ADDITIVE MANUFACTURING

emerging innovations for children

Collaboration with Harvard Consulting on Business and the Environment, and The George Washington University

OVERVIEW

Innovation Nodes at UNICEF Office of Innovation

Innovation Nodes are collaborative and transdisciplinary spaces to reflect, explore and create novel wisdom in new and unknown areas of potential innovation for children. These collaborations are with preeminent organizations, from research institutions to think tanks, with deep expertise and capabilities in new and unknown domains of impact on children.

Insight Reports are descriptive and exploratory products that serve as a resource for practitioners and decision-makers to gain awareness of new and unknown areas of potential innovation for children.

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TERMINOLOGY [1]

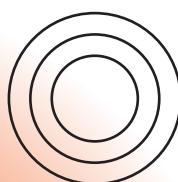|	
3D modeling	The process of developing a digital depiction of a three-dimensional object using computer aided design (CAD) software.
3D printing	3D printing is a process where a three-dimensional object is created from a digital model, usually by depositing multiple layers of material.
3D printer	A machine that produces a three-dimensional object one layer at a time. There are several different types of 3d printers each using a different 3D printing method.
3D printing pen	A handheld tool that uses FDM technology and thermoplastic filament to allow users to create three dimensional objects by laying down layers of extruded print material.
Additive manufacturing	The process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.
Additive manufacturing system	Additive manufacturing equipment, machine and auxiliary equipment used for additive manufacturing.
Additive manufacturing machine	A section of the additive manufacturing system including machine control software, required set-up software and peripheral accessories necessary to complete a build cycle for producing parts.
Bed (Print bed)	Another name for the build plate of an FDM-type 3D printer. It is usually made of aluminum or glass.
Binder jetting	An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
Bioprinting	A type of 3D printing that uses living cells, biomaterials, or bioinks to create biological structures, such as tissues or organs, with potential applications in medical research and regenerative medicine.
Build cycle	A single process cycle in which one or more components are built up in layers in the process chamber of the additive manufacturing system
Build surface	The surface on which a printed object is produced. Often various types of build surfaces will be placed onto or attached to the printer bed to improve adhesion.
Build volume	The maximum size of an object that a 3D printer can produce, measured in length times width times height.
Cracking	A 3D printing defect. Cracking occurs when one layer of print material bonds inadequately with another layer. When this happens, as the object cools, a split or crack occurs between the two inadequately bonded layers.
Curing	A chemical process which results in the ultimate properties of a finish or other material.

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1   International Organization for Standardization, ISO/ASTM 52900:2021. Standard Terminology for Additive Manufacturing - General Principles - Fundamentals and vocabulary, 2021, Geneva, Switzerland.

Directed energy deposition	An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. 'Focused thermal energy' means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.
Extrude	The process of forcing out a thin layer of melted thermoplastic onto a build surface to build up a printed object.
Feedstock	The source material, starting material, base material, original materia/ or bulk raw material supplied to the additive manufacturing building process. The bulk raw material is usually in forms such as liquid, powder, suspensions, filaments, sheets.
Filament	Filament is usually a thermoplastic that is fed by a cold end to the hot end as a solid. In the hot end it is heated to a printing temperature and extruded out through the print nozzle. Filament comes in different diameters and usually sold in spools. There is a wide variety and quality of filament materials available.
Fill density	A slicer program setting that is a measure of how much material will be printed inside the outer shell of the object in question. Infill density is used to conserve filament while printing and speed up printing times.
Formative manufacturing	A process in which a liquid is poured into a cavity, taking the cavity's shape as it hardens, e.g., different types of molding, forming and casting. Simple examples of the formative process are candle making or soap making.
G-Code	A program language that controls the actions of a 3D printer – things like motion, speed, rotation and depth. This code is generated by a slicer program.
Heat creep	Heat creep is a problem that occurs in FDM-type 3D printers when higher temperatures extend back and upwards from the hot end. This causes the "melt area" to extend father back, softening and melting the print material well before the nozzle end of the extruder, causing the nozzle to clog.
Heated print bed	A part on an FDM-type 3D printer. A heated print bed keeps the build surface warm, promoting greater adhesion and decreasing incidents of warping.
Layer	An individual thin section of print material that make up a printed object.
Laser sintering	A powder bed fusion process used to produce objects from powdered materials using one or more. lasers to selectively fuse or melt the particles at the surface, layer upon layer, in an enclosed chamber. Most LS machines partially or fully melt the materials they process.
Material extrusion	An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
Material jetting	An additive manufacturing process in which droplets of build material are selectively deposited.
Over-extrusion	A 3D printing issue that occurs when too much material is extruded, resulting in blobs, stringing, or other defects on the printed object. Over-extrusion can be caused by incorrect slicing settings, filament diameter inconsistencies, or extruder calibration issues.
Overhang	Any part of a 3D model that protrudes at angles greater than 45° and lacks support below it are considered overhangs.

Photopolymer	A material used in 3D printing that hardens when exposed to certain types of light. Photopolymers are used in Digital Light Processing (DLP) and Stereolithography (SLA).
Polycarbonate	A thermoplastic printing filament used in FDM-type 3D printers. It is an extremely strong, lightweight and transparent thermoplastic.
PolyJet	A 3D printing technology that allows for smooth surface finishes, high accuracy, and full-color models and multiple materials within the same part. It involves depositing photopolymers that are cured by being exposed to a UV light.
Polymer	A type of plastic used in FDM printing. A polymer is a material that is made up of multiple long molecular chains of a single substance.
Post-processing	The steps taken to finish and refine a 3D printed object after printing is complete.
Powder bed fusion	Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
Print nozzle	A part on a 3d printer. The print nozzle is attached to the bottom of the hot end and is where the melted thermoplastic printing material is extruded. A smaller diameter nozzle will produce finer details in the finished object, albeit at a slower print speed and a greater risk of clogging.
Print resolution (Print quality)	Horizontal resolution refers to the movements made by the print head along the x and y axes. The smaller the movements, the higher level of printing detail the printer produces. Vertical resolution refers to movements by the print head along the z axis. The smaller movements, the smoother the finished surface of the printed object.
Print speed	Print speed is how fast the print head travels while extruding filament. An optimal speed depends on the object being printed and the type of filament material used to fabricate the object. Print speed affect adhesion to the print surface, cause under or over extrusion and other problems.
Printing temperature	The optimal temperature for a thermoplastic printing material to be at for effective extrusion. The printing temperature differs from material to material.
Raft	A raft is a layer or layers of extruded thermoplastic that is used to stabilize a printed object. A raft helps an object to adhere to the print bed. Unlike a brim, a raft is connected to the perimeter and bottom of an object.
Rapid prototyping	The process of quickly creating physical prototypes or parts using 3D printing, allowing for faster design iterations and reduced product development time. Rapid prototyping was the first commercially significant application for additive manufacturing and is commonly used as a general term for this type of technology.
Rapid tooling	The application of additive manufacturing intended to produce tools or tooling components with reduced lead times as compared to conventional tooling manufacturing.
Repeatability	degree of alignment of two or more measurements of the same property using the same equipment and in the same environment
Sheet lamination	An additive manufacturing process in which sheets of material are bonded to form a part.

Slicer	A 3D slicer is a piece of 3D printing software that takes a digitized 3D model and converts it into printing instructions that a printer uses to turn the model into a physical object. The slicer takes the CAD model and "cuts" it into layers. It then calculates how much material needs to be used for that layer, where the material should go and how long it will take. It then converts the information for each layer into one G-Code file which is sent to your printer.
Slicing	The process of converting a 3D model into layers, or "slices," for 3D printing.
Soluble materials	Any thermoplastic printing material that is soluble, or dissolvable, when immersed in another substance, e.g., PVA and HIPA.
Support materials	Printing materials used to support overhangs on a designed object. Support materials are usually soluble to facilitate easy removal after printing.
Support structures	A layer or layers of extruded thermoplastic that is used to support overhangs on designed objects. Support structures are usually removed after printing is completed.
Subtractive manufacturing	The term for various processes that removes materials by cutting, boring, drilling, and grinding to create an object, e.g., CNC machining, laser cutting, water jet cutting, and electrical discharge machining.
Thermoplastic	A substance, usually a plastic, that can melt and harden at precise temperatures.
Under-extrusion	An issue that occurs when not enough material is extruded, resulting in gaps, thin walls, or weak layers in the printed object. Incorrect slicing settings, filament diameter inconsistencies, or extruder calibration issues can cause under-extrusion.
Vat photopolymerization	An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.
Warping	A common issue in 3D printing where the object's edges lift from the build plate due to uneven cooling and material contraction.
X, Y, and Z-Axis	The three axes of movement in 3D printing; X and Y correspond to the horizontal plane, while Z represents the vertical plane.

ABBREVIATIONS AND ACRONYMS

3DP	3D printing
ABS	Acrylonitrile Butadiene Styrene. A thermoplastic printing filament used in FDM-type 3d printers. It is a petroleum-based plastic that is not biodegradable bit it is recyclable. ABS is strong, durable and soluble in acetone.
AM	Additive manufacturing
CAD	Computer Assisted Design. CAD is the use of computer software to produce a digital design in either two- or three-dimensional formats that can then be used to print a physical object. CAD was originally developed for use in architecture and engineering.
CE	Circular Economy
CNC	Computer Numerical Control. A subtractive manufacturing method involving a machine removing parts from a block of material to create the finished part.
CSIRO	Commonwealth Scientific and Industrial Research Organization
DALYs	Disability adjusted life years
DBB	Droplet-based bioprinting
dECM	Decellularized extracellular matrix. Biomaterials formed by human or animal organs/tissues with the removal of immunogenic cellular components via decellularized technologies.
DED	Direct Energy Deposition. A form of metal 3D printing to create metal parts
DLP	Digital Light Processing. A form of 3D printing where a light source is used to cure photopolymer resin to produce a printed object
DMLS	Direct Metal Laser Sintering. A powder-bed fusion technology used to manufacture metal parts by directing a high-powered fiber laser beam at a single, thin layer of metal powder and fusing an outline of that layer onto the previous layers.
DMP	Direct metal printing. Also known as direct metal laser sintering (DMLS). An AM technology that builds high quality complex metal parts. In the machine, a high precision laser is directed to metal powder particles to selectively build up thin horizontal metal layers one after the other.
EBM	Electron Beam Melting. A form of metal 3D printing like DMLS but instead uses an electron beam rather than a laser.
ECM	Extracellular matrix. A dynamic 3-dimensional network of macromolecules that provides structural support for the cells and tissues.[2]
FDM	Fused Deposition Modeling. A 3D printing process where melted thermoplastic is deposited in successive layers to produce a finished object using a digital model.

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2   Karamanos, N. K., et al., 'A guide to the composition and functions of the extracellular matrix', The FEBS journal, vol. 288, no. 24, 2021, doi: 10.1111/febs.15776.

