

**ADDITIVE
MANUFACTURING
IN THE CIRCULAR
ECONOMY:**
OPPORTUNITIES AND
CONSTRAINTS FROM
A DESIGN PERSPECTIVE

Executive Summary

Since starting out as a rapid prototyping technology, Additive Manufacturing (AM) is now becoming a widely used production technology, capable of producing optimised end use components across a wide range of sectors. As its uptake increases and our awareness of the associated environmental impact grows, the true sustainability of AM will start to have a greater position in manufacturing decision making.

The circular economy (CE) is a systemic approach to economic development, which aims to improve upon the linear 'cradle-to-grave' model by eliminating the concept of waste. Whilst the environmental impact is important in this model, so are the economic and social implications which when balanced, enable an ideal sustainable product or process. This document identifies the potential for AM to fit into the CE through

the analysis of environmental, economic and social implications. The challenges AM faces to follow this approach are addressed and actions for further development are recommended.

These suggestions include:

- ▶ Developing a greater understanding of AM's life-cycle and collecting its data,
- ▶ Identifying how design for the environment (DfE) approaches can be tailored for design for AM (DfAM),
- ▶ Increasing the effectiveness of material recycling,
- ▶ Greater protection of intellectual property (IP) and control over regulated products,
- ▶ Gaining a deeper understanding of the hidden costs in AM.

1. Introduction

The popularity of Additive Manufacturing (AM) as an industrial manufacturing process is increasing as AM processes mature and their benefits are now being realised. This is indicated by new and novel processes emerging to meet current market needs, a rise in Technology Readiness Level (TRL) and a 21 percent year-over-year growth since 2019¹.

Despite this continuous growth, sustainability has not been at the forefront of AM strategy. In 2015, AM UK identified sustainability as a key development opportunity, but as of now, this has not yet been capitalised on². Therefore, the current gaps to meet this development opportunity can be identified by assessing AM's position in the circular economy.

This document identifies the current benefits and adoption constraints for AM in the circular economy, as well as identifying research gaps that can be exploited for further research. These will be addressed against three key models: the “circular economy”, “waste management hierarchy” and the “triple bottom line”. These models help to identify key elements that can be used to steer products and processes towards a circular economy approach. New tools and methodologies will be proposed that aid the design and manufacture of sustainable products through AM. Continued development of this area could help promote the use of AM, not only in performance driven applications, but also in sustainably-minded businesses where a more circular approach could bring about greater environmental, economic and social prosperity.

1 Hubs, Additive manufacturing trend report 2021, 2021, <https://www.hubs.com/get/trends/>

2 AM National Strategy, The Case for Additive Manufacturing, 2015 <http://www.amnationalstrategy.uk/wp-content/uploads/2015/05/AM-Strategy-Positioning-Paper.pdf>

2. The Circular Economy

As opposed to a linear economy (cradle-to-grave), where there is a distinct beginning and end to a product's life, a circular economy (cradle-to-cradle) attempts to eliminate waste through defined waste management strategies. These waste management strategies re-circulate waste back into the circular economy, minimising the need for new resources. This leads it to become a more self-sustaining model. Figure 1 illustrates an idealistic

circular economy where everything possible is done before resorting to landfill. An example from the plastics sector indicates a circular economy has the potential to reduce global plastic pollution in oceans by over 80%³. Although not directly related to AM or industrial manufacturing, these metrics provide an idea of the potential impact that could be achieved by moving towards a circular economy.

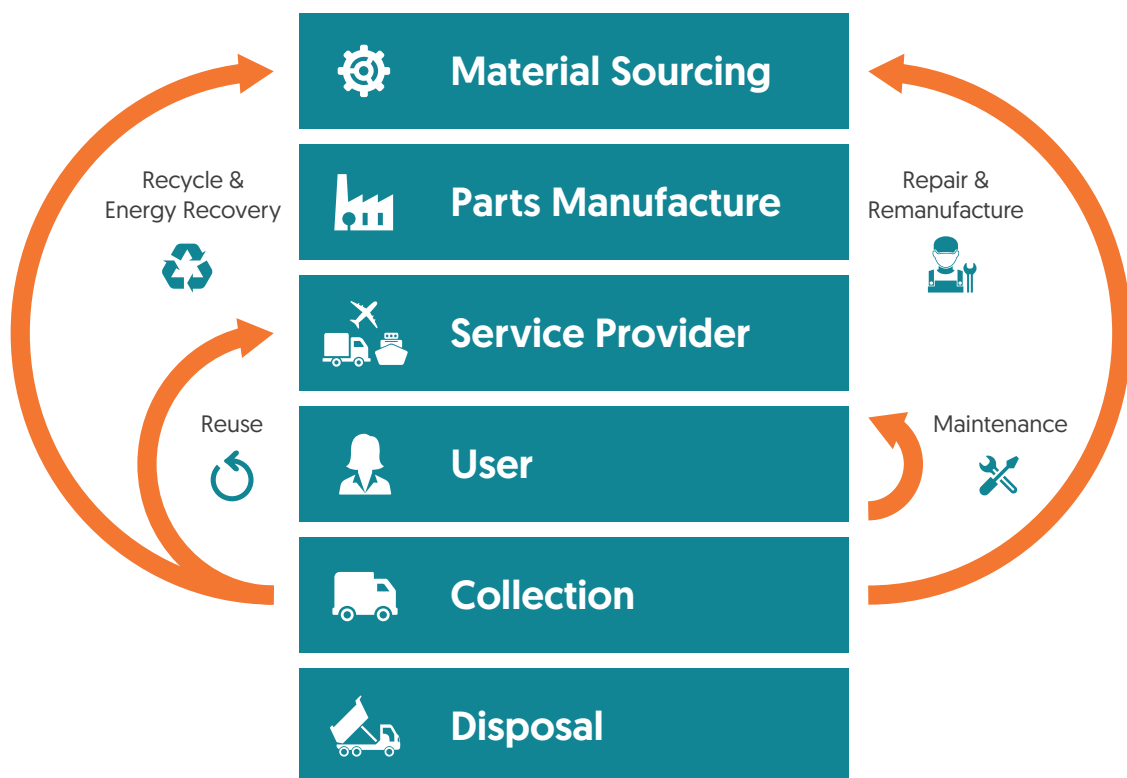


Figure 1: Outline of a circular economy

3 PEW, "Breaking the Plastic Wave", 2020, https://www.pewtrusts.org/-/media/assets/2020/10/breakingtheplasticwave_mainreport.pdf

2.1 Waste Management

Understanding where and when a product's environmental impacts can be minimised is critical to maintaining a circular economy. One method of identifying these aspects is by using the waste management hierarchy (Figure 2), which defines waste management methods. The most sustainable method is at the top of the inverted pyramid, with each subsequent method being less sustainable than the last, either using more resources or producing more waste.

