals. This should include s*ystem thinking,* i.e., looking at the whole system when considering impacts and generating new solutions. It can increase creativity while avoiding optimizing one part to the detriment of the whole. Several methods for supporting its adoption exist in sustainable design[31–33]. However, even without them, the basic concept can be powerful. One example is finding materials that solidify chemically at room temperature rather than being melted. Sourcing these from agricultural waste (e.g., pecan shells or sawdust) has been shown to reduce print energy by 75% and reduce material impacts by 80% compared to standard melting (MEX) of ABS plastic, reducing material costs by 50%[30]. However, they are not yet a drop-in replacement for plastics.

AM parts could be improved by incorporating design for sustainability into existing DfAM principles and heuristics[34]. LCA might be integrated into existing optimization software to guide material choice, process parameters, and geometry. Designers should be trained to accept that, from a sustainability point of view, the material with the best mechanical performance is not always the rational choice unless other gains justify its application. Besides, there is the need for data-driven design support tools capable of addressing challenges of improving sustainability from a system-thinking perspective[35]. Such tools should advance material discovery for sustainability[36] and drive the optimized distribution of materials to reduce the environmental impact[9]. They should support AM holistically, involving data-sharing among stakeholders and providing computational support to allow informed decisions.

Besides, we must include social issues when reflecting on where AM should go. Unfortunately, the social dimension is rarely considered. AM's positive or negative impacts on fair wages, wealth inequality, political power inequality, community support, and other cultural factors are currently challenging to assess. Methodologies for measuring these impacts are not as detailed or agreed upon as environmental metrics. Some case studies[37] and methodological suggestions[38] exist, but the state of research is still exploratory[39]. AM tools generally require less operator time than Computer Numerical Controlled machining. This could be considered favorable for decreasing labor burden or negative for increasing unemployment. OECD's recommendations suggest that AM may assist entrepreneurs by lessening their need for capital in manufacturing tooling, thus opening more opportunities to the lower and middle classes[6]. However, this is a hypothesis not yet backed up by empirical studies.

The role of AM in democratizing manufacturing has been recognized widely, given the adoption of consumer-grade AM systems in homes, maker spaces, and schools[40]. It has also stimulated noteworthy cultural transformations. The continuous shift from the abstract to the physical world helps unlock our imagination[41]. AM strongly supports this shift, particularly the role of inexpensive, desktop-scale MEX systems in stimulating students' creativity and consciousness about their abilities. However, promoting a culture of sustainable prototyping and manufacturing among the young generation is also essential, e.g., by discouraging the printing of the so-called *phatic objects,* namely *"objects printed without a real purpose"*[42], favoring strategies involving repairing and adjustment[42]. Promoting this culture also requires the availability of affordable solutions and practices to enable the reuse or recycling of failed prints or those prints that have reached their end-of-life.

One social aspect already studied in detail is worker health and safety regarding material toxicity hazards. This overlaps extensively with the environmental sustainability of materials. Quantitative empirical studies have investigated the outgassing of particulates that could be inhaled while printing polymers[43,44] or metals[45]; others have investigated the toxicity of printed parts themselves[46,47]. Some fine powders, such as aluminum, have long been known to be explosion hazards[48]. However, these studies lack direct comparisons to CM. Future works should make such comparisons and examine new AM materials that reduce health and safety risks to workers and environmental impacts. Consequences to stakeholders upstream in the life cycle must also be included. Decisions in the early design phase, such as material selection for AM, may impact local communities, e.g., conflict materials, land grabbing, and working conditions in supply chains.

Sustainable-by-design with AM

AM's contribution to sustainable growth can be further raised if AM technologies are used to implement established practices in sustainable design. The digital transition and sustainable development comply with scenarios where radical changes are needed and, to some extent, are already taking place. Despite the AM community being ready to accept these transformations and demonstrating a significant commitment, indications are still lacking on aligning this transformation with principles for a sustainable society[49]. Although the relationship between Sustainable Design and DfAM seems evident, a standard list of shared principles and strategies is lacking. As Sustainable Design has evolved, some sub-disciplines have matured enough to represent independent research areas[55], including sustainability-oriented Design for X (DfX) methods. AM could be a means for consolidating and successfully applying such methods[50]. How to reach this is discussed below.