FFF	Fused Filament Fabrication. Another name for FDM.
FFM	Fused Filament Manufacturing. Another name for FDM.
GelMA	Methacrylated gelatin
HA	Hyaluronic acid
HIPS	High impact polystyrene. A 3D printing filament that is strong, durable, non-toxic and recyclable. It combines the hardness of polystyrene with the elasticity of rubber to produce a high-impact thermoplastic that is tough and strong without being brittle.
ISO	International Organization for Standardization
IIC	Invisible In-Canal
ITC	In-the-Canal
ITE	In-the-Ear
LCA	Life cycle assessment
LCEs	Liquid crystal elastomers
LMICs	Low-and middle-income countries
MEM	Melted and Extruded Modeling. Another name for FDM printing
MJ	Material jetting
MPa	Megapascal
OBJ	Object File. A 3d file format used by CAD programs as an alternative to STL files when information about color or material is important.
PEG	Polyethene glycol
PC	Polycarbonate
PEEK	Polyether Ether Ketone. A high-performance thermoplastic 3D printing material with excellent mechanical properties, high temperature and chemical resistance.
PEI	Polyetherimide. Used in FDM printing on the bed of a printer to improve adhesion.
PETG	Polyethylene Terephthalateglycol. A thermoplastic printing filament that produces objects that are very strong and high-quality finish.
PLA	Polylactic Acid. A biodegradable, environmentally friendly thermoplastic that is manufactured out of natural substances, usually corn or sugarcane.
PMM	Polymethyl Methacrylate. A thermoplastic printing filament widely used as an alternative to glass in applications where more strength and durability is needed.
PP	Polypropylene. A 3D printer filament used in FDM.
PVA	Presenting Visual Acuity
PVA	Polyvinyl Alcohol. A 3D printer filament used in FDM.
SLA	Stereolithography. A 3D printing technology. SLA focuses a UV laser onto a tank of photopolymer resin. The light cures or hardens the top layer of the resin, building the object from the top down. SLA produces high resolution objects with extremely smooth finishes.
SLM	Selective laser melting

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SLS	Selective Laser Sintering. A 3D printing technology used to combine tiny particles of plastic powder (nylon and carbon) with laser technology to produce a solid object.
SMAs	Shape memory alloys
SMPs	Shape memory polymers
STL	Stereolithography File. A common file format file format for model data describing the surface geometry of an object as a tessellation of triangles used to communicate 3D geometries to machines to build physical parts.
TBI	Traumatic brain injury
TPU	Thermoplastic Polyurethane. An extremely flexible and durable extrusion printing filament that is resistant to abrasion, grease, oil, and wide variety of solvents.
UAVs	Unmanned Aerial Vehicles
VNP	Virtual Private Network
YLDs	Year lived with disability

CONTENTS

SUMMARY

Additive manufacturing (AM) is a rapidly evolving group of technologies that enables design flexibility and fabrication of highly complex objects. AM can be understood as an end-to-end process that starts with creating a digital design file and involves the process of joining materials to make objects, usually layer upon layer. The printing or fabrication of the object, commonly known as 3D printing, is a part of the AM process. The International Organization for Standardization (ISO) defines 3D printing as "the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology."

There are seven types of additive manufacturing printing processes. Each process has unique characteristics such as materials used, energy source, build speed, processing temperature, production rate, product properties, surface quality, lifecycle, skills and technical knowledge required, and impact, such as set-up and maintenance cost, emissions, energy consumption, biodegradability, waste stream and recyclability, and potential applications. Below is an overview of the current strengths and limitations of additive manufacturing (including 3D printing).

Summary of AM strengths and limitations

AM domains	Strengths	Challenges
Limitations Design	• Enable efficient and flexible model of design optimization for product development and product innovation	• Limited knowledge and skills in 3D modelling and R&D • Legal ambiguities about who is responsible if the component design and manufacturing process goes wrong
Manufacturing	• Manufacture complex parts • Capture user feedback faster due to rapid prototyping • Decrease manufacturing lead time • Opportunity for decentralized manufacturing, shifting closer to the point of consumption	• Manufacturing speed is slower than conventional manufacturing for high-volume production • Processes and applications need clear standards and certification • 3D-printed products often need post-processing

AM domains	Strengths	Challenges
Product	• Develop and test new products effectively before committing to expensive manufacturing processes and tooling • Produce highly customized and complex products in low volumes • Production of critical spare parts in emergencies	• Prone to poor product surface accuracy and rough and imperfect surface finish • 3D-printedRepeatability and consistency of 3D-printed parts need to be improved • Not suitable for high-volume manufacturing
Material	• Reduce the volume of materials required for production • Some filaments or resins can be recycled • Recycle metal powders during SLS or melting processes • 'Shape memory' smart materials can potentially transform rehabilitation equipment and medical implants for children	• Photopolymers cannot produce large-sized objects due to lack of materials strength • Lack of fit-for-purpose material standardization and certification • Some materials are susceptible to inconsistency • Potential toxicity of some materials
Cost	• Reduced transport costs • Reduce additional expenses of creating new physical tools • Save on large-scale investment in factories and machinery	• Relative high cost remains a barrier to wide AM adoption, particularly in LMICs • High cost of machine maintenance
Sustainability	• Reduce over-production and decrease energy and material consumption • Biodegradable materials • Less material wastes during manufacturing • Spark new business models with an improved carbon footprint	• Lack of sustainability metrics and modelling for waste streams in the printing process • Lack of awareness of and capacity to 'remanufacture' - converting waste into products • Non-recyclability of multi-material products
Supply Chain	• Improve supply chain efficiency	• Lack economies of scale

This Insight Report highlights examples of diverse applications of additive manufacturing and its potential multiplier effect for the humanitarian and development sector. The use of AM has progressed beyond rapid prototyping. Its potential has increased due to advances in digital production technologies, advanced robotics, machine capabilities (printers) and materials such as high-performance metals and biomaterials. For example, AM has revolutionized tissue engineering and regenerative medicine. It has made it possible to create individualized implants and prosthetics that improve patient comfort and outcomes in orthopaedic applications, especially for children. The multidimensional impact of additive manufacturing for the sustainable development goals (SDGs) points to the potentially transformative applications as well as the risks of this technology for the humanitarian and development sector.

Additive manufacturing and the Sustainable Development Goals

1 NO POVERTY

- AM can contribute to poverty reduction and disaster relief (Target 1.5) by enhancing the resilience of young people and their communities and reducing their exposure to disasters. (Chapters 3 and 4)
- AM enables local production of critical spare and customized parts required by Water, Sanitation, and Hygiene (WASH) or/and hospitals during natural disasters and other humanitarian crisis when access is difficult due to logistical or security issues. (Chapter 4.2)
- AM can address the need for housing after disasters (earthquakes) and contribute to post-conflict reconstruction. (Chapter 4.3)
- For poverty reduction, a 3D printer, powered by renewable energy such as a mobile PV solar energy unit could provide employment for young people who can offer products and services to isolated communities. (Chapter 6.1)

2 ZERO HUNGER

- AM can potentially enhance agricultural productive capacity by enabling the production of customized tools and spare parts for farming, but issues of affordability and accessibility need to be addressed. (Chapter 4)

3 GOOD HEALTH AND WELL-BEING	• The biomedical and allied health industries have been early adopters of AM. (Chapter 5) • 3D bioprinting is common practice in tissue engineering and regeneration such as cardiac, bone, corneal, cartilage, neural, and skin, drug development, personalized medicine, and systems biology. (Chapter 5) • 3D bioprinting offers unique opportunities to improve disease modelling and speed up accurate screening platforms for drug discovery. (Chapter 5) • Other applications of AM for health include bone tissue engineering, spinal implants, and implants with antibiotics. (Chapter 5) • 4D printing, still at the R&D stage, will enable smart orthopaedics implants that can change their shape after being implanted in the patient's body. One of the major challenges in orthopaedics is developing artificial bones and implants that can grow as the child grows and develops.,4D printed implants offer potential solutions as they can react to different stimuli and change their structure with the passage of time. (Chapter 7.1)
4 QUALITY EDUCATION	• AM supports inclusive education by improving learning opportunities for young people with disabilities from hearing, vision to physical mobility by designing and fabricating bespoke assistive technology. (Chapter 6)
5 GENDER EQUALITY	• Though there is an evidence gap in this area, the potential of AM to accelerate gender equality appears to be limited at this stage of development. • Women are underrepresented in the AM field as technical specialists and researchers. The adoption of AM by architects and cultural historians opens other pathways for women to engage with the technology (Chapter 4.3)
6 CLEAN WATER AND SANITATION	• AM can greatly improve access to clean drinking water in several ways, including water toxicity treatment and water quality monitoring. (Chapter 3.3) • 3D-printed water membranes and filters are particularly useful for remote areas and in humanitarian emergencies (Chapter 3.3)
7 AFFORDABLE AND CLEAN ENERGY	• Additive manufacturing opens huge opportunities by revolutionizing the design, development and repair of more efficient components within the renewable energy sector. AM can be used to make energy production devices and components in solar panels and circuits, wind turbines, fuel cells and energy storage. (Chapter 3.2)
8 DECENT WORK AND ECONOMIC GROWTH	• AM impact of employment opportunities is ambiguous and under researched. On the one hand, the field offers new opportunities for a skilled workforce and product customization may expand some markets, thereby increasing labour demand. (Chapter 6.1) On the other hand, automation of AM processes and advanced manufacturing will displace certain segments of the labour market.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	• AM can enhance supply chain resilience localized distributed manufacturing (Chapter 4.2) • AM technologies foster inclusive and sustainable innovation in other industries such as construction (Chapter 4.3) and transport. Engineers in the aerospace industry can design intricate and complex geometric structures with less lead time and eliminate the need for large amounts of material. This ensures aircraft consume less fuel and reduce CO_2 emissions.
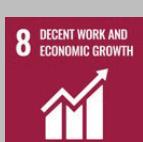
10 REDUCED INEQUALITIES

- AM offers an 'on-site, on demand, on time' solution to the last mile challenge in humanitarian and development operations. 3D printing technologies can enhance logistical capabilities of humanitarian organizations to ensure critical spare parts reach the poorest, hardest-to-reach communities and to survivors impacted by disasters and crises. (Chapter 4.2)
- AM contributes to social and economic inclusion when it is used to design and develop assistive devices and technologies for children with certain impairments. Such AM-enabled innovations empower children, restore their dignity, and improve their quality of life, access to education and employment opportunities. (Chapter 6)

11 SUSTAINABLE CITIES AND COMMUNITIES
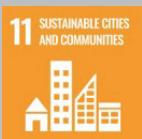
- AM offers the opportunity to make use of a range of materials with varying properties depending on the application -- which can range from strong large-scale objects like a building, to highly flexible nano-scale objects (Chapter 4.3)
- The technology has enabled the design and construction of accessible and affordable housing solution in earthquake prone regions and in post-disaster and post-conflict situations (Chapter 4.3).
- Buildings or building components made of AM have exhibited lower energy requirement and higher energy efficiency than conventionally manufactured buildings (Chapter 4.3)

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

- AM can potentially contribute to the creation of a circular economy and radically improve resource efficiency by eliminating the concept of waste and shifting away from the linear take-make-waste model to a closed-loop resource model. 3D printing can improve resource recovery. But more research is needed to understand enablers and barriers for AM to reach its full potential for a circular economy, particularly in identifying new opportunities in waste streams. (Chapter 7.1)

13 CLIMATE ACTION

- Scientists designed and additively manufactured an aluminium device that enhances the capture of carbon dioxide emitted from fossil fuel plants and other industrial processes. (Chapter 3.1).
- Cement-based additive manufacturing construction is an emerging technology that has the potential of becoming a climate solution for the cement sector. (Chapter 4.3)

14 LIFE BELOW WATER

- 3D-printed reefs have been successfully produced and installed under the sea to preserve and restore coral reefs. The geometrical shape and surface structure provide sufficient habitat conditions for coral polyps and fish. (Not included in this report.[3])

15 LIFE ON LAND

- AM supports the sustainable use of raw material and development of new materials using renewable sources. (Chapters 4.3 and 7.1)

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3 Research on 3D printed coral reefs: Levy, N., et al., 'Emerging 3D technologies for future reformation of coral reefs: Enhancing biodiversity using biomimetic structures based on designs by nature', Science of The Total Environment, 2022, doi: 10.1016/j.scitotenv.2022.154749 and Yoris-Nobile, A., et al., 'Artificial reefs built by 3D printing: Systematisation in the design, material selection and fabrication', Construction and Building Materials, vol. 362, 2023, doi: 10.1016/j.conbuildmat.2022.129766