Prevent

Prevention can be best achieved in the design phase where design for the environment (DfE) approaches can be implemented.

Re-use

Parts can be re-used through good maintenance or given new life through cleaning, inspection, refurbishment and fixing.

Repurpose

Parts can be given a second life through identifying new applications, which could be achieved through adaptations to the parts and re-manufacture.

Recycling

What waste material is created from manufacturing or at the end of life can be reprocessed into new feedstock material through mechanical, chemical or thermal processes.

Recovery

Where materials cannot be re-processed, the waste can still be captured and be used for energy harvesting or by products used for material production.

Disposal

This migrates from circular to a linear economy where there is no recovery of resources or energy to feed back into the cycle.

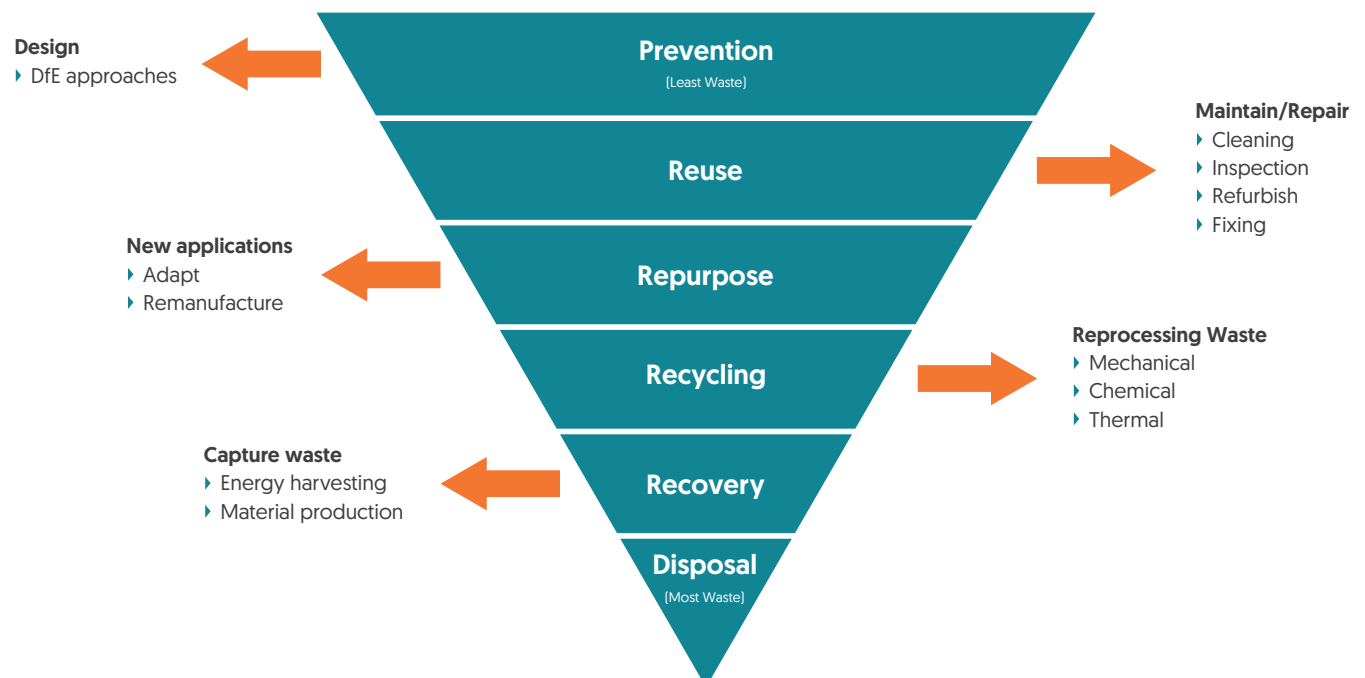


Figure 2: Waste management hierarchy⁴

⁴ DEFRA, "Guidance on applying the Waste Hierarchy," 2011, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69403/pb13530-waste-hierarchy-guidance.pdf

Prevention being the greatest waste management approach is backed up by the European Commission's estimate that over 80% of all product related environmental impacts can be influenced during the design phase⁵. DfE methodologies can be the most influential methods for sustainable products. These key DfE methodologies include:

- ▶ **Design for life extension** – extending the proposed life of the product to prevent the need for re-manufacture.
- ▶ **Waste source reduction design** – reducing the amount of material both in terms of the product itself and packaging.
- ▶ **Design for material substitution** – substituting to more sustainability superior materials.
- ▶ **Modular design** – easily interchanged and repaired as well as being adaptable to meet future needs.
- ▶ **Design for reusability** – standardising components so that they can be re-used in future products.
- ▶ **Design for disassembly** – improving the ease of disassembly in order to recover resources.
- ▶ **Design for recycling** – using high content of recyclable materials and allowing simple separation of dissimilar materials.
- ▶ **Design for energy recovery** – utilising materials that can be burned for energy recovery with minimal toxic or harmful emissions.
- ▶ **Design for disposability** – using materials that can be disposed of as ecologically as possible.

5 European Commission, A European Strategy for Plastics in a Circular Economy 2018 <https://cor.europa.eu/en/engage/studies/Documents/Plastic-Strategy.pdf>

2.2. Triple bottom line of Sustainability

Very few if any products have a positive impact on the environment. This is because each stage causes environmental implications from the need for continued resources and energy usage. However, prioritising the environmental impact of a product isn't enough to ensure it is sustainable since if there is no social benefit or profit to be raised, the product will not be bought or used.

The concept of producing a sustainable product or process is therefore one that minimises the negative environmental impact⁶ whilst maximising their economic and social impact. This forms the triple bottom line concept, illustrated in Figure 3.