Design for product repair and maintenance

This method promotes designing product architectures for easy disassembly and reassembly to service or replace parts[51,52]. AM can fabricate replacements on-demand instead of manufacturers storing spare parts for years. Alternatively, AM can produce parts the manufacturer no longer supplies[53]. This often requires redesigning parts for AM because current parts are designed for other manufacturing methods; this is time-consuming, but methods for such redesign are being developed[54]. Companies should be prepared to manage the integration of printed parts within already consolidated product architectures. Fundamental limits exist to what replacement parts can be printed today (e.g., circuit boards and chips are difficult or impossible). Researchers estimate that at most 7.5 – 29% of repairs in repair cafés might be helped by AM spare parts[55]. Since mass-scale production usually has a lower impact in the case of CM, AM is currently most useful for replacing parts not supplied by manufacturers or fixing large parts in situ[56]. Data-driven design for repair via AM is underexploited[57], and it is unclear how much intelligent AM and design[58] could improve this.

Design for Upgradability

This method targets improving and updating components to meet changing customer expectations to prolong product lifetimes[59,60]. New or improved functionalities can be added thanks to easy-to-upgrade features in the design[60]. Design for Upgradability also works for CM, but AM represents a powerful tool when products are not designed for CM, or the manufacturer does not provide upgrade parts[53]. AM also has an advantage when upgrades involve "customization" or "personalization". Personalization could extend product life due to the user establishing emotional attachment. In the area of AM, it is unclear how effective this will be for sustainability. The same attribute could stimulate worse consumerism. Insufficient research exists to show actual benefits versus costs in practice. It is worth investigating, but setting an ethical threshold concerning personalization is a complex strategy. How to support companies in guaranteeing both the profitability and sustainability of their upgrade services and whether AM alone or hybrid AM-CM strategies should be leveraged are open issues to be explored.

Design for Remanufacturing or Reuse

This method aims to give parts a second life after their first lifecycle[61], focusing on their easy disassembly and reassembly into a new product or a direct reuse[62]. As with repair, parts can be provided by CM or AM. Since current remanufacturing rarely happens at scale, AM has many opportunities to support designing parts that can be easily disassembled with the least damage or repaired after the disassembly if the damage occured[63]. Developing guidelines[64], decision support[65], and smart systems[66] facilitates Design for Remanufacturing, which can, in turn, be supported by AM[67] or hybrid AM-CM processes[68]. The suitability of AM for remanufacturing has led to the proposal of shared guidelines on Design for Additive Remanufacturing[63]. There is a growing interest in it[69], with a call for more automation[70], even if multiple open issues must be addressed, such as the durability of AM components or improving repair and restoration phases[69]. As with repair, depending on the production scale, AM of replacement parts can cause higher impacts than CM remanufacturing parts, just as it does for virgin product production. Break-even points should be identified[71].

Design for Recycling

Even if less effective than other Circular Economy (CE) approaches, Design for Recycling plays a fundamental role in extracting value from waste[72]. The challenge with recycling is that the raw material is usually downcycled, i.e., it loses its original quality and properties[73]. AM already allows the processing of thermoplastic materials with different percentages of recycled content[74]. However, further research is needed to understand how to collect the waste and treat the recycled material properly[75], since many printers are not robust to impurities in feedstocks. Some AM studies have also explored upcycling agricultural waste into semi-durable goods[30], though more development is required for commercial viability. Boosting market demand for secondary plastics is also essential[76]. Multi-material printing and the possibility of embedding electronics[77] could make the recycling process even more challenging. The chemodiversity of materials affects recycling[78]. Studies on multi-material printing must continue, but recyclability must be considered unless it is demonstrated that the new multi-material solution can significantly improve the product lifecycle.

Ongoing issues

These DfX fields have overlapping borders[57,61,67] because of commonly shared objectives. What is indisputable is their support for fulfilling CE goals and the central role AM can play[53].

In addition, there is difficulty in assessing which DfX strategy to follow to best comply with CE principles, i.e., design out waste and pollution, keep products and materials in use, or regenerate natural systems[79]. This aspect transcends the AM field and is a shared open issue across domains. Besides, we also face methodological challenges concerning developing robust tools to support policymakers in strengthening the uptake of CE[80].