16 PEACE, JUSTICE AND STRONG INSTITUTIONS	• AM has opened a largely under-regulated pathway to the private manufacture of operational weapons within an otherwise highly regulated environment in most countries. 3D and 4D printing could have significant impact on the future of warfare as they have the potential to change how conflict is carried out and raises questions of legitimacy of violence and accountability. (Chapter 7.3)
17 PARTNERSHIPS FOR THE GOALS	• To fully realize the potential of AM to address complex global challenges, we need to bring together skills and resources from partners from a range of sectors and disciplines at local, national and level. This also means collaborative relationships between partners across diverse regions
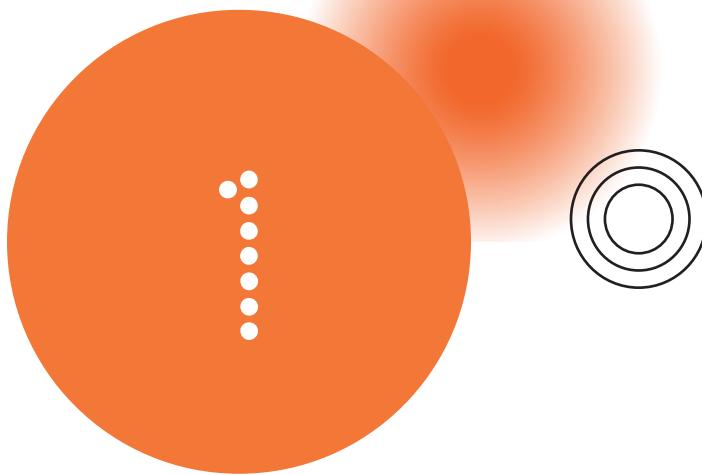
INTRODUCTION

In the past twenty years, some innovations have received both hype and scepticism in international development. Additive manufacturing (AM) is one of these. The International Organization for Standardization (ISO) defines additive manufacturing as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies".[4] It is the capability to create a physical object from a digitally encoded design through the deposition of material via a 3D printing process.[5]

What is the link between AM and 3D printing (3DP)? AM is an end-to-end process and system of technologies that enables the fabrication of 3D objects. 3D printing is a part of the AM process. The ISO defines 3D printing as "the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology".[6] The term is often used interchangeably with additive manufacturing in non-technical context.[7] For purpose of this report, we use the ISO definition of AM and 3DP.

4   International Organization for Standardization, ISO/ASTM 52900:2021. Standard Terminology for Additive Manufacturing - General Principles - Fundamentals and vocabulary, 2021.
5   Gartner, Additive Manufacturing, <https://www.gartner.com/en/information-technology/glossary/additive-manufacturing>, accessed 21 Jan 2024.
6   International Organization for Standardization, ISO/ASTM 52900:2021. Standard Terminology for Additive Manufacturing - General Principles - Fundamentals and vocabulary, 2021.
7   International Organization for Standardization, ISO/ASTM 52900:2021. Standard Terminology for Additive Manufacturing - General Principles - Fundamentals and vocabulary, 2021. The ISO notes that during the development of additive manufacturing, terms used to describe the technology were linked to specific technique and applications. This has caused confusion.

1.1 Beyond rapid prototyping

Since the emergence of AM technology in the 1970s, 3D printing is considered a useful rapid prototyping tool. AM is now grouped among a host of technological innovations that the World Economic Forum calls the 'fourth industrial revolution', often referred to as Industry 4.0 (named after Germany's Industrie 4.0).[8] Industry 4.0 is characterized by increasing automation and integration of digital technologies, including Internet of Things, cloud computing and analytics, and AI and machine learning. Thanks to advances in fabrication hardware, digital technology, material science and processing power, AM has moved beyond rapid prototyping of objects to designing and manufacturing solutions for challenges from disaster risk reduction and recovery and climate change adaptation to health and WASH - all areas with high impact on the wellbeing of all children.

The Gartner Hype Cycle (Figure 1) shows the diversity of AM technologies and their different applications.

Figure 1: 2018 Gartner hype cycle for 3D printing.
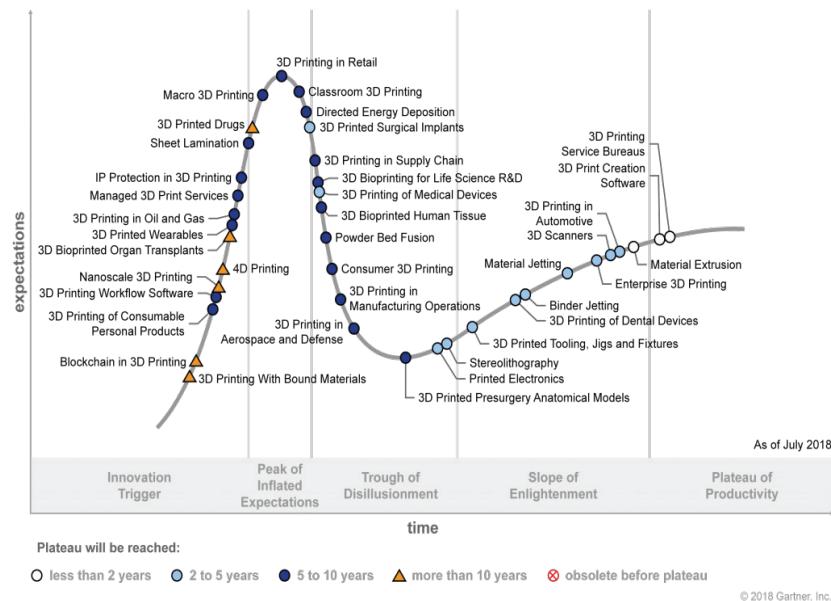
A Gartner Hype Cycle is an evidence-based tool that identifies the risks and opportunities of innovation. A Hype Cycle has 5 phases:

Innovation trigger: a technological breakthrough that generates excitement.

Peak of inflated expectations: product usage increases, but more evidence is

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8   Kagermann, H., Wahlster, W., and Helbig, J., Recommendations for implementing the strategic initiative Industrie 4.0: Final report of the Industrie 4.0, Working Group Acatech, 2013. München, Germany. World Economic Forum, An Additive Manufacturing Breakthrough: A How-to Guide for Scaling and Overcoming Key Challenges, 2022, Geneva, Switzerland.

needed to proof the innovation can deliver.

Trough of disillusionment: early adopters report performance issues and low ROI.

Slope of enlightenment: early adopters see initial benefits and others start to understand how to adapt the innovation to their organizations.

Plateau of productivity: more users see real-world benefits and the innovation goes mainstream.

Source: Gartner Hype Cycle.

A 2023 report on innovation trends in additive manufacturing published by the European Patent Office shows that between 2013 to 2020, patents filings in additive manufacturing grew at a rate of 26.3 per cent annually–nearly eight times faster than all technology fields combined in the same period[9] (Figure 2).

Figure 2: Trends in all additive manufacturing technologies.
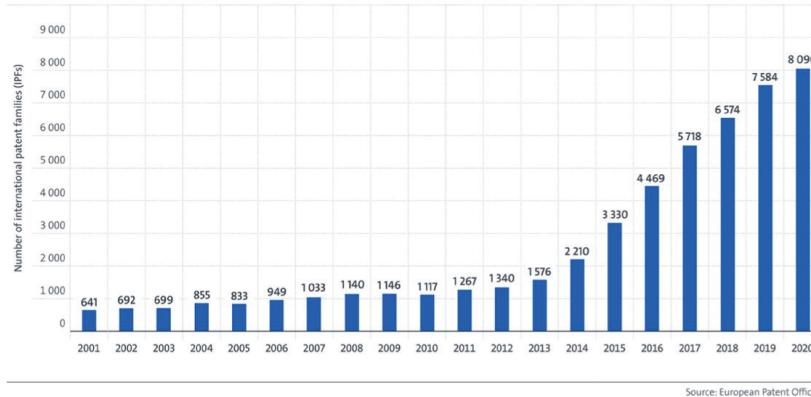
Source: European Patent Office

Major US, European and Japanese corporations such as General Electric, HP, Siemens, Fujifilm, Hitachi, 3M, and BASF are the major patent applicants.[10] The trend analysis of AM patent applications between 2001-2020 shows that the technology has gained significant traction in the health and transportation sectors.[11] Machine tooling, electronics, consumer goods, and the energy, construction and food sectors are also seeking to adopt AM technology.[12]

1.2 About the Insight Report

Beyond the initial hype and trough of disillusionment, the value of additive manufacturing, substantiated by over 40 years of research and development, must be taken seriously by the international

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9   European Patent Office, Innovation Trends in Additive Manufacturing Report, 2023, Munich, Germany, ISBN 978-3-89605-354-1.
10   Ibid.
11   Ibid.
12   Ibid.

humanitarian and development sectors. The aim of this Insight Report is to demystify additive manufacturing and 3D printing and showcase their potential application to global challenges. The question is: what are the main application areas of additive manufacturing that would result in better outcomes for children? The motivation of this report is to showcase the *evolving capability* and *potential* of AM.

Scope

The Report does not attempt to provide an exhaustive inventory of all recent and emerging breakthroughs in additive manufacturing. Rather, it highlights selected novel technologies and processes that reflect the thematic breadth of the AM landscape. The focus is on different types of AM printing processes, material compatibility across 3D printing technologies and novel applications that are pertinent for the humanitarian and development sectors. Digital technologies, AI and machine learning, automation and robotics are out of scope of this report.
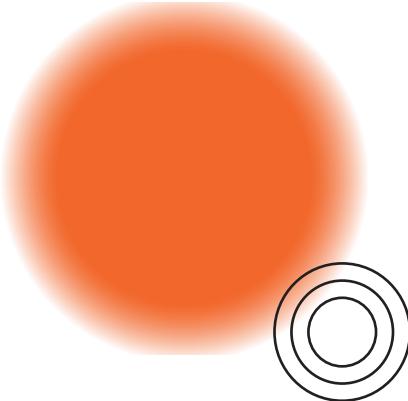
Method

An extensive literature search and review was performed using the following databases: Science Direct, Scopus and Web of Science. The review concentrated on publications in peer-reviewed academic journals and in English language. Online sources such as websites of research institutions, industry bodies, and companies were also taken into consideration.

Structure of this report
Chapter 2: Additive manufacturing: the fundamentals
This chapter demystifies additive manufacturing and the distinction between 3D printing and additive manufacturing. It describes the seven categories of AM printing process and the wide of range of materials currently used. The choice of printing process and material depends on the desired characteristics of the end-product.

Chapter 3: Application: Climate change, renewable energy, and water
This chapter looks at the application of additive manufacturing to address global challenges such as climate change, renewable energy and access to clean water. It showcases how researchers are using AM to design and fabricate carbon capture devices, components for solar panels, wind turbines, fuel cells, and geothermal energy and water treatment innovations.

office of innovation
unicef
for every child

Chapter 4: Application: Resilience
This chapter examines the potential impact of additive manufacturing to improve community resilience, disaster preparedness, and reconstruction. It showcases how 3D printing technologies can enhance earthquake early warning systems, build houses for low-income communities and improve logistical capabilities of humanitarian organizations to ensure critical spare parts reach the poorest, hardest-to-reach communities and to survivors impacted by disasters and crises.

Chapter 5: Application: Biomedical
This chapter focuses on 3D bioprinting and the opportunities of bioprinting to improve health and wellbeing. 3D bioprinting is a rapidly growing technology that is widely used in tissue engineering, disease studies, and drug discovery, and bone tissue engineering for neural, bone, and spinal implants.

Chapter 6: Application: People with disabilities
This Chapter highlights the ways in which additive manufacturing offers many promising solutions for people with disabilities. It specifically looks at how AM is transforming the field of prosthetics in low-income and remote regions and enabling the design and fabrication of light-weight 3D-printed bionic prosthetics for children. It also explores promising innovations for people with hearing and vision-impairment.

Chapter 7: Future of additive manufacturing
The final chapter considers the future of AM and asks how it can contribute to a circular economy. It investigates 4D printing, a significant progress in additive manufacturing techniques that can achieve self-assembly, self-repair, and multi-functional purposes. Additive technologies have opened a largely under-regulated pathway to the private manufacture of operational weapons within an otherwise highly regulated environment in most countries and this raises peace and security risks. The barriers to adoption of AM for international development are identified. The Chapter concludes with a call to action to unlock the potential of AM for international humanitarian and development.