Environmental (Planet) – minimising the impact a product, service or process has on the environment through the entire lifecycle.

Social (People) – ensuring decisions are made that benefit a wide population and not solely focused on one individual or group.

Economic (Profit) – delivering profitable outcomes.

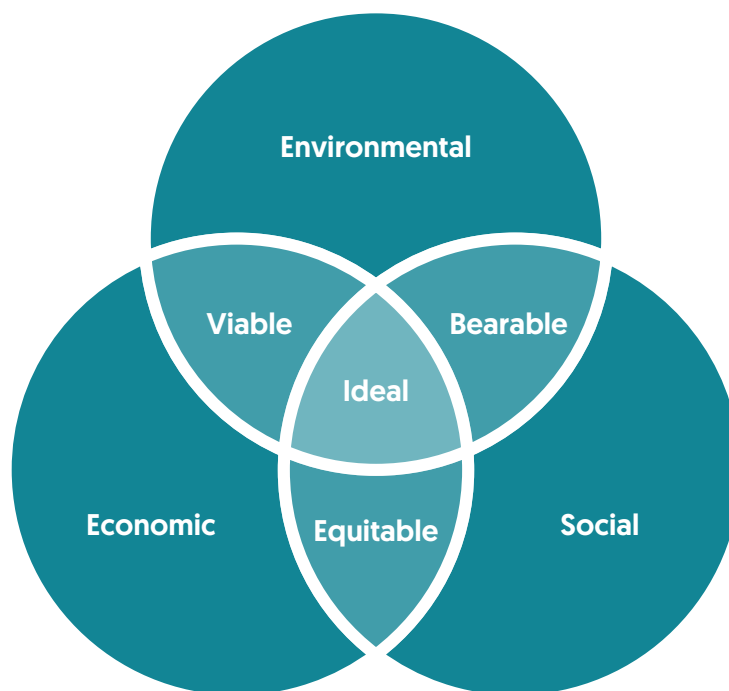


Figure 3: Triple bottom line

⁶ O. Diegel, S. Singamneni, S. Reay and A. Withell, "Tools for Sustainable Product Design: Additive Manufacturing," *Journal of Sustainable Development*, vol. 3, no. 3, pp. 68-75, 2010.

3. Potential for AM in the Circular Economy

The wide ranging capabilities of the many AM processes provides great opportunity to strategically align their benefits to the circular economy approach. With each process providing trade-offs between a range of factors such as material, resolution, production volume and post processing requirements, no one process is likely to provide all these benefits, however, it indicates ways in which these processes can be used for more sustainable manufacturing.

This section outlines the potential for AM in the circular economy by using key elements of the waste management hierarchy and the triple bottom line models.

3.1 Environmental Benefits

AM can provide environmental benefits that allow it to fit into a circular economy. These benefits can be highlighted through the waste management hierarchy, summarised in Figure 4 and with greater explanation in Table 1.

The environmental benefits have been categorised through using the waste management hierarchy, illustrating where the greatest benefits can be realised.