A future scenario

Systems thinking is an enabler of sustainable AM, and helps AM enable other sustainable design. It urges designers to consider multiple aspects of product lifecycles, from materials procurement to usage scenarios and end-of-life. Manageable closed loops can be essential for AM to support sustainable development, thus strengthening AM's role in facilitating CE practices. To enable this, a new role for AM should be envisioned. Figure 1 illustrates a vision of a sustainable AM production system scenario.

Figure 1 assumes that AM is used in a digital, flexible, and adaptable manufacturing system strategy for circular material flows and recursive improvement cycles. This vision incorporates the previously discussed aspects of where AM should develop and how sustainable-by-design with AM can be leveraged, and it is founded on the following assumptions:

- AM supports the scale-up of production volumes in multiple industrial fields;
- AM is used for manufacturing final parts and products, together with spare parts for repair, refurbishment, and upgrade to prolong product lifetime;
- A new generation of AM technologies and materials are exploited, whose impacts and life cycle are improved;
- Implementing sustainable-by-design with AM methods represents a consolidated strategy that allows design engineers to make informed design choices concerning raw materials, the component in-service resource consumption, and socio-technical effects (e.g., repair and remanufacturing).

Everything starts with the *Raw Materials.* They are crucial since materials give physicality to ideas. Products should be designed and produced with bio-based or recycled material components. Also, recycled content from other industrial processes can be used to transform a cost into a new business opportunity.

In parallel, *Part Design* is performed. The product’s design solution should consider sustainability, functional, and aesthetic requirements. Sustainable design tools should be exploited to identify sustainability hot spots in the product life cycle and minimize impacts during raw material acquisition, manufacturing, usage, and return-to-life phases. Design requirements should include responsible material choice, optimal resource use in manufacturing, elimination of hazardous substances, safe working conditions, product lifetime and resource usage optimization, and the proper management of parts’ end-of-life.

The design requirements considered for the *Part Design* are also relevant for the *Printer Design* because AM process and machine impacts are embodied in the manufactured products. Optimizing energy consumption in the printing phase is strategic; increasing the machine's ‘smartness’ to minimize production waste and prevent failed prints, plus reuse what waste exists, is essential.

Once the *raw material is manufactured* and the part and printer design are complete, the *Printing* can start. Although our view is oriented to AM, AM and CM processes will integrate or hybridize to optimize sustainable manufacturing. CM can be combined to overcome some acknowledged limits of AM to foster the adoption of win-win schemes in manufacturing. Once successful strategies in AM are identified, they could also be tailored to work for CM. What little waste from this step and previous manufacturing stages exists should be recirculated and reused through dedicated recycling/composting processes. In addition, the possibility of sharing information related to the operating phase of the machine directly with the machine manufacturer could provide helpful feedback for the design of the next generation of machines. Conversely, the machine manufacturers will have to share the best practices leading to the optimal use of their systems. In this phase, attention must be paid to the equipment characteristics and the processes implemented. The AM system hardware (e.g., motors, extruders, lasers) is relevant in environmental assessments. Likewise, the energy needed to make AM systems work is critical to the sustainability of the process. This situation can be alleviated by minimizing energy consumption and using renewable energy sources.

Finished parts will enter an assembly cycle, and the product life will start after production. That is the *Product Manufacture & Life Cycle* phase. During this phase, collecting information about the product operating conditions can provide valuable data for designing the next generation of products. The product may also be subjected to repair, which can extend its useful life. The information retrieved during the maintenance phase is another relevant feedback for the *Part Design* phase. At the end of the use phase, two situations could occur: 1) users have developed a strong attachment to the product and require an upgrade, or 2) a new life starts for the product in other users' hands through remanufacturing or refurbishment, likewise supported by AM. The information gathered during these phases is essential to update the know-how guiding new product design.

When the product definitively ends its useful life, it is processed, disassembled, and reintroduced as recycled material or components that can undergo a remanufacturing cycle. In the hypothesis that no hazardous materials are present in the product, everything will be reused, recycled, or composted.

The role of policymakers in this scenario is to make decisions that provide guidance and tools for driving sustainability in all phases. Tools that can promote the proposed actions in the scenario are currently lacking. Let this be a call for more studies examining policy design in relation to sustainable AM and investigating impacts on workers, entrepreneurs, and society.