2

ADDITIVE MANUFACTURING (AM) VALUE CHAIN

2.1 Additive manufacturing (AM) value chain

AM encompasses a broad set of technologies and processes that is employed to build physical parts and products from digital data. The manufacturing process leverages 3D printing technologies (and material science). 3D printing is the process used to form the object. A 3D printer is a machine that builds the part. But AM is not limited to the layer-by-layer build process, there are also pre- and post-processing steps. The AM value chain has 5 processes (Figure 3). Innovation in any process along the AM value chain would grow the field of potential applications.

Figure 3: Additive manufacturing value chain.

1 Design and 3D model creation	2 STL file generation	3 Machine and material selection	4 Fabrication	5 Post processing
A 3D model of the object is created using computer-aided design and drafting (CAD) or a 3D object scanner.	CAD model is converted to a Standard Tessellation Language (STL) file to tessellate the 3D shape and slice it into digital layers.	Additive manufacturing technology (printer) and material are selected. STL file is transferred to the machine using custom machine software.	Printer builds the object by depositing material layer by layer.	The object is removed from the build platform. Support structure removal and/or surface finishing if required.

2.2 Additive manufacturing - printing processes and materials

The ISO has categorized 7 types of additive manufacturing printing processes [13] (Figure 4). Each process is distinctive in features such as materials used, energy source, build speed, processing temperature, production rate, product properties, surface quality, lifecycle, skills and technical knowledge required; impact such as set-up and maintenance cost, emissions, energy consumption, biodegradability, waste stream and recyclability, and potential applications.

Figure 4: Categories of additive manufacturing process technologies.
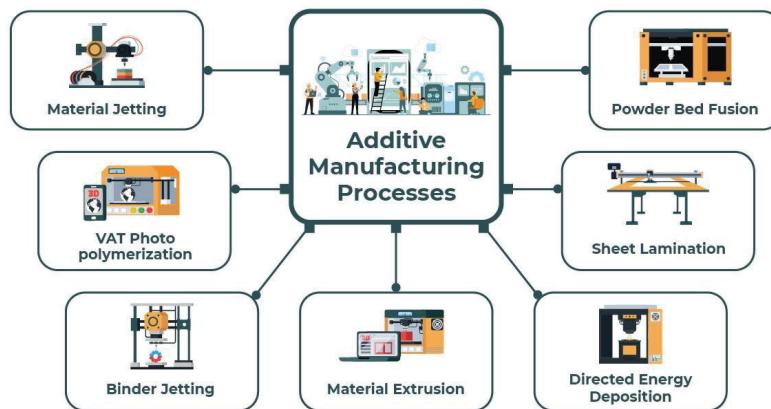
Source: The Manufacturing Report

The following sections in the chapter take a closer look at the characteristics of each AM process and the types of materials currently used to create objects.[14]

Figure 5:

© International Journal on Interactive Design and Manufacturing
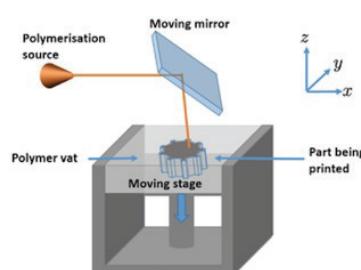
Vat photopolymerization

An AM printing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.[15] Mirrors are used to direct ultraviolet light, whilst a platform moves the object being made downwards after each new layer is cured.

13   International Organization for Standardization, ISO/ASTM 52900:2021. Standard Terminology for Additive Manufacturing - General Principles - Fundamentals and vocabulary, 2021.

14   The images for the 7 types of AM processes are from: de Pastre, M-A., Quinsat, Y, and Lartigue, C., 'Effects of additive manufacturing processes on part defects and properties: a classification review', International Journal on Interactive Design and Manufacturing, vol. 16, 2022, doi: 10.1007/s12008-022-00839-8.

15   Ibid.

Figure 6:

© International Journal on Interactive Design and Manufacturing

Directed energy deposition

An AM printing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.[16] It is a complex printing process used to repair or add additional material to existing components.
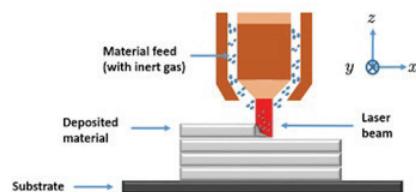
Figure 7:

© International Journal on Interactive Design and Manufacturing

Powder bed fusion

An AM printing process in which thermal energy selectively induce fusion (sintering or melting) between the particles of a plastic or metal powder one layer at a time in regions of a powder bed.[17]
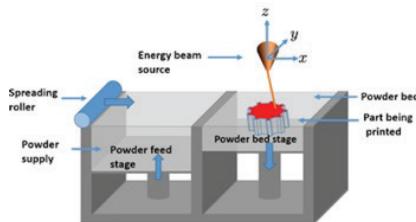
Figure 8:

© International Journal on Interactive Design and Manufacturing

Material extrusion

An AM printing process in which material is selectively dispensed through a nozzle or orifice.[18] Material is drawn through a nozzle, where it is heated and is deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited.

▶ **VIDEO: ADDITIVE MANUFACTURING - PRINTING PROCESSES**

Figure 9:

© International Journal on Interactive Design and Manufacturing
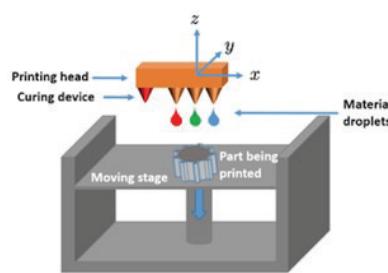
Material jetting

An AM printing process in which droplets of feedstock material are selectively

16   Ibid.
17   Ibid.
18   Ibid.

deposited.[19] Material is jetted onto a build platform using either a continuous or Drop on Demand (DOD) approach.

Figure 10:

© International Journal on Interactive Design and Manufacturing
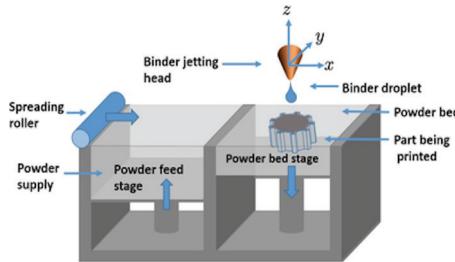
Binder jetting

An AM printing process in which a liquid bonding agent is selectively deposited to join powder materials.[20] A print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material.

Figure 11:

© International Journal on Interactive Design and Manufacturing
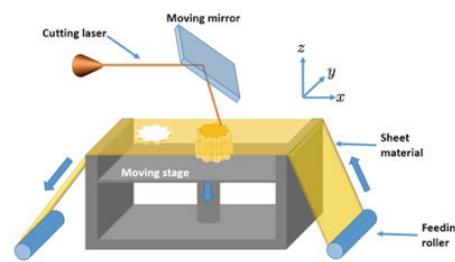
Sheet lamination

An AM printing process in which sheets of material are bonded to form a part.[21] It is one of the oldest additive manufacturing techniques that create net shape parts from bonded stacked layers of thin sheets using multiple methods.

Materials for additive manufacturing

Materials have a vital part to play for the evolution and innovation in additive manufacturing applications. A wide range of raw materials is currently used for different processes (Figure 5). The materials or feedstock, in AM terminology, come in different states, e.g., particle, liquid, powder, filament, pellets, granules, resin, and sheet.[22]

The choice of material depends on its compatibility of AM printing process and material attributes such as layer adhesion, heat resistance, impact resistance, visual quality, load stress, ease of printing, flexibility, stiffness, and porosity, and the cost of raw

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19 Ibid.
20 Ibid.
21 Ibid.
22 Kumar, M. B. and Sathiya, P., 'Methods and materials for additive manufacturing: A critical review on advancements and challenges', Thin-Walled Structures, vol. 159, 2021, doi: 10.1016/j.tws.2020.107228.

material.[23] Increasingly, research is focusing on the development of newer materials for specific applications.

Figure 12: Materials for additive manufacturing.[23]

Image adapted from A review of various materials for additive manufacturing: Recent trends and processing issues.

Advancements in materials with new or enhanced properties are opening new possibilities for AM solutions. For example, hybrid materials such as composites have emerged as a significant innovation in the field of additive manufacturing. These materials are composed of two or more different materials that are blended in various ways to create a new material with unique properties that yield benefits, such as reduced production costs and lead times and improved strength, durability, and functionality.[25] Table 1 is a summary of the fundamentals of the additive manufacturing process and the range of applications.

23 Kumar, K. and Acherjee, B., 'Revolutionizing manufacturing: A comprehensive overview of additive manufacturing processes, materials, developments, and challenges', Journal of Manufacturing Processes, vol. 107, 2023, doi: 10.1016/j.jmapro.2023.10.024.

24 Srivastava, Manu & Rathee, Sandeep & Patel, Vivek & Kumar, Atul & Koppad, Praveennath. (2022). A review of various materials for additive manufacturing: Recent trends and processing issues. Journal of Materials Research and Technology. 21. 10.1016/j.jmrt.2022.10.015.

25 Ibid.

Table 1: Summary of AM categories, processes, principles, materials and current applications

AM categories	AM processes	AM principle	AM materials	Applications
Vat photop-olymerization	• Digital light process (DLP) • Stereolithography (SLA)	• Polymerization	• Photopolymers • Metal • Ceramics • Composite • Biomaterials	• Surgical learning tools • Face prostheses • Hearing aids • Injection mould-like prototypes • Casting patterns • Soft tooling • Investment casting
Directed energy deposition	• Laser engineered net shaping (LENS) • Directed light fabrication (DLF) • Direct metal deposition (DMD) • Direct laser deposition (DLD)	• Direct energy melting	• Ceramics • Metal powder • Multimaterial	• Non-functional prototypes & rapid prototyping • Printable electronics • Wearable devices • Smart materials • Flexible nanoelectronics
Power bed fusion	• Selective laser sintering (SLS) • Selective laser melting (SLM) • Direct metal laser sintering (DMLS) • Electron beam melting (EBM	• Melting & solidification of powder	• Thermoplastic powder • Metal powder • Ceramics • Composites	• Jaw reconstruction • Knee replacement • Hip joint • Titanium alloy cranial implants • Bioprinting • Pharmaceuticals • Tissue engineering • Automotive and aviation parts
Material extrusion	• Fused deposition modelling (FDM) • Fused filament fabrication (FFF)	• Melting & freezing filaments	• Thermoplastic filament • Photopolymers • Metal • Composites • Biomaterials • Food • Concrete	• Construction, housing • Automotive Parts • Electrical Components • Medical Devices • Medical Implants • Food Packaging • Bioprinting

Material jetting	• Polyjet wax casting • Drop on demand (DOD)	• Inkjet	• Thermoplastics • Photopolymers • Metals • Ceramics • Biomaterials • Multimaterial • Sand • Sugar • Plaster • Pharmaceuticals	• Small metal parts, e.g., industrial components, spare parts, & filters • Full-coloured product prototypes, e.g., medical & dental models • Casting patterns • Bioprinting
Binder jetting	• Inkjet 3D printing • Sand binder jetting • Metal binder jetting	• Inkjet, binder & UV curing	• Metals • Ceramics • Biomaterials • Sand	• Casting patterns • Functional metal parts • Full-colour objects Sand casting
Sheet lamination	• Laminated object manufacturing (LOM) • Ultrasonic additive manufacturing (UAM)	• Sheet joining	• Thermoplastics • Paper • Metals • Composites	• Electronics, wires, and sensors • Injection mould-like prototypes • Casting models

3

APPLICATION: CLIMATE CHANGE, RENEWABLE ENERGY AND WATER

3.1 Carbon capture

Every child is already affected by at least one climate or environmental shock, and over one billion are at extremely high risk.[26] Close to 90 per cent of the burden of disease attributable to climate change is borne by children under the age of five.[27]

Increase in global temperature presents significant risks to food and water systems, to biodiversity, and to all life on Earth. Mobilizing stronger and more ambitious climate action is urgently required achieve the goal of the Paris Agreement to limit the temperature increase to 1.5°C and safeguard a liveable climate for all.[28] One method to control rising temperature is carbon capture.