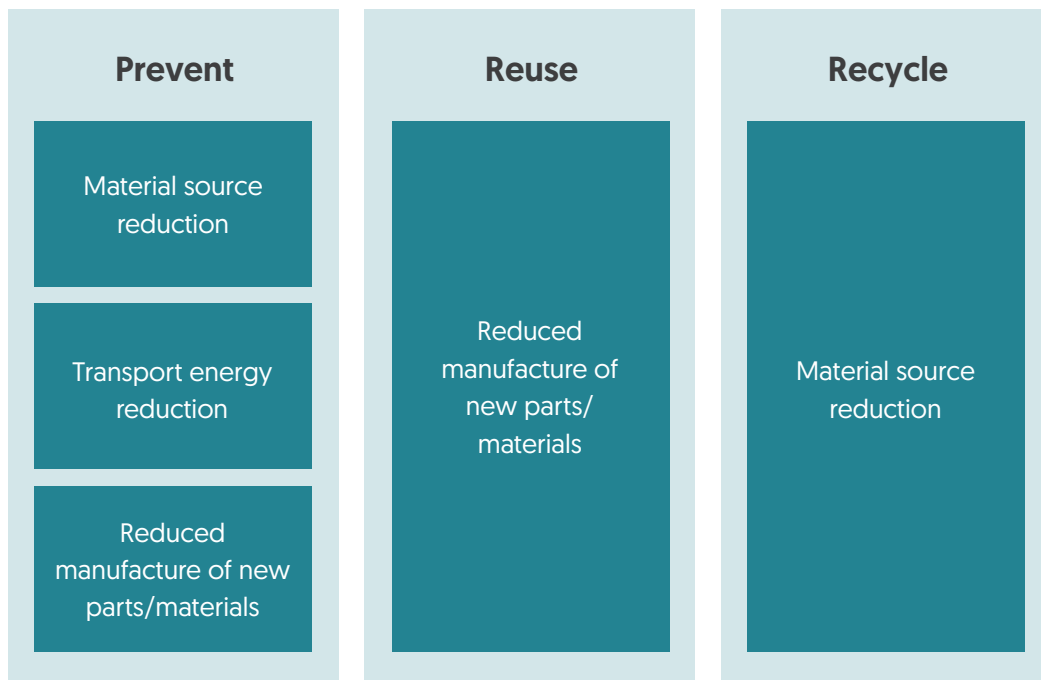


Figure 4: Environmental benefits of AM

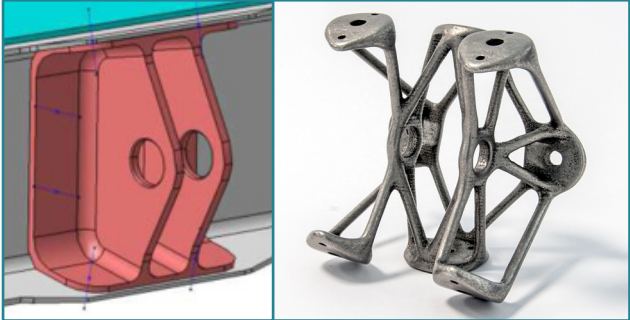
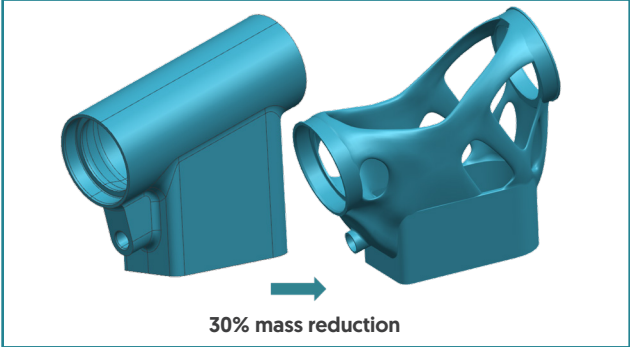
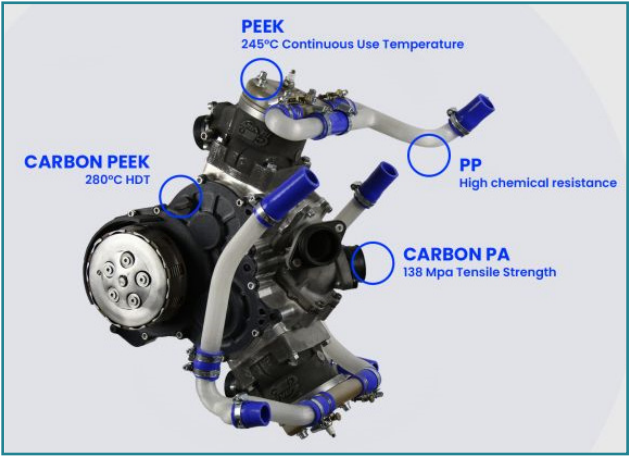
BENEFIT (Waste Management Technique)	EXPLANATION	IMAGE
<p>Prevention</p> <p>Material Source Reduction</p>	<p>The added geometric freedom in AM allows for highly optimised designs that require significantly less material than if designed for another manufacturing process. This as well as AM being a near net shape process, less material resources are required to produce the final component. In aerospace this is known as the buy to fly ratio and AM components can have a ratio below 2:1. In comparison, the same component machined from a billet may be as large as 15 - 1 and if cast then machined, around 4 -1.</p> <p>In a study by Digital Alloys, they found that CNC was 4.5 times more energy intensive per kg for a titanium part, mostly due to the energy required for mining and primary production of materials⁷.</p> <p>AM also allows for the production of parts directly from a CAD model. This means that in some applications tooling can be eliminated that would otherwise use resources and energy to produce as well as constraining the design which could further increase material usage.</p>	 <p>Waste material was reduced by 90% through utilising AM over the conventional machining process for the EWIRA bracket. (MTC)</p>
<p>Prevention</p> <p>Transport Energy Reduction</p>	<p>Energy associated with transportation can be significantly reduced by a lower mass component. This can include both transit of the part during shipping and active use in a transport application where there will be a fuel saving over the products life. Component re-design and targeted material substitution are the main methods to maximise this benefit through AM.</p> <p>Design for Additive Manufacturing (DfAM) methods such as topology optimisation and the use of lattices ensure material is only used where required, and can significantly increase stiffness whilst minimising mass. Furthermore, part consolidation can enable further weight reduction through removal of fasteners and connecting features. This also has a secondary benefit of optimising the overall system assembly.</p> <p>Composite materials and other high performance polymers such as carbon reinforced polymers and PEEK are able to challenge metals in some applications offering significant mass reduction as their densities are a lot lower.</p> <p>Titanium is a common metal used in AM, however it is much more challenging when used in conventional manufacturing processes, therefore, it may not have been considered for material selection. With titanium being almost half as dense as steel and boasting similar mechanical properties, using it in an AM process can offer mass savings even before it has been redesigned for AM.</p>	 <p>30% mass reduction</p> <p>Topology optimisation can reduce mass by suggesting where material should be used under certain loading conditions. (MTC)</p>  <p>PEEK 245°C Continuous Use Temperature</p> <p>CARBON PEEK 280°C HDT</p> <p>PP High chemical resistance</p> <p>CARBON PA 138 Mpa Tensile Strength</p> <p>High performance polymers are less dense than metals and have the potential to replace metal in specific applications. (Image courtesy of Roboze)⁸</p>

Table 1: Explanation of environmental benefits associated with AM

- 7 Digital Alloys, "Energy Consumption in Metal Additive Manufacturing," Digital Alloys, 28 03 2019 <https://www.digitalalloys.com/blog/energy-consumption-metal-additive-manufacturing/>
- 8 A. Lorusso, "Re-think Manufacturing. Re-shore Production," 2020 <https://www.cecimo.eu/wp-content/uploads/2020/11/Alessio-L.-Roboze.pdf>.