AM is not inherently circular or sustainable, but this scenario shows how AM can support sustainable development and CE. Exploring these possibilities is now required, with AM’s weight in the global manufacturing scenario becoming relevant soon. AM has not yet finished scaling, and technologies are still evolving. Hence, there is still time for action, before they become entrenched. Simultaneously, consumption cycles and how we conceptualize product life must be transformed. Each product has a history that must be valued. Each material can create value for a product. From waste, we can create value. Refurbished components can contribute to increasing the added value of new products, and innovations in AM and DfAM can thus contribute to developing this value. A vision for sustainable additive manufacturing will happen only if all the actors and stakeholders involved in the product value chain have a synergy of intents and commitment toward sustainability targets.

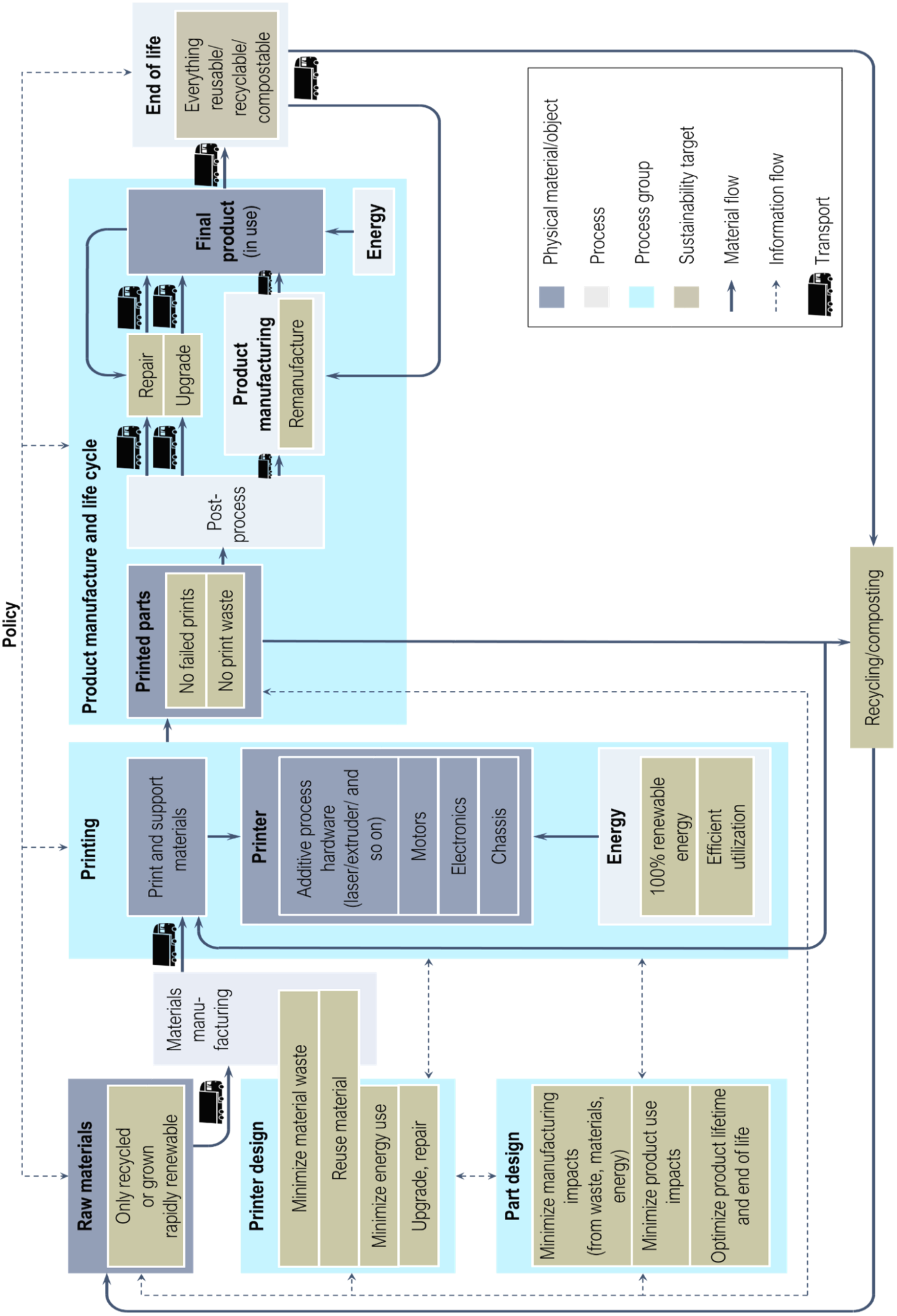

Fig. 1. A scenario for sustainable AM driving sustainable product development.