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26 A Liveable Planet for Every Child UNICEF's Strategy-at-a-Glance for Climate, Environment, Energy and Disaster Risk Reduction — CEED (2022-2030) https://www.unicef.org/documents/liveable-planet-every-child

27 Sheffield, P. E., & Landrigan, P. J. (2011). Global climate change and children's health: threats and strategies for prevention. Environmental health perspectives, 119(3), 291-298.

28 Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104. The Paris Agreement - a legally binding international treaty on climate change adopted by 196 Parties at the UN Climate Change Conference in Paris, France, on 12 December 2015.

Carbon capture technologies aim to capture the CO2 generated by burning fossil fuels before it is released to the atmosphere. Removing carbon from the atmosphere requires a system of filters, heat exchangers, condensers, gas separators, and compressors.[29] The components of these technologies are complex geometries that require a high degree of precision. Precision metal additive manufacturing, a rapidly evolving field with innovative technologies and processes, can produce geometrically complex objects that cannot be manufactured using conventional methods.[30]

Scientists from the US Department of Energy have designed and additively manufactured a first-of-its-kind aluminium device that enhances the capture of carbon dioxide emitted from fossil fuel plants and other industrial processes. [31] The 3D-printed devices were able to mitigate a key challenge in conventional absorption of carbon which typically produces heat that can limit its overall efficiency. By using AM, researchers were able to custom design a multifunctional device that greatly improves the process efficiency by removing excess heat while keeping costs low.[32]

Figure 13: 3D printed mass exchanger and heat exchanger as a single multifunctional device.

© Carlos Jones/ORNL, U.S. Dept. of Energy.

The team tested the novel circular device, which integrates a heat exchanger with a mass-exchanging contactor (Figure 6). The researchers conducted a series of experiments to determine which

29   Green, S. and Attwood, M., The Role of Additive Manufacturing in Combatting Climate Change, <https://3dprint.com/293864/the-role-of-additive-manufac-turing-in-combatting-climate-change>, accessed 09 Dec 2024.

30   Cooke, S., et al., 'Metal additive manufacturing: Technology, metallurgy and modelling', Journal of Manufacturing Processes, vol. 57, 2020, doi: 10.1016/j.jmapro.2020.07.025. Aerospace and automotive industries are already deploying precision mental additive manufacturing technologies to produce highly complex components.

31   Miramontes, E., et al., 'Process intensification of CO2 absorption using a 3D printed intensified packing device'. AIChE Journal, 2020, doi: 10.1002/aic.16285.

32   Ibid.

operating conditions would produce the greatest carbon capture efficiency. The 3D-printed device significantly improved carbon dioxide absorption efficiency and served as an initial proof of concept for process intensification of CO2 absorption with 3D-printed packed beds.[33] Future research will concentrate on optimizing operating conditions and device geometry to produce additional improvements in the carbon capture absorption process.[34]

Figure 14: Polymer additive manufacturing in renewable energy.

Source: Paragon AM Technologies

Power the world
Additive manufacturing can be used to make energy production devices & components

Solar panels & circuits
▶ Fastenings
▶ Cross compund parabolic concentrators
▶ Connectors & controller components

Wind
▶ Turbines
▶ Transformer switches
▶ Anemometer cups

Fuel cells
▶ Fastenings & connectors
▶ Cooling ducts, motor mounts

Charge points
▶ Fastening & clips
▶ Dials, switches & button pads
▶ Magnetic sensors

3.2 Renewable energy

Additive manufacturing opens huge opportunities in the renewable energy sector by revolutionizing the design, development and repair of more efficient components (Figure 7).

Industry leaders such as Siemens Energy claim that additive manufacturing will act as a catalyst in some cases and accelerate and drastically improve the performance of systems such as turbines, fuel cell systems, and heat exchangers.[35] Siemens Energy has a strong AM research programme with projects on rapid prototyping, rapid repair, spare parts on demand, and rapid manufacturing.[36] Its highly durable and high-end 3D-printed turbines have accumulated more than 1.5 million hours of successful operation demonstrating the potential of AM for decarbonization.[37]

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33 Ibid.
34 Ibid.
35 Everett, H., Powering the Renewable Energy Transition with 3D printing: Component Optimization, 29 April 2022, < https://3dprintingindustry.com/news/powering-the-renewable-energy-transition-with-3d-printing-component-optimization-208619>, accessed 5 Dec 2023.
36 Siemens Global Energy, Additive Manufacturing for the Energy Industry, <https://www.siemens-energy.com/global/en/home/products-services/service/additive-manufacturing.html>, accessed 5 Dec 2023.
37 Navrotsky, V., 'Siemens Energy's Additive Manufacturing brings speed to decarbonization journey', Turbomachinery International, 2 Sep 2021, <https://www.turbomachinerymag.com/view/siemens-energy-s-additive-manufacturing-brings-speed-to-decarb-journey>, accessed 5 Dec 2023.

Solar energy

3D printing applications for solar cell development and solar cell fabrication processes are receiving a lot of attention.[38] The technology has enabled next generation design of photovoltaics, which many scientists consider to be the future of high energy solar cells. The start-up T3DP is testing its patented technologies to produce nature-inspired volumetric 3D print perovskite solar cells that are modelled on an exact replica of a fly's eye.[39] According to the founder of T3DP, volumetric 3D printing has enabled the manufacturing of copper-plated hexagon scaffolds that are capable of harnessing twice as much energy as conventional solar panels.[40]

Wind energy

The GE renewable energy research team has designed and manufactured lighter 3D-printed wind turbine blades based on their long experience in developing and commercializing similar aerodynamic structures in their aviation business.[41] GE's 3D-printed turbine blade tips require less material and produce less scrap in comparison to conventional manufacturing processes (Figure 8). The

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38   Hunde, B. R., and Woldeyohannes, A. D., '3D printing and solar cell fabrication methods: A review of challenges, opportunities, and future prospects', Results in Optics, vol. 11, May 2023, doi: 10.1016/j.rio.2023.100385.

39   Everett, H., Powering the renewable energy transition with 3D printing: solar, 19 Feb 2023, <https://3dprintingindustry.com/news/powering-the-renewable-energy-transition-with-3d-printing-solar-204566>, accessed 5 Dec 2023.

40   Ibid.

41   Everett, H., GE to advance competitiveness of wind energy with 3D printed turbine blades, 8 Feb 2021, <https://3dprintingindustry.com/news/ge-to-advance-competitiveness-of-wind-energy-with-3d-printed-turbine-blades-183959>, accessed 5 Dec 2023.

simplified production process will lower the manufacturing cost of the part and potentially increase the supply chain flexibility of the turbine blade tips, reduce the part's design cycle time and use more recyclable materials.[42] At first, the AM technology will be used for new turbines, but eventually it could be retrofitted onto old turbines to optimize local wind resources.

Geothermal energy

New tools and equipment are required to help harness steam from superheated rock deep beneath the earth's surface for emerging geothermal energy technologies.[43] Current packers or plugs are made of rubber or plastic, which degrades at geothermal temperatures. Machining the part would be ineffective because a critical component of the packer technology is a ring system with internal. Direct Metal Laser Sintering (DMLS) is becoming the technology of choice because it can handle the complex design of metal component manufacturing and can be specifically designed for geothermal wells' high temperatures, high pressures, and corrosive nature.[44] A metal tool can withstand the extremely high temperatures. Italian renewable energy company Enel Green Power is using 3D printing to repair critical technical parts in its geothermal power plants.[45]

The transition to affordable and accessible renewable energy, especially solar, is one of the best investments that can be made to reduce the risks from climate change and to ensure a liveable planet for children.[46]

3.3 Water

Water is life. Access to and sustainable management of clean water are critical for health of people and planet. Millions of people die every year from diseases associated with polluted water. Young

42   Ibid.
43   A packer is a tool for the zonal isolation of a well, and at high pressure and high temperature conditions, which is common for geothermal wells. See Abid, K., et al., 'A Review on Geothermal Energy and HPHT Packers for Geothermal Applications', Energies, vol. 15, no. 19: 7357. 2022, doi: 10.3390/en15197357.
44   Shaikhnag, A., Protolabs and downholes emerging technologies: A novel approach toward metal 3DP geothermal Energy, 16 Jan 2023, < https://3d-printingindustry.com/news/protolabs-and-downhole-emerging-technol-ogies-a-novel-approach-toward-metal-3dp-geothermal-energy-219839>, accessed 5 Dec 2023.
45   Enel Green, Renewable Energies, <https://www.enelgreenpower.com/learn-ing-hub/renewable-energies>, accessed 5 Dec 2023.
46   UNICEF, Renewable energy: emerging technologies and innovations. Insight Report No.2, UNICEF Office of Innovation, New York, 2023. License: CC-BY 4.0

children are particularly vulnerable.

Environmental scientists and engineers are exploring the benefits of 3DP for membrane separation, desalination, water purification, and water quality monitoring. 3DP technology can be used for the fabrication of miniature devices for water toxicity management and environmental assessments, and of specific parts of water treatment systems or membrane modules. The use of 3DP technologies for water and wastewater treatment and resource recovery can reduce costs and industrial waste from manufacturing processes, with substantial benefits to treatment performance.[47]

Water toxicity management

The combination of 3DP methods such as fused deposition modelling (FDM), direct ink wetting (DIW) and stereolithography (SLA) with nature-derived biopolymers and biopolymer-based materials including chitosan, polylactic acid (PLA), alginate and cellulose acetate (CA) offer enormous potential for developing bio-based, reusable, custom-optimized and scalable water purification filters, meshes and membranes suitable for removal of water contaminants such as metals and dyes as well as for oil separation applications[48] (Figure 9). Similar 3D printing technologies for wastewater treatment provide remote communities and remote health services significant benefit from potential on-site fabrication of membrane units suitable to their specific wastewater challenges.[49] 3D printing of customized membranes provides an opportunity for a fast response to disastrous events such as water contamination associated with toxic by-products from algal blooms, chemical spills, and fires. These 3D-printed membranes could be ready for installation within hours.

47 Aghaei, A., et al., 'The implications of 3D-printed membranes for water and wastewater treatment and resource recovery', The Canadian Journal of Chemical Engineering, June 2022, doi: 10.1002/cjce.24488.

48 Fijoł, N., Aguilar-Sánchez, A. and Mathew, A. P., '3D-printable biopolymer-based materials for water treatment: A review', Chemical Engineering Journal, vol 430, 3, 2022, doi: 10.1016/j.cej.2021.132964.

49 Yanar, N., et al., 'A New era of water treatment technologies: 3D printing for membranes', Journal of Industrial and Engineering Chemistry, vol 91, 2020, doi: 10.1016/j.jiec.2020.07.043.

Figure 15: 3D printed biopolymer for water treatment.

Source: Fijoł, N., Aguilar-Sánchez, A. and Mathew, Aji P., '3D-printable biopolymer-based materials for water treatment: A review', Chemical Engineering Journal, vol. 430, 2022, doi: 10.1016/j.cej.2021.132964.
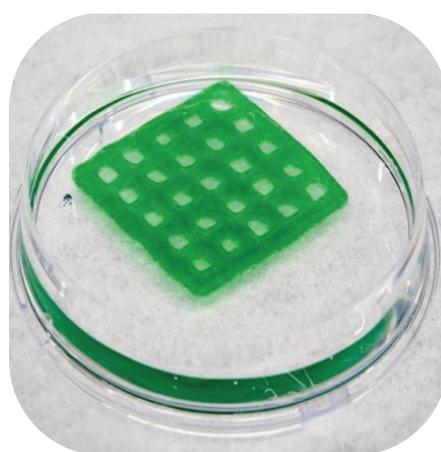
Water treatment

A multidisciplinary team at the University of California, San Diego, has produced a genetically engineered bacteria that removes pollutants and then dissipates once the task is completed.[50] The bacteria produce an enzyme that transforms organic pollutants into harmless molecules[51] (Figure 10). A polymer derived from seaweed is hydrated to make a gel and mixed with cyanobacteria and then loaded into a 3D printer to create a filter.[52] Through a series of experiments, the scientists discovered a grid-like structure is most effective at keeping the bacteria alive because it has a higher surface area to volume ratio, placing the bacteria near the surface and making decontamination more effective.[53]

50 Datta, D., et al., 'Phenotypically complex living materials containing engineered cyanobacteria', Nature Communications, vol. 14, no 1, 2023, doi: 10.1038/s41467-023-40265-2.