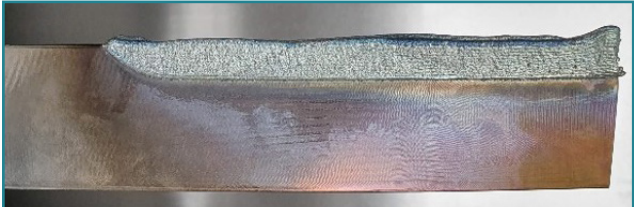

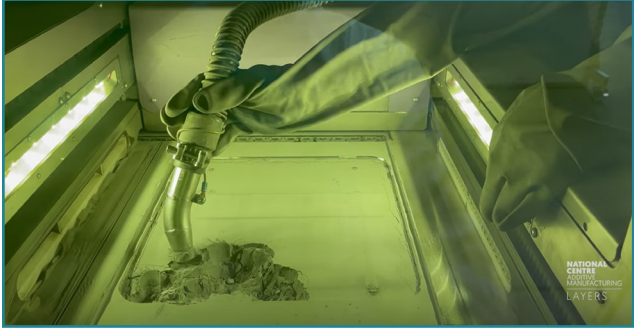
<p>Prevention</p> <p>Reduced Manufacture of New Parts/ Materials</p>	<p>The greater freedom and customisation offered by AM can ensure products are highly optimised for the intended application. This can lead to increased desirability or emotive connection that is commonly linked with prolonged product life.</p> <p>Assemblies can be made up of parts with different lifespans and therefore risk being disposed of at the first failure of a component. AM allows legacy parts to be manufactured even if tooling was used originally, allowing these parts to be re-produced easily in low volumes. The lowering of cost barriers to acquire a desktop AM machine and their increase in production quality allow consumers to replace and even upgrade parts to extend product life.</p>		<p><i>A customised prosthetic is optimised for the customer. The potential increased emotive connection with a custom design can be linked to increased product life. [MTC]</i></p>
<p>Reuse</p> <p>Reduced Manufacture of New Parts/ Materials</p>	<p>In some AM processes like directed energy deposition (DED), material can be added onto a worn or damaged component allowing the part to be returned to service. This process is not limited to just the original material, but also allows for the use of dissimilar materials that could be harder or more wear-resistant furthering part life.</p> <p>A percentage of powder can be recovered and reused in polymer and metal powder-based processes for subsequent builds. It is common for this powder to be mixed with virgin powder to maintain powder quality and consistency. There is a limit to the number of cycles that powder can be reused due to oxidation or other changes in the material composition which can affect the mechanical properties. This limit is governed by the material, storage conditions and its thermal history within the build chamber.</p> <p>Unused material can also be recovered in some vat polymerisation processes. The resin can be strained and recovered for future builds. It is key to ensure that the material is used before the designated pot life to prevent it from solidifying.</p>		<p><i>DED repair adding material to damaged surface (OpenHybrid - MTC)</i></p>
			<p><i>DED repair machined to spec (OpenHybrid - MTC)</i></p>
			<p><i>Powder recovery for reuse in subsequent builds [MTC]</i></p>

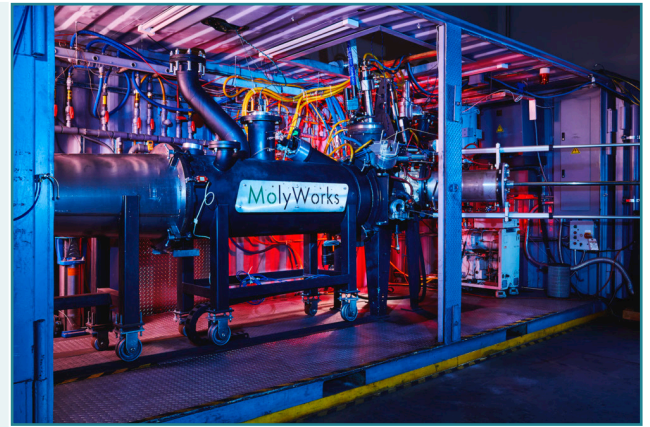
Table 1: Explanation of environmental benefits associated with AM (cont)

Recycling

Material Source Reduction

Material waste can be recycled into feedstock for a variety of AM processes. There are many examples of commercially available recycled polymer materials, such as PLA and ABS, which can be purchased in the form of filament. Recycled metal feedstock is less established however, there are examples of commercially available equipment to turn scrap into powder.

The ease of mass customisation by AM allows for unique part identification through labelling built into the part. It can be used for many purposes such as traceability, ease of assembly and for improving recyclability. Recording of material composition can make separation and recovery of materials much easier as it reduces the need for material identification by more intensive methods.



Industrial powder atomisation from recycled waste- MolyWorks Materials Corporation Greyhound System (Image courtesy of MolyWorks)⁹



Enhanced material identification through using embedded QR codes - 3D printed part with QR code by MolyWorks (Image courtesy of MolyWorks)¹⁰

Table 1: Explanation of environmental benefits associated with AM (cont)

9 MolyWorks, <https://www.molyworks.co/greyhound>

10 MolyWorks, <https://www.molyworks.co/industries>

3.2 Economic Benefits

AM can be a more expensive manufacturing route because of its infancy in the manufacturing sector, however it has the opportunity to reduce costs across

a number of areas. These will only increase as the technology is developed and used more widely. A summary of these can be found in Table 2.

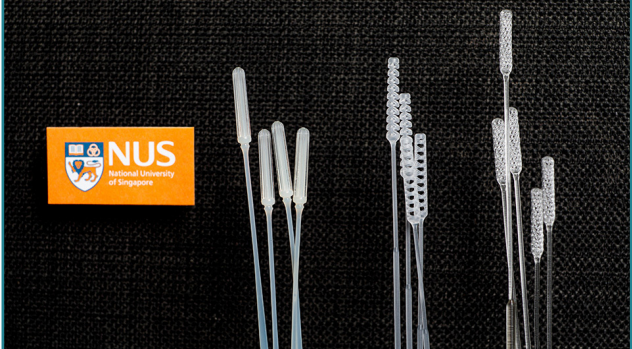
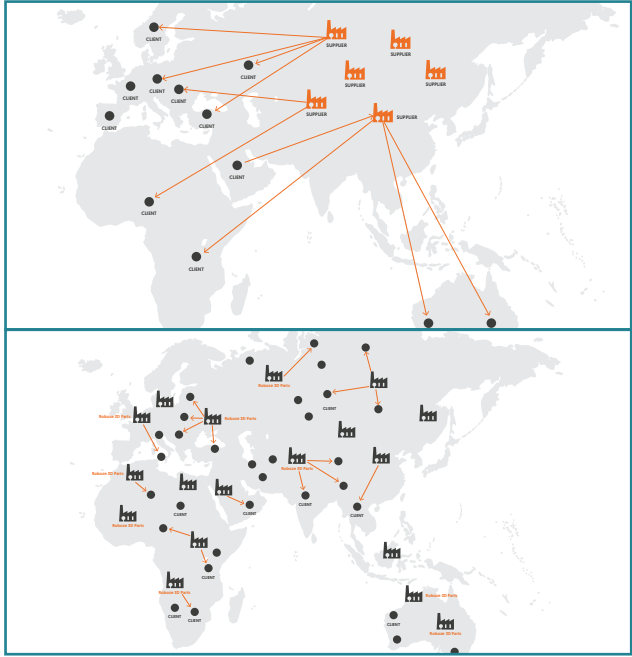
BENEFIT	EXPLANATION	IMAGE
<p>Reduced Low-Volume Production Costs</p>	<p>Although AM is not well suited to high production volumes, it is an efficient method of manufacture for small-scale production runs and one-off parts because AM eliminates the need for tooling. Tooling can be a high cost if only distributed over a small number of parts.</p> <p>The lack of tooling also makes it easier to apply mass customisation to designs. The main function of the part remains the same, however, it provides the opportunity for added value features.</p>	 <p><i>Iterative design of nasal swabs for Covid testing, enabled by AM being a tool less process, allowed development times to be significantly reduced and faster time to market (Image courtesy of the National University of Singapore)¹¹</i></p>
<p>Rapid Product Development</p>	<p>AM is a proven process for rapid prototyping, enabling rapid iterative design. This can lead to a reduced time-to-market and a therefore the ability to capitalise on development costs faster. For complex parts or large assemblies, small sections of a design can be built and tested in isolation to speed up development times.</p>	
<p>Reduced Transportation Costs</p>	<p>The ability for AM to produce an almost infinite range of products and components reduces the need for centralised manufacturing sites that specialise in the manufacture of a single product.</p> <p>A distributed network significantly reduces the environmental impacts of transport costs whilst minimising lead times for components that may need to be shipped from the other side of the globe. This can be especially important for spares and repairs. Although this manufacturing model may work for some components, it can have a negative impact as the high efficiency of mass production may outweigh the benefits of distributed manufacturing.</p>	 <p><i>Transition from a centralised manufacturing network to a decentralised network can minimise transport costs. (Image courtesy of Roboze)¹²</i></p>