References

1. Gibson, I., Rosen, D., Stucker, B. & Khorasani, M. *Additive Manufacturing Technologies*. (Springer International Publishing, Cham, 2021). doi:10.1007/978-3-030-56127-7. **This book comprehensively overviews Additive Manufacturing technologies, detailing the main process principles, materials, design opportunities, and digital workflow.**
2. Precedence Research. Additive Manufacturing Market. https://www.precedenceresearch.com/additive-manufacturing-market (2023).
3. *ISO/ASTM 52900:2021, Additive Manufacturing — General Principles — Fundamentals and Vocabulary*. (2021).
4. Thompson, M. K. *et al.* Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals* **65**, 737–760 (2016).
5. Rosen, D. & Wong, J. Introduction to Design for Additive Manufacturing. in *Additive Manufacturing Design and Applications* 1–14 (ASM International, 2023). doi:10.31399/asm.hb.v24A.a0006947.
6. OECD. *The Next Production Revolution: Implications for Governments and Business*. (OECD Publishing, Paris, Paris, 2017). doi:10.1787/9789264271036-en.
7. Telenko, C. & Seepersad, C. A comparison of the energy efficiency of selective laser sintering and injection molding of nylon parts. *Rapid Prototyp J* **18**, 472–481 (2012).
8. Azevedo, J. M. C., CabreraSerrenho, A. & Allwood, J. M. Energy and material efficiency of steel powder metallurgy. Powder Technol **328**, 329–336 (2018). **This paper shows by an example how to objectively consider and analyze different aspects of a possible future manufacturing scenario in which AM would be scaled up to current production volumes.**
9. Raabe, D., Tasan, C. C. & Olivetti, E. A. Strategies for improving the sustainability of structural metals. *Nature* **575**, 64–74 (2019).
10. Shi, Y. & Faludi, J. Using Life Cycle Assessment To Determine If High Utilization Is The Dominant Force For Sustainable Polymer Additive Manufacturing. *Addit Manuf* **35**, 101307 (2020).
11. Liu, J. *et al.* Current and future trends in topology optimization for additive manufacturing. *Structural and multidisciplinary optimization* **57**, 2457–2483 (2018).
12. Priarone, P. C. & Ingarao, G. Towards criteria for sustainable process selection: On the modelling of pure subtractive versus additive/subtractive integrated manufacturing approaches. *J Clean Prod* **144**, 57–68 (2017).
13. Takeda, O. & Okabe, T. H. Current status of titanium recycling and related technologies. *Jom* **71**, 1981–1990 (2019).
14. Khorram Niaki, M. & Nonino, F. *The Management of Additive Manufacturing*. (Springer International Publishing, Cham, 2018). doi:10.1007/978-3-319-56309-1.

15. Van Sice, C. & Faludi, J. COMPARING ENVIRONMENTAL IMPACTS OF METAL ADDITIVE MANUFACTURING TO CONVENTIONAL MANUFACTURING. *Proceedings of the Design Society* **1**, 671–680 (2021).

16. Gutowski, T. *et al.* Note on the Rate and Energy Efficiency Limits for Additive Manufacturing. *J Ind Ecol* **21**, S69–S79 (2017).

17. Yi, L. & Aurich, J. C. Energy performance evaluation of selective laser melting. *Procedia CIRP* **105**, 559–564 (2022).

18. Jørgen Hanssen, O. Environmental impacts of product systems in a life cycle perspective. *J Clean Prod* **6**, 299–311 (1998).

19. Pörtner, H. O. *et al. Climate Change 2022: Impacts, Adaptation and Vulnerability*. https://edepot.wur.nl/565644 (2022).

20. Kellens, K. *et al.* Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. *J Ind Ecol* **21**, (2017).

21. Faludi, J., Baumers, M., Maskery, I. & Hague, R. Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate? *J Ind Ecol* **21**, S144–S156 (2017).