51 University of California, '3D-printed 'living material' could clean up contaminated water', ScienceDaily, 5 September 2023. <www.sciencedaily.com/releases/2023/09/230905124850.htm>, accessed 5 Dec 2023.

52 Ibid.

53 Ibid.

Water quality monitoring

Another application of 3D printing technologies is in sensor development for water quality monitoring due to their high versatility, fast fabrication and modification, ability to work with different materials and ease of incorporation with other sensor systems. Researchers at University of British Columbia have designed and built a tiny device using a 3D printer that can monitor drinking water quality in real time and help protect against waterborne illness. The research has produced promising results for 3D-printed miniature water quality sensors that can operate continuously and can be deployed anywhere in the water distribution system, regardless of water pressure or temperature.[54] The highly portable sensor system is capable of constantly measuring several water quality parameters such as turbidity, pH, conductivity, temperature, and residual chlorine, and sending the data to a central system wirelessly.[55]

A dedicated Innovation Node Insight Report on the Future of WASH is available and reviews emerging approaches and technologies that hold potential benefit for children and their communities.

54   Banna, M., et al., '3D Printing-Based Integrated Water Quality Sensing System', Sensors, vol. 17, no. 6, 2017, doi: 10.3390/s17061336.
55   University of British Columbia Okanagan campus, '3-D-printed water quality sensor tested', ScienceDaily, 19 July 2017, <www.sciencedaily.com/releases/2017/07/170719092142.htm>, accessed 6 Dec 2023.

APPLICATION: DISASTER RISK REDUCTION AND CLIMATE RESILIENCE

4.1 Earthquake early warning

Oil and gas extraction, particularly hydraulic fracturing, can trigger small, slow-moving, longer-lasting earthquake tremors.[56] Geoscientists at Sandia National Laboratories and Purdue University are using 3D-printed rocks and an advanced, large-scale computer model of past earthquakes to understand and prevent earthquakes triggered by energy exploration. They have developed 3D-print models of rocks that would fracture under the same conditions and pressure caused by injecting water underground to help them understand different types of fault failures and their warning signals[57] (Figure 11). The ability to design and produce these rocks under controlled conditions and with specific variability allows the geoscientists to collect important information about the fundamental processes of fracturing and its impact on fluid flow in rocks.[58] The fracturing rock samples produce acoustic waves which are signs of microcracks.

56   Yu, H., et al., 'Fluid-injection-induced earthquakes characterized by hybrid-frequency waveforms manifest the transition from aseismic to seismic slip', Nature Communications 12, 6862, 2021, doi: 10.1038/s41467-021-26961-x.

57   DOE/Sandia National Laboratories, 'Catching energy-exploration caused earthquakes before they happen', ScienceDaily, <www.sciencedaily.com/releases/2021/03/210310150426.htm>, accessed 5 December, 2023.

58   Ibid.

The team used a machine-learning technique known as a random forest algorithm to cluster the micro seismic events into groups that were caused by the same types of microstructures and identify about 25 important features in the microcrack sound data and ranked these features by significance.[59] The research team believes they will be able to detect hidden faults that might become unstable due to carbon sequestration or geothermal energy stimulation and induced earthquakes related to fossil fuel activities in oil or gas fields faster and with a higher level of accuracy than conventional earthquake monitoring systems within five years.[60]

▶ **VIDEO: SANDIA NATIONAL LABS - CRACKING ROCKS TO CATCH QUAKES.**

4.2 Local manufacturing

In the past decade, additive manufacturing, especially 3D printing technologies have improved their usability and to a degree, affordability for use in local manufacturing.[61] 3D printing offers an 'on-site, on demand, on time' solution to the last mile challenges in humanitarian and development operations.[62] During times of crisis, supply chain costs rise, resources are in short supply and time is of essence.[63] 3D printing technologies can enhance logistical capabilities of humanitarian organizations to ensure critical spare parts reach the poorest, hardest-to-reach communities.[64]

59   Ibid.
60   Jiang, L., et al., 'Mineral Fabric as a Hidden Variable in Fracture Formation in Layered Media', Scientific Reports, vol. 10, no.1, 2020, doi: 10.1038/s41598-020-58793-y.
61   Savonen, B., et al., 'Development of a Resilient 3-D Printer for Humanitarian Crisis Response', Technologies, vol. 6, no. 1, 2018, doi:10.3390/technologies6010030, and Wong, J. Y., 'Ultra-Portable Solar-Powered 3D Printers for Onsite Manufacturing of Medical Resources', Aerospace Medicine and Human Performance, vol. 86, no. 9, 2015, doi: 10.3357/AMHP.4308.2015.
62   Saripalle, S. et al., '3D printing for disaster preparedness: Making life-saving supplies on-site, on-demand, on-time', in 2016 IEEE Global Humanitarian Technology Conference, 2016, doi: 10.1109/GHTC.2016.7857281.
63   De la Torre, N., Espinosa, M. M., and Domínguez, M., 'Rapid Prototyping in Humanitarian Aid to Manufacture Last Mile Vehicles Spare Parts: An Implementation Plan: Rapid Prototyping in Humanitarian Aid', Human Factors and Ergonomics in Manufacturing & Service Industries, vol. 26, no. 5, 2016, doi:10.1002/hfm.20672.
64   Corsini, L., et al., 'Using Digital Fabrication Tools to Provide Humanitarian and Development Aid in Low-Resource Settings,' Technology in Society, vol. 58,

Whereas conventional manufacturing methods deliver cost effectiveness through economies of scale, AM allows for economies of scope - efficiencies resulting from variety and diversification. 3D printing enables humanitarian organizations to respond to changing needs without significant investment in tooling and fixed costs.[65] Humanitarian and development organizations such as the UN Office for the Coordination of Humanitarian Affairs (OCHA)[66], ELHRA's Humanitarian Innovation Fund, Médecins Sans Frontières (MSF), Oxfam, American Red Cross, and Field Ready, just to name a few, are exploring and deploying this technology to produce 3D-printed solutions (often vital parts) whenever a need arises, close to the deployment points or locations, and in remote environments. Oxfam deployed 3D-printed water pipes and medical equipment part of its Nepal earthquake relief effort.[67]

Several studies suggest 3D printing for localized and distributed manufacturing would bring significant value in low-resource environments, including:[68]

- reduce complexity in planning and needs identification;[69]
- reduce shipping cost and time;[70]
- reduce storage need and cost;[71]
- enhance ability to produce bespoke items that are not readily available to meet the need of the situation;[72]
- improve resource efficiency - the same material can be used to manufacture different parts[73] and
- improve technical skills of local people so they can address their

2019, doi: 10.1016/j.techsoc.2019.02.003.

65 Baumers, M., et. al., 'The cost of additive manufacturing: Machine productivity, economies of scale and technology-push', Technological Forecasting and Social Change, vol. 102, 2016, doi: 10.1016/j.techfore.2015.02.015.

66 James, E. and Gilman, D. Shrinking the Supply Chain: Hyperlocal manufacturing and 3D printing in humanitarian response, UN office of the Coordination of Humanitarian Affairs, OCHA Policy and Studies Series 14, July 2015.

67 Tess, '3D Printed Water Pipes and Medical Equipment Part of Oxfam's Major Nepal Earthquake Relief Effort', 3ders, November 15, 2016, <https://www.3ders.org/articles/20161115-3d-printed-water-pipes-and-medical-equipment-part-of-oxfams-major-nepal-earthquake-relief-effort.html>, accessed 23 Jan 2024.

68 James, L., 'Opportunities and challenges of distributed manufacturing for humanitarian response', in 2017 IEEE Global Humanitarian Technology Conference, 2017, doi: 10.1109/GHTC.2017.8239297.

69 Shah, et al., 'Contribution of Additive Manufacturing Systems to Supply Chain', in 2017 International Conference on Industrial Engineering, 2017, doi: 10.1109/ICIMSA.2017.7985586.

70 Ibid.

71 Behl, A. and Dutta, P., 'Humanitarian Supply Chain Management: A Thematic Literature Review and Future Directions of Research', Annals of Operations Research, vol. 283, 2019, doi: 10.1007/s10479-018-2806-2.

72 Ibid.

73 da Costa, S. R. A., et al., 'Supply Chains in Humanitarian Operations: Cases and Analysis', Procedia – Social and Behavioral Sciences, vol. 54, 2012, doi: 10.1016/j.sbspro.2012.09.777.

own needs.[74]
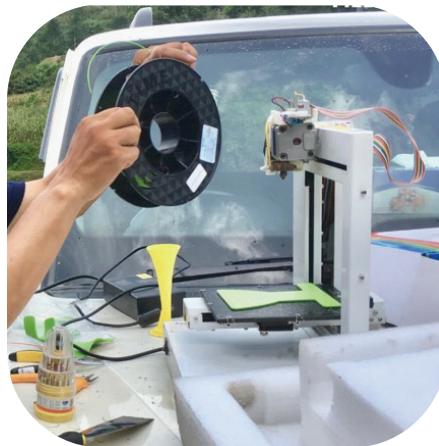
Field Ready, established in 2014, has leveraged AM and 3D printing technology to improve the delivery of humanitarian assistance (Figure 12). 3D printing has allowed Field Ready to develop low-cost solutions for health and sanitation exactly where it is needed in a range of country contexts, including Nepal, Bangladesh, Kenya, Somalia, Colombia, Haiti, Syria, Jordan, Iraq and the Pacific.[75] Since 2017, they have created kits that provided all the equipment and information needed for reliable local manufacture of specific supplies and parts, enabling their most useful designs to be replicated in other places.

Use case: 3D-printed umbilical cord clamp in Haiti

Neonatal umbilical sepsis accounts for as much as 5 per cent of newborn fatalities in Haiti.[76] A clinic needs about 50 umbilical cord clamps a month but they are expensive and can only be bought in bulk from China. Strings and shoelaces have been used but this increases the likelihood of sepsis and of the cord not being closed properly. International volunteers bring clamps in their luggage but this is highly unpredictable. Using a basic design that is tailored to meet local preferences, onsite manufacturing of clean umbilical cord clamps using a basic 3D printing can print dozens of inexpensive clamps a day.[77]

SEE SECTION 7: THE FUTURE OF ADDITIVE MANUFACTURING

FOR MORE INFORMATION ON EFFECTIVE LOCALISATION.

74   Davies, S., 'Industry 4.0 Manufacturing Principles Leveraged in Disaster Areas by Field Ready', Tct Magazine, June 28, 2018, <https://www.tctmagazine.com/3d-printing-news/industry-4.0-manufacturing-disaster-areas-field-ready>, 29 Dec 2023.
75   Field Ready, <www.fieldready.org>, accessed 24 Jan 2024.
76   Saripalle, S. et al., '3D printing for disaster preparedness: Making life-saving supplies on-site, on-demand, on-time'.
77   Ibid.