Table 2: Explanation of economic benefits associated with AM

11 NUS, "Novel COVID-19 swabs to address shortage," 2020, <https://news.nus.edu.sg/novel-covid-19-swabs-to-address-shortage/>

12 A. Lorusso, "Re-think Manufacturing. Re-shore Production," 2020, <https://www.cecimo.eu/wp-content/uploads/2020/11/Alessio-L-Roboze.pdf>.

3.3 Social Benefits

There is minimal research into the social effects of AM, however, there are some clear benefits that when exploited can benefit a wide population. A summary of these can be found in Table 3.

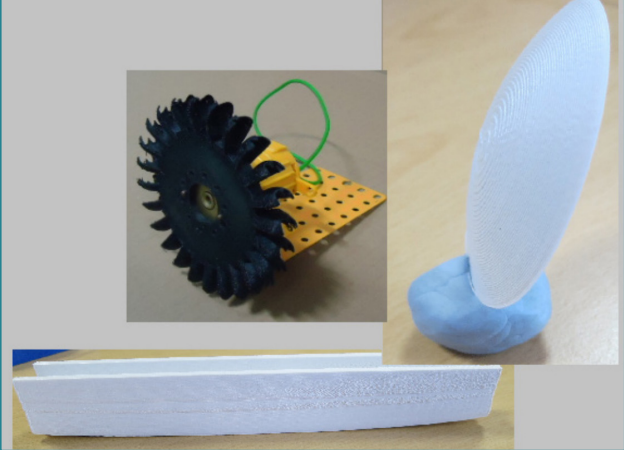
BENEFIT	EXPLANATION	IMAGE
<p>Easy Access for Education</p>	<p>AM spans a range of different processes and although most are out of reach for many, low cost material extrusion processes are widely used by hobbyists and are being introduced into schools. Bringing accessible manufacturing into schools can provide a unique learning experience and inspire the next generation of designers, engineers and manufacturers to start creating and making things that can help to change the world for the better.</p>	 <p><i>As a resource, AM is able to provide a wide range of learning opportunities such as computing, design, business, science, engineering and maths¹³</i></p>
<p>Decreased Time to Market</p>	<p>As a combination of distributed manufacturing and the ability to produce almost any geometry, AM is capable of rapid product development, reducing the time to market. This was especially prevalent during Covid-19 where supply chains could not keep up with the required volumes of swabs and ventilators. Companies were able to adapt the conventional designs for AM, provide additional benefits such as part consolidation and reduced assembly steps and supply regulated components to the medical industry within weeks.</p>	 <p><i>Ventilator parts were in short supply at the beginning of the Covid pandemic however, key components were able to be reverse engineered and manufactured using AM to meet demand [Courtesy of Michele Faini]</i></p>

Table 3: Explanation of social benefits associated with AM

13 DfE, "3D printers in schools: uses in the curriculum," 2013, "https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/251439/3D_printers_in_schools.pdf

4. Adoption Challenges

4.1 Environmental Challenges

Despite the numerous potential benefits of AM as a sustainable manufacturing method, there are still a number of adoption challenges in implementing AM for the circular economy.

These challenges are summarised in Table 4, Table 5 and Table 6 in terms of environmental, ethical, and economic factors respectively.

CHALLENGE	DESCRIPTION
Lack of Life-Cycle Knowledge	It is difficult to calculate the impact of AM parts due to the large number of potential unknowns. These unknowns may relate to material sourcing, processing energy, distribution and transportation costs, benefits during service and end-of-life considerations. As such, current life-cycle assessments of AM parts are often subject to a large degree of uncertainty and therefore it is difficult to objectively identify AM as a 'sustainable solution'.
No Clear DfE for AM	Existing approaches to DfE need to be specifically tailored towards AM processes. Since the wide variety of materials and AM processes may require different environmental considerations to be made, an in depth review would be required. Due to the underlying data required to support this guidance not being well understood, this could only currently be done with low confidence.
Material Recycling	Examples of typical recycling issues include: <ul style="list-style-type: none"> ▶ The ability to identify and sort AM parts into recyclable and non-recyclable materials. ▶ The ability to process and recycle common AM polymers via commercial waste streams. ▶ The inability to recycle composite materials and photo-polymer resins. ▶ Understanding the effects of recycling on the properties of recycled materials, including: the effects of oxidation and other contaminants on the mechanical properties of parts; the allowable number of recycles; and re-qualification for use.

Table 4 - Summary of environmental challenges for AM

4.2 Ethical Challenges

CHALLENGE	DESCRIPTION
IP Protection	Given the decentralised nature of AM and the large number of open-access online file directories and resources, IP protection is much more difficult to control.
Potentially Dangerous Parts	The freedom to design and print parts at home without individual regulation enables individuals to manufacture potentially dangerous parts. A major difficulty in regulating online file sharing is the variability in laws across different countries, as well as the inherent difficulties in policing the internet.