22. Olivetti, E. A. & Cullen, J. M. Toward a sustainable materials system. *Science* **360**, 1396–1398 (2018). **This paper promotes a systemic view towards achieving sustainable products by considering the environmental life cycle of materials.**

23. Yang, S., Min, W., Ghibaudo, J. & Zhao, Y. F. Understanding the sustainability potential of part consolidation design supported by additive manufacturing. *J Clean Prod* **232**, 722–738 (2019).

24. Markus Kayser. Solar Sinter Project. (Royal College of Art, 2011).

25. Rosenthal, M., Henneberger, C., Gutkes, A. & Bues, C.-T. Liquid Deposition Modeling: a promising approach for 3D printing of wood. *European journal of wood and wood products* **76**, 797–799 (2018).

26. Ronald Rael & Virginia San Fratello. *Printing Architecture: Innovative Recipes for 3D Printing*. (Princeton Architectural Press, 2018).

27. Mogas-Soldevila, L., Duro-Royo, J. & Oxman, N. Water-Based Robotic Fabrication: Large-Scale Additive Manufacturing of Functionally Graded Hydrogel Composites via Multichamber Extrusion. *3D Print Addit Manuf* **1**, 141–151 (2014).

28. Horn, M. *et al.* Multi-Material Additive Manufacturing – Recycling of binary Metal Powder Mixtures by Screening. *Procedia CIRP* **93**, 50–55 (2020).

29. Hiller, J. D. & Lipson, H. Fully Recyclable Multi-Material Printing. in *2009 International Solid Freeform Fabrication Symposium* (University of Texas at Austin, 2009). doi:10.26153/tsw/15092.

30. Faludi, J., Van Sice, C. M., Shi, Y., Bower, J. & Brooks, O. M. K. Novel materials can radically improve whole-system environmental impacts of additive manufacturing. *J Clean Prod* **212**, 1580–1590 (2019). **This paper provides a foundational study on novel, bio-based, AM materials, supported by a system-level analysis of their sustainability impacts.**

31. Byggeth, S., Broman, G. & Robèrt, K.-H. A method for sustainable product development based on a modular system of guiding questions. *J Clean Prod* **15**, 1–11 (2007).

32. Hallstedt, S. I. & Isaksson, O. Material criticality assessment in early phases of sustainable product development. *J Clean Prod* **161**, 40–52 (2017).

33. Hallstedt, S. I. Sustainability criteria and sustainability compliance index for decision support in product development. *J Clean Prod* **140**, 251–266 (2017). **This paper provides a novel approach to define the sustainability design space and long-term sustainability criteria of a product solution, considering the complete life cycle.**

34. Blösch-Paidosh, A. & Shea, K. Industrial evaluation of design heuristics for additive manufacturing. *Design Science* **8**, e13 (2022).

35. Alexander, S. M. *et al.* Qualitative data sharing and synthesis for sustainability science. *Nat Sustain* **3**, 81–88 (2020).

36. Gomes, C. P., Fink, D., Van Dover, R. B. & Gregoire, J. M. Computational sustainability meets materials science. *Nat Rev Mater* **6**, 645–647 (2021).

37. Soares, B. *et al.* Social life cycle performance of additive manufacturing in the healthcare industry: the orthosis and prosthesis cases. *Int J Comput Integr Manuf* **34**, 327–340 (2021).

38. Naghshineh, B., Ribeiro, A., Jacinto, C. & Carvalho, H. Social impacts of additive manufacturing: A stakeholder-driven framework. *Technol Forecast Soc Change* **164**, 120368 (2021).

39. Matos, F. & Jacinto, C. Additive manufacturing technology: mapping social impacts. *Journal of Manufacturing Technology Management* **30**, 70–97 (2018).

40. Alemán, M. W., Tomko, M. E., Linsey, J. S. & Nagel, R. L. How do you play that makerspace game? An ethnographic exploration of the habitus of engineering makerspaces. *Res Eng Des* **33**, 351–366 (2022).

41. Brown, T. *Change by Design. How Design Thinking Transforms Organizations and Inspires Innovation*. (HarperCollins Publishers Inc, 2019).