4.3 Construction

AM technologies have advanced significantly since the first structure was tested by NASA in 2013.[78] After years of evolution, additive manufacturing is developing the capacity to print large-scale architectural models and buildings and reinvigorating the early interest to apply this technology to provide low-cost housing and offer fast recovery in post-disaster scenarios.[79]

Construction materials

The most common materials for 3D printing structures are concrete, polymer and metallic materials. Alternative materials, particularly local materials such as marine sediments, glass/basalt fibre mixed with seawater, raw soil, cellulose such as rice husks and straw, lime, clay, and bark are also being tested.[80] But a feasible construction material must be able to go through a 3D printer's pump and nozzle with ease and must be strong enough to resist deformation under stress.[81]

Sustainable construction examples

Assistant Professor of Architectural Engineering at The British University in Egypt Deena El-Mahdy's research in the behaviour of ants, termites, bees, and wasps and their natural environment led to using additive manufacturing to construct architectural forms that use sustainable local materials but only the minimum amount of needed and generate less waste.[82] El-Mahady has experimented with different materials

78   Wu, P., Wang, J., and Wang, X., 'A critical review of the use of 3-D printing in the construction industry', Automation in Construction, vol. 68, 2016, doi: 10.1016/j.autcon.2016.04.005.

79   Bazli, M., et al., '3D printing for remote housing: Benefits and challenges', Automation in Construction, vol. 148, 2023, doi: 10.1016/j.autcon.2023.104772.

80   L. Li, B. Xiao, Z. Fang, Z. Xiong, S. Chu, A. Kwan, Feasibility of glass/basalt fiber reinforced seawater coral sand mortar for 3D printing, Additive Manufacturing 37 (2021) 101684, doi: 10.1016/j.addma.2020.101684.

81   El-Sayegh, S., Romdhane, L., and Manjikian, S., 'A critical review of 3D printing in construction: benefits, challenges, and risks', Archives of Civil and Mechanical Engineering, vol. 20, no. 2, 2020, doi: 10.1007/s43452-020-00038-w.

82   El-Mahdy, D., Hisham S. Gabr, H. S. and Abdelmohsen, S., 'SaltBlock as a 3D printed sustainable construction material in hot arid climates', Journal of building engineering, vol. 43, 2021, doi: 10.1016/J.JOBE.2021.103134.

such as salt, sand, clay, algae, and earth, and eventually developed SaltBlock (salt rock mixed with clay) - a 3D-printed sustainable construction material in hot arid climates.[83]   Her unique approach to sustainable construction combines the use of Karshif a salt-based traditional building material used in Siwa Oasis in Western desert region in Egypt with AM to develop a low-cost composite with thermal performance that is particularly suitable for hot arid climates.[84] This research is an encouraging demonstration of how technology, conservation and cultural heritage can work together for socio-economic empowerment and sustainable regeneration in challenging environments.

In Estonia, the University of Tartu and the Estonian University of Life Sciences have created a low-cost 3D-printed concrete material made primarily of milled peat, with oil shale ash serving as a binder.[85] Silica nanoparticles are added to the mix. Their study concludes that using peat composites in the construction industry allows reducing CO_2 emissions from partially mined peatlands (currently the one of the largest contributors to the total CO_2 emission from Estonia) and increasing the reuse of oil shale ash while providing a cheap and affordable raw material.[86]

3D-printed houses

Though 3D-printed houses remain a niche space, industrial 3D printers implemented by entities like Apis Cor and ICON, are printing houses and buildings around the world.[87] Once the equipment is sourced, the cost effectiveness of 3D-printed houses is highly attractive.

83   Ibid.
84   El-Mahdy, D. and Mohamed, A., 'Assessing the solar radiation performance of self-shaded 3D-printed clay-based façades', Architectural Engineering and Design Management, 2023, doi: 10.1080/17452007.2023.2285325.
85   Saunders, S., 'Estonian Researchers Create 3D Printable Peat Mixture for Cost-Effective Home Construction', 11 July 2018, <https://3dprint.com/219054/3d-printed-peat-houses>, 12 Dec 2023.
86   Jüri Liiv, J., et al., 'Novel ecosustainable peat and oil shale ash-based 3D-print-able composite material', Sustainable Materials and Technologies, vol 17, e00067, 2018, doi: 10.1016/j.susmat.2018.e00067.
87   3dsourced, 12 Most Exciting 3D Printed Houses in 2024, <https://www.3dsourced.com/guides/3d-printed-house-2>, accessed 17 Jan 2024.

ICON, a US-based 3D printing construction company, has built over 800 low-cost houses in Haiti, El Salvador, Bolivia and Mexico [88]. COBOD International is using AM technology to design and build schools and houses in Malawi, Kenya, Angola, Malaysia, Indonesia and Egypt.[89] Dubai aims to 3D print 25 per cent of new buildings by 2030.[90]

Cost and eco-efficiency

The construction sector accounts for 36 per cent of worldwide energy demand, and 40 per cent of the global energy and process related emissions.[91] Table 2 is a comparison of the cost between traditional and 3D printing methods for a building wall.

A recent study assessed the eco-efficiency of 3D printing compared to conventional construction methods in large-scale structural fabrication in the UAE.[92] The UAE case is of particular interest from a sustainability perspective due to the environmental footprint of the ample construction activities in the country, combined with the ambitious strategic plans to achieve SDGs.[93] The comparative analysis was carried out on a single-story house and found 3D printing method better environmental performance due to the absence of formworks, steel reinforcement and the lower use of materials, compared to conventional construction alternatives (Figure 16).[94] Similar studies show that 3D-printed construction has up to a 49 per

Table 2: Cost between traditional and 3D printing methods for a wall made from 40 MPa concrete.

Source: Bazli, M., et al., '3D printing for remote housing: Benefits and challenges', Automation in Construction, vol. 148, 2023, doi: 10.1016/j. autcon.2023.104772.

Item	Traditional method			3D Printing		
	Cost ($/m3)	Amount (m3)	Price ($)	Cost ($/m3)	Amount (m3)	Price ($)
Concrete	200	150	30,000	250	150	37,50
Pumping	20	150	3000	20	150	3000
Labour	20	150	3000	–	–	–
Formwork	100	1500	150,000	–	–	–
Total			186,000			40,50

88   For more information, www.iconbuild.com/projects
89   For more information, https://cobod.com/projects-partners
90   Jezard, A., 'One-quarter of Dubai's buildings will be 3D printed by 2025', May 15, 2018, <https://www.weforum.org/agenda/2018/05/25-of-dubai-s-build-ings-will-be-3d-printed-by-2025>, accessed 15 Dec 2023.
91   17 Global Goals, 'Sustainable development goals, and the construc-tion industry', 2020, <https://17globalgoals.com/sustainable-develop-ment-goals-and-the-construction-industry>, accessed 20 Dec 2023.
92   Abdalla, H., et. al., 'Environmental Footprint and Economics of a Full-Scale 3D-Printed House', Sustainability, vol. 13, 11978, 2021, doi: 10.3390/su132111978.
93   Ibrahim, I., et al., '3D Printing in Sustainable Buildings: Systematic Review and Applications in the United Arab Emirates', Buildings, vol. 12, 2022, doi: 10.3390/buildings12101703.
94   Abdalla, H., et. al., Environmental Footprint and Economics of a Full-Scale 3D-Printed House'.

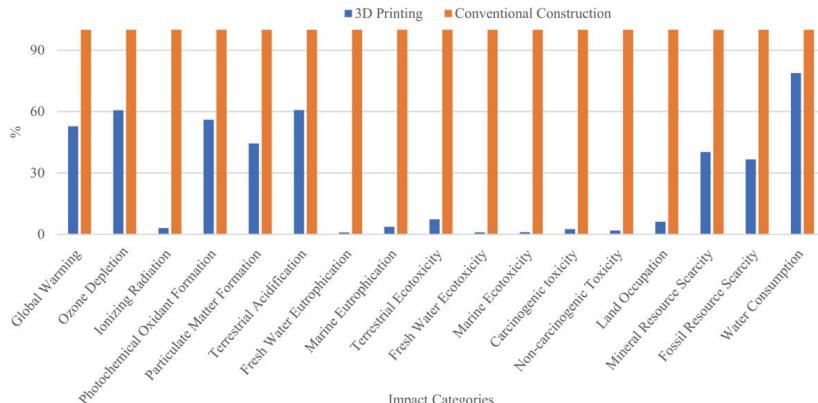**Figure 16: Environmental impacts of 3D printed & conventionally constructed houses.**

Source: Abdalla, H., et. al., 'Environmental Footprint and Economics of a Full-Scale 3D-Printed House', Sustainability, vol. 13, 11978, 2021, doi: 10.3390/su132111978.

cent smaller environmental footprint and was 78 per cent more cost-effective than conventional construction techniques.[95]

Context-resilient design

COBOD International, a global leader in industrial 3D printers partnered with the Danish architecture company 3DCP Group to design and Central and South America's cement industry leader, Progreso, to design and create a 3D-printed house that can resist a 9.0 magnitude earthquake in Guatemala.[96] The 49 square meter house was constructed in 26 printing hours over seven nights (Figure 14). The resistance to earthquakes is achieved through an "organic" design, like the one of living organism with curves that result in strength.[97] The roof was made of palm leaves that can be found throughout Central America and are a traditional construction material. The key goal of the project was to test and verify the structural integrity of 3D construction printing in a seismic-prone region.

The key goal of the project was to test and verify the structural integrity of 3D construction printing in a seismic-prone region.[98]

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95   Ibrahim, I., et al., '3D Printing in Sustainable Buildings: Systematic Review and Applications in the United Arab Emirates'.

96   Duboust, O., 'Progreso 3D-Printed a House That Can Withstand a 9.0 Magnitude Earthquake', 25 Oct 2023, <https://amchronicle.com/news/progreso-3d-printed-a-house-that-can-withstand-a-9-0-magnitude-earthquake>, accessed 13 Dec 2023.

97   Chang, B., 'Guatemala's first 3D-printed tiny home is 527 square feet and was designed to resist earthquakes', 2 Nov 2023, < https://www.businessinsider.com/3d-printed-tiny-home-guatemala-earthquke-resistant-photos-2023-11?op=1>, accessed 13 Dec 2023.

98   Duboust, O., 'Progreso 3D-Printed a House That Can Withstand a 9.0 Magni-

Post-conflict application

The non-profit technology and humanitarian start-up TEAM4UA is using 3D printing technology from COBOD International to build new schools. The school will be a hybrid of 3D-printed spaces and sections built by hand using wood and other materials and is intended as a potential blueprint for erecting similar facilities.[99] This is an example of possible post-conflict application including but not limited to houses, schools and clinics.

Moving forward

Construction additive manufacturing is still far from full-scale commercial deployment, but the technologies have demonstrated operational effectiveness in various real-world contexts. The future value of additive manufacturing for affordable housing, emergency shelters, and other structures will depend on raising awareness of the benefits and addressing the challenges to implementation at scale outlined below[100] (Table 3).

Table 3: Benefits and challenges of 3D printing for constructions.

Benefits	Challenges
• Shorten construction time • Reduction in project cost • Flexibility in design, reconfiguration and modification • Sustainability and construction waste reduction • Printing non-structural elements - furniture, kitchen bench	• Product appearance (looks rough and unfinished) • Construction setup and planning • Initial cost of accessing and transporting equipment • Materials suitability • Integration of utilities • Lack of codes and standards on the use of 3D printing in construction • Structural integrity and durability - properties of 3D-printed elements could change over time. • Training needed for construction workers

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tude Earthquake', 25 Oct 2023.
99   See www.wearehit.org
100 Bazli, M., et al., '3D printing for remote housing: Benefits and challenges', Automation in Construction, vol. 148, 2023, doi: 10.1016/j.autcon.2023.104772.