Table 5: Summary of ethical challenges for AM

4.3 Economic Challenges

CHALLENGE	DESCRIPTION
Hidden Costs	Current studies into AM costs are limited in their scope due to the complex nature of AM production lines and the difficulties associated with assigning costs to different AM processes. AM cost models therefore often omit key areas, such as the costs associated with reduced lead times, minimised transportation, decreased risk to supply chain disruption and an increase in lifetime value. Another key area which is not currently addressed is the cost of qualifying AM parts and materials. Qualification of components is application dependant and has the potential to be at a greater cost than with conventional manufacturing as AM is a less mature technology. This also makes it difficult to fit into a standardised cost model as there can be great variability in the workflow steps between different AM processes.

Table 6: Summary of economic challenges for AM

5. MTC's Current Solutions

AM for the Circular Economy: MTC's Sustainable Design Checklist for AM

Two new checklists have been created in order to combat the lack of clarity in the design of AM parts for the circular economy. These checklists encompass a number of different environmental, ethical, and economic factors – allowing users to create more sustainable parts with AM.

The first checklist focuses on the role of the designer and addresses the key environmental considerations required to conceive an idea and develop it into a detailed, sustainable design. The document is designed to prompt environmental questions early on in the design process, making it far easier for them to be implemented. The second checklist is aimed at AM engineers and is designed to address the various sustainable manufacturing considerations within the manufacturing workflow. The manufacturing checklist highlights the key decisions taken at the manufacturing stage and should be completed at the manufacturing readiness review.

Design For:	Question	Example	Response
Life Extension	Can the part be optimised to extend life?	Topology optimisation, Generative design, Field driven design	Y / N / N/a
	Can desirability be increased to extend life?	Customisation, high quality	Y / N / N/a
Waste source reduction	Can a recycled feedstock material be used?	Factoring in potential reduced mechanical or material properties	Y / N / N/a
	Can the amount of material be reduced in the part?	Topology optimisation, Generative design, Field driven design	Y / N / N/a
	Can the amount of material be reduced in supports?	Self supporting features	Y / N / N/a
	Can the part be oriented to reduce time and material usage?	Lower Z height generally reduces build time	Y / N / N/a
	Has stock material been optimised for post processing and surface finishing?	Confirm to prevent excess material removal or scrap from undersize	Y / N / N/a
	Has the energy efficiency of the process been considered?	Using a less energy intensive process	Y / N / N/a
	Can transportation of the component be reduced?	Manufacturing on site or using local suppliers	Y / N / N/a
Material substitution	Can materials be substituted for more sustainable ones?	Using bioderived, biodegradable, recycled or recyclable feedstock	Y / N / N/a
Modularity	Can parts be replaced without creating excess waste?	Splitting parts up with different expected service life	Y / N / N/a
Reusability	Can the part be repurposed at end-of-life?	Consider potential secondary uses	Y / N / N/a
Disassembly	Can materials be separated easily for waste recovery?	Modularity and using single materials can be more easier to recover materials	Y / N / N/a

Figure 12: DfAM sustainable design checklist (MTC)

Each checklist is inspired by the application of DfE methodologies for AM:

- ▶ **Design for life extension** – Optimisation software such as topology optimisation or generative design can enable highly functional parts which ensure they are used for as long as possible. Desirability and emotive connection is linked with prolonged product life which can be achieved in AM through customisation.
- ▶ **Waste source reduction design** – Using lattices or topology optimisation can help to reduce the amount of material used whilst retaining the structural integrity of the part. Parts can be consolidated to reduce material usage and assembly steps.
- ▶ **Design for material substitution** – AM can be limited in material choice, however, when there is the potential for a variety of materials to be chosen from, the environmental benefits should be considered. Advanced AM materials have the potential to substitute more dense materials which can reduce energy use in transportation.
- ▶ **Modular design** – Through creating modular components where there is a significant difference in life span, only the defected part will need to be replaced, therefore saving energy and resources compared to making the whole component again. A trade off must be made between this and part consolidation.
- ▶ **Design for reusability** – Although AM is a great process for customisation, standardising certain aspects of the design may allow for re-use in future products.
- ▶ **Design for disassembly (DfDA)** – Considering how the part could be dismantled into individual materials can be important to ensure that each resource can be recovered at end of life.
- ▶ **Design for recycling (DfR)** – Recycled material should be considered where possible. Eco-labelling practices should be used to identify materials for easier recycling.
- ▶ **Design for energy recovery** – Materials that give off toxic fumes when burned should be avoided if it likely the part will be incinerated.
- ▶ **Design for disposability** – Where disposal is inevitable, the use of toxic materials should be minimised or eliminated. Consider using biodegradable materials which can be composted at industrial waste facilities.

6. Further Development and Recommendations

In order to fully embrace AM for the circular economy, there are still a number of areas which require further research and development. These areas primarily relate to the lack of consistent, reliable and freely-available information regarding AM in the circular economy. Some of the key research areas and potential tools are identified below:

More Diverse Environmental Data

In order to successfully implement LCA in the AM design workflow, there is a need for more widespread and reliable data relating to the environmental impacts of various AM materials and processes. Although some data exists in literature as a result of individual case studies and research, there is a need for considerable further study, and the documentation of data in a centralised and open-access platform.

A detailed LCA tool could be created as either a stand-alone LCA software package, or an open database of AM metrics which could be imported into existing LCA software or CAD package by means of a plug-in or library.

A tool like this would allow for the comparison of a wide range of AM materials and processes against a variety of environmental metrics – allowing designers to make informed and confident decisions in the design of sustainable parts.

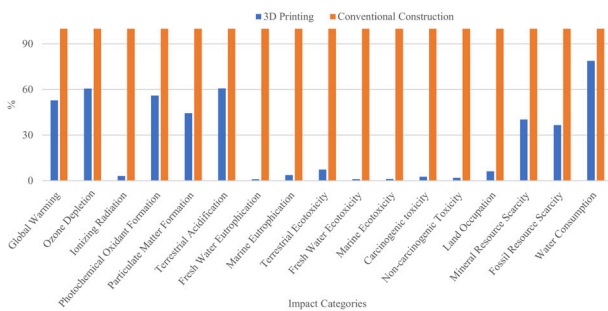


Figure 13: Example use of Life Cycle Assessment Software for manufacturing process comparison¹⁵

Material Recycling and Product Labelling

There are limited options for recycling waste material produced through AM. Further research is required to establish the most suitable waste management strategies to recover waste materials and turn them into recycled feedstock. Work needs to be done with recycling companies to establish viable routes for recycling AM waste.