42. Bosqué, C. What are you printing? Ambivalent emancipation by 3D printing. *Rapid Prototyp J* **21**, 572–581 (2015).

43. Stephens, B., Azimi, P., El Orch, Z. & Ramos, T. Ultrafine particle emissions from desktop 3D printers. *Atmos Environ* **79**, 334–339 (2013).

44. Azimi, P., Fazli, T. & Stephens, B. Predicting concentrations of ultrafine particles and volatile organic compounds resulting from desktop 3D printer operation and the impact of potential control strategies. *J Ind Ecol* **21**, (2017).

45. Chen, R. *et al.* Exposure, assessment and health hazards of particulate matter in metal additive manufacturing: A review. *Chemosphere* **259**, 127452 (2020).

46. Oskui, S. M. *et al.* Assessing and Reducing the Toxicity of 3D-Printed Parts. *Environ Sci Technol Lett* **3**, 1–6 (2016).

47. Tedla, G., Jarabek, A. M., Byrley, P., Boyes, W. & Rogers, K. Human exposure to metals in consumer-focused fused filament fabrication (FFF)/ 3D printing processes. *Science of The Total Environment* **814**, 152622 (2022).
48. Mason, R. B. & Taylor, C. S. Explosion of aluminum powder dust clouds. *Ind Eng Chem* **29**, 626–631 (1937).
49. Broman, G. I. & Robèrt, K.-H. A framework for strategic sustainable development. *J Clean Prod* **140**, 17–31 (2017). **This paper presents a framework including overarching socio-ecological sustainability principles used from a backcasting perspective for defining a sustainability vision.**
50. Yang, S. & Zhao, Y. F. Additive manufacturing-enabled design theory and methodology: a critical review. *The International Journal of Advanced Manufacturing Technology* **80**, 327–342 (2015). **This review paper analyzes the suitability of engineering design theory and methodology to support DfAM and finds it lacking since it does not encourage the development of creative ideas that benefit from AM's potential.**
51. Ackermann, L. Design for Product Care: Enhancing Consumers' Repair and Maintenance Activities. *The Design Journal* **21**, 543–551 (2018).
52. De Fazio, F., Bakker, C., Flipsen, B. & Balkenende, R. The Disassembly Map: A new method to enhance design for product repairability. *J Clean Prod* **320**, 128552 (2021).
53. Sauerwein, M., Doubrovski, E., Balkenende, R. & Bakker, C. Exploring the potential of additive manufacturing for product design in a circular economy. *J Clean Prod* **226**, 1138–1149 (2019). **This article provides a wide perspective on the opportunities enabled by AM when it comes to designing products while aiming at the realization of CE principles and includes insights from both the literature and empirical research.**
54. Bolaños Arriola, J., van Oudheusden, A. A., Flipsen, B. & Faludi, J. *3D Printing for Repair Guide*. (TU Delft OPEN Publishing, Delft, 2022). doi:10.5074/t.2022.003.
55. Samenjo, K., van Oudheusden, A., Arriola, J. B., Flipsen, B. & Faludi, J. Opportunities For 3D-printable Spare Parts: Estimations From Historical Data. in *PLATE 2021: the 4th Conference on Product Lifetimes and the Environment* (2022).
56. Wilson, J. M., Piya, C., Shin, Y. C., Zhao, F. & Ramani, K. Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis. *J Clean Prod* **80**, 170–178 (2014).
57. Aziz, N. A., Adnan, N. A. A., Wahab, D. A. & Azman, A. H. Component design optimisation based on artificial intelligence in support of additive manufacturing repair and restoration: Current status and future outlook for remanufacturing. *J Clean Prod* **296**, 126401 (2021).
58. Xiong, Y., Tang, Y., Zhou, Q., Ma, Y. & Rosen, D. W. Intelligent additive manufacturing and design: state of the art and future perspectives. *Addit Manuf* **59**, 103139 (2022).
59. Go, T. F., Wahab, D. A. & Hishamuddin, H. Multiple generation life-cycles for product sustainability: the way forward. *J Clean Prod* **95**, 16–29 (2015).

60. Aziz, N. A., Wahab, D. A., Ramli, R. & Azhari, C. H. Modelling and optimisation of upgradability in the design of multiple life cycle products: a critical review. *J Clean Prod* **112**, 282–290 (2016).

61. Lindkvist Haziri, L. & Sundin, E. Supporting design for remanufacturing - A framework for implementing information feedback from remanufacturing to product design. *Journal of Remanufacturing* **10**, 57–76 (2020).

62. Potting, J., Hekkert, M., Worrell, E. & Hanemaaijer, A. Circular Economy: Measuring innovation in product chains. in (ed. PBL Netherlands Environmental Assessment Agency) (The Hague, 2016).

63. Schlesinger, L., Koller, J., Pagels, M. & Döpper, F. Alignment of design rules for additive manufacturing and remanufacturing. *Journal of Remanufacturing* (2022) doi:10.1007/s13243-022-00122-9.

64. Charter, M. & Gray, C. Remanufacturing and product design. *International Journal of Product Development* **6**, 375 (2008).

65. Yang, S. S., Ong, S. K. & Nee, A. Y. C. A Decision Support Tool for Product Design for Remanufacturing. *Procedia CIRP* **40**, 144–149 (2016).

66. Ke, C., Jiang, Z., Zhang, H., Wang, Y. & Zhu, S. An intelligent design for remanufacturing method based on vector space model and case-based reasoning. *J Clean Prod* **277**, 123269 (2020).

67. Kandukuri, S., Günay, E. E., Al-Araidah, O. & Okudan Kremer, G. E. Inventive solutions for remanufacturing using additive manufacturing: ETRIZ. *J Clean Prod* **305**, 126992 (2021).

68. Liu, J., Zheng, Y., Ma, Y., Qureshi, A. & Ahmad, R. A Topology Optimization Method for Hybrid Subtractive–Additive Remanufacturing. *International Journal of Precision Engineering and Manufacturing-Green Technology* **7**, 939–953 (2020).

69. Kanishka, K. & Acherjee, B. A systematic review of additive manufacturing-based remanufacturing techniques for component repair and restoration. *J Manuf Process* **89**, 220–283 (2023).

70. Kerin, M. & Pham, D. T. A review of emerging industry 4.0 technologies in remanufacturing. *J Clean Prod* **237**, 117805 (2019).

71. Ardente, F., Talens Peiró, L., Mathieux, F. & Polverini, D. Accounting for the environmental benefits of remanufactured products: Method and application. *J Clean Prod* **198**, 1545–1558 (2018).

72. King, S. Recycling our way to sustainability. *Nature* **611**, S7–S7 (2022).

73. Syberg, K. Beware the false hope of recycling. *Nature* **611**, S6–S6 (2022).

74. Mikula, K. *et al.* 3D printing filament as a second life of waste plastics—a review. *Environmental Science and Pollution Research* **28**, 12321–12333 (2021).

75. Cruz Sanchez, F. A., Boudaoud, H., Camargo, M. & Pearce, J. M. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *J Clean Prod* **264**, 121602 (2020).

76. DeWeerdt, S. How to make plastic less of an environmental burden. *Nature* **611**, S2–S5 (2022).
77. Jiang, R., Kleer, R. & Piller, F. T. Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technol Forecast Soc Change* **117**, 84–97 (2017).
78. Zuin, V. G. & Kümmerer, K. Chemistry and materials science for a sustainable circular polymeric economy. *Nat Rev Mater* **7**, 76–78 (2022).
79. de Oliveira, C. T. & Oliveira, G. G. A. What Circular economy indicators really measure? An overview of circular economy principles and sustainable development goals. *Resour Conserv Recycl* **190**, 106850 (2023).
80. Polverini, D. Regulating the circular economy within the ecodesign directive: Progress so far, methodological challenges and outlook. *Sustain Prod Consum* **27**, 1113–1123 (2021).

Correspondence should be addressed to Serena Graziosi.

Acknowledgements

The authors wish to acknowledge the Design Society (www.designociety.org) for supporting and promoting the activities of its Special Interest Groups (SIGs). This perspective paper results from a collaboration between the Design for Additive Manufacturing (DfAM) SIG and the Sustainable Design SIG.

Author contributions

S.G., J.F., T.S., Y.B., N.M., S.I.H., and D.W.R. contributed equally to conceptualizing, drafting, and revising the manuscript. S.G. coordinated the research team for the writing of the article.

Competing interests

The authors declare no competing interests.