There is currently no standard practice in the labelling of AM parts, making it incredibly difficult to identify and recycle AM materials during end-of-life. Although labelling tools would enable designers to combat this issue as individuals, a more widespread solution would require legislating the use of environmental labelling for all additive manufacturers.

An automated product labelling tool for AM parts would allow parts to be identified by material group and increase the likelihood of recycling. This tool would allow users to select from a wide range of AM materials, and then automatically place a standard identification marker onto the 3D model. Identification markers would follow the standard format for the selected country / region. For example: in the UK, all plastics are classified under a numerical resin identification code (RIC). This tool could take the form of a standalone piece of software, or ideally – a universal plug-in for common CAD packages, slicers, and build preparation software.



Figure 14: Adding Recycling Codes to 3D Prints¹⁴

14 E. Hunt et al. "Polymer Recycling Codes for Distributed Manufacturing with 3-D Printers," 2015

15 H. Abdalla et al. "Environmental Footprint and Economics of a Full-Scale 3D-Printed House" 2021

Central Knowledge Hub

The most important area to address is the lack of accurate, reliable, and freely-accessible unbiased knowledge on the sustainability of AM. Therefore, one of the biggest needs within the industry is a centralised platform to up-to-date and open-access information.

LCA manufacturing databases can provide a wide range of manufacturing data to measure environmental impact, however, these need to be expanded to provide a greater range of data across more manufacturing technologies. This will give engineers and designers the tools to understand the environmental impact of the products they create.

The Additive Manufacturing Green Trade Association (AMGTA) is a new non-profit trade group founded to promote the environmental benefits of additive manufacturing to key industries and the general public. The AMGTA seeks to educate the public and industry about these positive environmental benefits, promote the adoption of AM as an alternative to traditional manufacturing, develop best practices for additive manufacturing, and help manufacturers grow their businesses and acquire new customers. Although the AMGTA is a fairly new organisation, its aim is to fulfil the widespread need for knowledge and information, and could represent a new driving force in the adoption of sustainable AM.

Based at the MTC, The National Centre for Additive Manufacturing (NCAM) hosts the Knowledge Hub, an online resource for the UK manufacturing supply chain (Accessible at: <http://knowledgehub.the-mtc.org/>). This database provides a central source for a wide range of information to help manufacturers begin and develop their journey with AM and would be a suitable base for additional content focusing on sustainability and the prospects of a circular economy.



Figure 16: AMGTA¹⁶ or NCAM could be used as a centralised resource

16 AMGTA <https://amgta.org/>

17 A. Busachi, J. A. Erkoyuncu, P. Colegrove, R. Drake, C. Watts, F. Martina, N. Tapoglou and H. Lockett, "A system approach for modelling additive manufacturing in defence acquisition programs," in 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 2018.

Greater understanding of ill-structured costs for more standardised cost modelling

Current studies into AM costings are limited in their scope due to the complexities of measuring AM costs. Key costs from reduced lead times, supply chain effects and increase in lifetime value are currently not considered in conventional cost comparisons.

A guidance framework for the costing of AM parts could be generated to help highlight some of the hidden costs and outline how to go about estimating them. This framework would form the basis of a comprehensive costing tool which could be used by additive manufacturers to more accurately cost their parts and production lines.



Figure 15: Example of a cost model tool for AM¹⁷

Better Understanding of Social Impacts

In general, the social impacts of AM are still not well understood. As such, it is difficult to recommend any specific tools or practices to remedy them. There is therefore a need for further research into the social and ethical aspects of AM, with a particular emphasis on investigating any potentially negative impacts. This need for better understanding of social impacts is now more important than ever, as the growing public awareness of AM means more potential for the spread of misinformation [positive or negative].

IP Protection

There are currently limited possibilities to protect IP, meaning that the sharing of potentially dangerous designs, or theft and redistribution of confidential designs is easy to do with very little consequence. Software to encrypt and lock build files to specific machines is being developed, however, greater protection of IP and prevention of unregulated data being spread across the internet is still required.

7. Sustainability at the MTC and NCAM

At the MTC we are working across a wide range of sectors to work towards a more sustainable manufacturing future. You can see some of our sustainability focused projects in Table 7. As a research and technology organisation we are well positioned to work with businesses to develop sustainability strategies and roll out our initiatives to help achieve net zero objectives.

If you are interested in getting support to achieve net zero objectives or get access to the tools described in this paper please visit our website or e-mail us at NCAM@the-mtc.org.

PROJECT	IMPACT
Sustainable AM facility	Assessed the environmental impact of NCAM's existing Metal Powder Bed [MPB] Facility using a combination of existing data and modelling. The project identified key opportunities for improvement to furthered research and develop technology solutions.
Sustainable Packaging	To understanding good design for sustainable packaging, in terms of user perception and how company markets the product.
Thermo Electric Energy Recovery [TEER]	To investigate using thermoelectric generators [TEGs] to harvest waste heat energy from an electric motor.
Legacy LTP	Reducing the need for new machines and reusing what we have though retrofitting of sensors to legacy machines and enable digitalization.
PowderCleanse	PowderCleanse is a system designed to sieve and monitor powder in a safe and enclosed environment. It conducts contamination detection in metal powders to reduce powder waste.
Automated Remanufacturing of Rail Components [AURORA]	To increase the life of railway wheels by adding material to the outer running face of them, using weld deposition [cladding].
Repair of Moulds and Dies	Moulds and dies wear in use. Laser and/or arc cladding can be used to add material to the faces, to enable them to be reused, rather than scrapped.
Low Heat Input for Yellow Goods	Hybrid welding laser & MIG. A combination of using a laser source with any arc process gives higher welding speed, and therefore higher production volumes using less energy reduction.

Table 7 - Summary of sustainability projects at the MTC

the-mtc.org

**NATIONAL
CENTRE
ADDITIVE
MANUFACTURING**

mtc
Manufacturing
Technology Centre