5
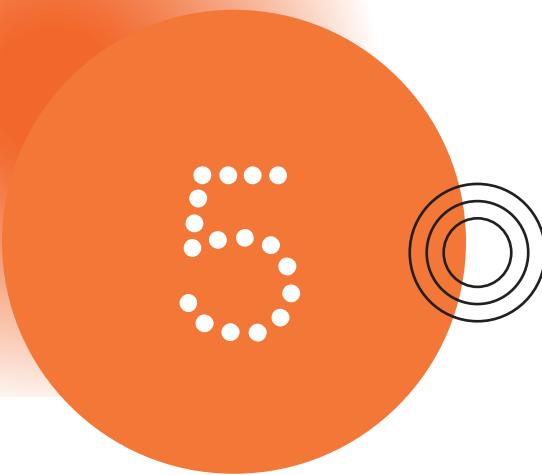
APPLICATION: BIOMEDICAL

5.1 Bioprinting

3D tissue fabrication is common practice in tissue engineering and regenerative medicine. But conventional 3D biofabrication techniques such as scaffolding, microengineering, and fiber and cell sheet engineering are limited in their capacity to build precise and controllable complex tissue constructs that is needed to replicate biologically relevant tissues.[101] 3D bioprinting is emerging as a promising approach for fabricating complex biological constructs in a precise and controlled manner for numerous clinical applications.[102]

The advent of 3D bioprinting is transforming animal-free research models. 3D bioprinting combines additive manufacturing, biology and material sciences to create layer-by-layer models, but instead of using customary materials such as plastic, ceramic, or metal, they deposit layers of biomaterial that may include living cells to build complex structures to like blood vessels, bone, or skin tissue, and, potentially, whole organs for use in medical procedures, training and testing.[103] The value 3D bioprinting brings is a highly sustainable and

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101 Heinrich, M. A., et al., '3D Bioprinting: from Benches to Translational Applications', Small, vol. 15, no. 23, 2019, doi: 10.1002/smll.201805510.

102 Dey, M., and Ozbolat, I.T., '3D bioprinting of cells, tissues and organs', Scientific Report, vol. 10, 2020, doi: 10.1038/s41598-020-70086-y.

103 Ozbolat, I. T., 3D Bioprinting: Fundamentals, Principles and Applications, Elsevier Inc., Amsterdam, 2016.

adaptable technique and technology to carry out preclinical research on tissue regeneration such as cardiac, bone, corneal, cartilage, neural, and skin, drug development, personalized medicine, and systems biology.[104] Not surprisingly, the biomedical industry has been early adopters of the technology.

Trends in 3D bioprinting

Based on a detailed review of almost 10,000 scientific publications, from 2000 to 2020, with most of them published in the last few years, R&D on 3D bioprinting is focusing in three key areas:[105]

- Application - research on specific use of 3D bioprinting.[106]
- 3D bioprinting technology - research to improve the resolution and accuracy of 3D bioprinting, while avoiding cell damage, support the design of complex shapes, reduce printing time and costs, and allow specific functionalities.[107]
- Bioink - research to develop novel bioink formulations that improve printability and functionality.[108]

Application-driven research

In the review of the applications of 3D bioprinting, about 40 per cent of all publications refer to a specific tissue or organ starting with their title.[109] Many papers are on bone, cartilage and articular cartilage, vascularized tissue, cardiac tissues, liver, neural tissue, skin, pancreas, cornea, kidney, muscle, drug discovery, drug screening, and pharmaceutical applications.[110] Emerging topics include dental tissue, nerve regeneration, lung, intestine, thyroid gland, urethra and encapsulated T-cells, wound healing, graft and implants, epilepsy, diabetes, degenerative diseases, pathology models, and organs-on-a-chip, immune-enhanced organoids for immunotherapy (Figure 15).[111]

3D bioprinting technology

Bioprinting technologies are classified into three major groups including extrusion-, inkjet- and laser-based bioprinting techniques (Figure 16).

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104 Ibid.
105 Santoni, S., et al., '3D bioprinting: current status and trends - a guide to the literature and industrial practice', Bio-design and Manufacturing, vol. 5, 2022, doi: 10.1007/s42242-021-00165-0.
106 Ibid.
107 Ibid.
108 Ibid.
109 Ibid.
110 Ibid.
111 Ibid.

Figure 17: Scientific publications on applications of 3D bioprinting.

Source: Santoni, S., et al., '3D bioprinting: current status and trends - a guide to the literature and industrial practice' Bio-design and Manufacturing, vol. 5, 2022, doi: 10.1007/s42242-021-00165-0.
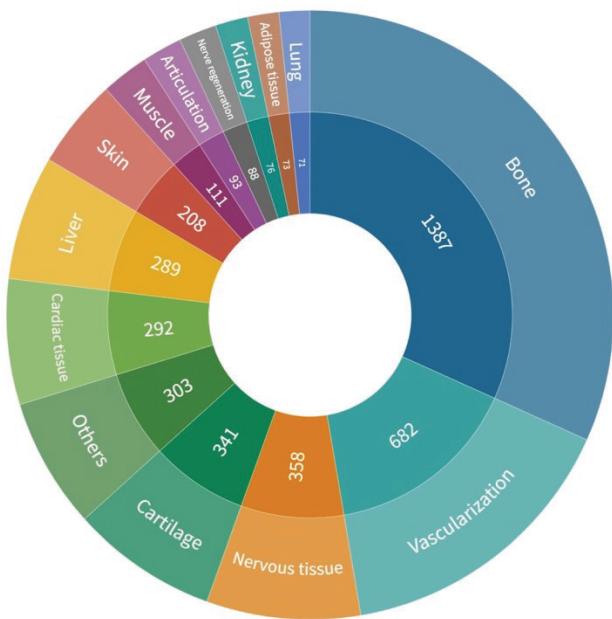
Figure 18: Schematic representation of the main 3D bioprinting technologies.

Source: Gungor-Ozkerim, P Selcan et al., 'Bioinks for 3D bioprinting: an overview', Biomaterials science vol. 6, no. 5, 2018, doi:10.1039/c7bm00765e
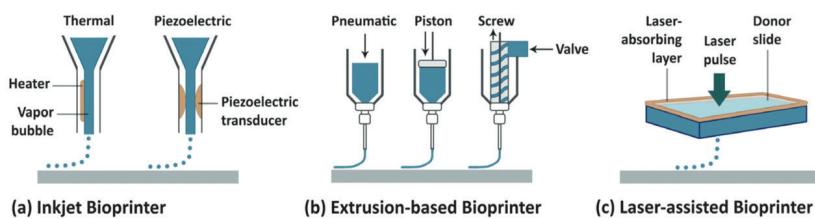
Extrusion-based bioprinting employs mechanical, pneumatic or solenoid dispenser systems to deposit bioinks in a continuous form of filaments.[112] The technology has great versatility in printing various biologics including cells, tissues, tissue constructs, organ modules, and microfluidic devices in applications from basic research and pharmaceutics to clinics.[113] The technology can print a wide range of bioinks including tissue spheroids, tissue strands, cell pellet, microcarriers, decellularized matrix components, and cell-laden hydrogels due to its flexibility in using large nozzles and a wide variety of extrusion mechanisms.[114]

Droplet-based bioprinting (DBB) relies on the generation of bioink droplets by thermal, acoustic or electrical stimulation.[115] It offers simplicity and agility with precise control on deposition of biologics including cells, growth factors, genes, drugs, and biomaterials.[116]

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112 Dey, M., and Ozbolat, I.T., '3D bioprinting of cells, tissues and organs'.
113 Ozbolat, I. T., 3D Bioprinting: Fundamentals, Principles and Applications.
114 Ibid.
115 Dey, M., and Ozbolat, I.T., '3D bioprinting of cells, tissues and organs'.
116 Ozbolat, I. T., 3D Bioprinting: Fundamentals, Principles and Applications.

DBB technology has numerous application areas, including tissue engineering and regenerative medicine, transplantation and clinics, pharmaceutics and high-throughput screening, and cancer research.[117] But inkjet-based bioprinting faces several challenges such as a restricted range of bioink materials available, bioprinting-induced cell damage at substantial levels, limited mechanical and structural integrity of bioprinted constructs, and restrictions on the size of constructs due to lack of vascularization and porosity.[118]

Laser-assisted bioprinting uses laser power to 3D print structures such as in Stereolithography by a photopolymerization principle.[119] Laser-based bioprinting provides high resolution and precision in fabrication of high-cell density tissue constructs.[120] But laser-based bioprinting complex and costly laser-involved setup and limited ability to generate heterocellular three-dimensional thick constructs means it used less in bioprinting domain than other bioprinting modalities.[121] Table 4 outlines the advantages and disadvantages of three 3D bioprinting technology.

Table 4: Advantages and disadvantages of 3D bioprinting technologies

3D bioprinting technology	Advantages	Disadvantages	Applications
Inkjet-based	• Easy modification • Simple operation • Good precision • Fast printing speed • Colour printing and readily available • Nonflat surfaces can be used as substrates • Concentration can be varied	• The size is enormous. • Limited variety of bioink • Thermal and acoustic stress is generated on cells • Nozzles are prone to clogging • Limited printing height • Lack of effective structural integrity	• Skin • Cartilage • Bone • Blood vessel

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117 Ibid.
118 Ozbolat, I. T., 3D Bioprinting: Fundamentals, Principles and Applications.
119 Dey, M., and Ozbolat, I.T., '3D bioprinting of cells, tissues and organs'.
120 Ozbolat, I. T., 3D Bioprinting: Fundamentals, Principles and Applications.
121 Ibid.

Extrusion-based	• Wide range of biomaterial available • Open access software and hardware available • Multiple material can be printed simultaneously • Large organs can be fabricated • Porous complex models can be printed	• Mechanical or shear stress causes low cell viability • Gelation and solidification of the polymer is required • High temperature may damage cells	• Blood vessel • Cartilage and bone • Muscle • Liver-on-a-chip
Laser-assisted	• A wide range of viscosity can be printed • Cell viability is high • Noncontact nozzle-free printing • Nanoscale precision • Possible for multiple cell deposition at once • High cell density bioink	• Limited control over printing direction • Difficulty in handling heterogeneous cells • UV lights may damage the structure • Limited photo cross-linking agents can be used • Possible metallic residual • Tissue damage may occur due to laser light	• Vascular networks • Skin • Organ-on-a-chip

Source: Tripathi, S., et al., '3D bioprinting and its innovative approach for biomedical applications', MedComm, 2023, doi:10.1002/mco2.194

Bioinks

Bioinks are soft biomaterials, usually polymers, loaded with living cells.[122] They are the raw material of bioprinting processes. Polymers are organic biomaterials possessing long chains with high water contents, providing a hydrated tissue-like environment that supports cell functions and tissue regeneration.[123] The development of bioink materials allows scientists to manipulate biological and biochemical environments as well as living cells to create complex biological constructs.[124] Bioinks constitute a crucial element of bioprinting procedures as they are used to create the final shapes of the tissue structures, and they are stabilized during or immediately after bioprinting.[125]

Bioinks are classed as natural, synthetic and hybrids. Natural bioinks are derived from biological sources and include collagen,

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122 Hospodiuk, M., et al., 'The bioink: A comprehensive review on bioprintable materials', Biotechnology Advances, vol. 35, no. 2, 2017, doi: 10.1016/j.biotechadv.2016.12.006.
123 Chen, X.B., et al., 'Biomaterials / bioinks and extrusion bioprinting', Bioactive Materials, vol. 28, 2023, doi: 10.1016/j.bioactmat.2023.06.006.
124 Ibid.
125 Ibid.

gelatin, alginate, fibrin, and hyaluronic acid.[126] These bioinks are biocompatible and often have built-in biological cues to promote cellular interactions.[127] Synthetic bioinks are engineered materials, designed to have precise control over their chemical and physical properties, and include polyethylene glycol (PEG), polylactic acid (PLA), and polycaprolactone (PCL).[128] Hybrid bioinks combine natural and synthetic biomaterials. See Appendix A for types of bioink, their advantages and disadvantages, and applications.

The ideal bioink should have the following properties:[129]
- printing adaptability;
- biocompatibility;
- mechanical stability;
- biodegradability;
- simulates the in vivo environment of cells, and
- ability to support and promote cell activities. (Figure 17)

Figure 19: Bioink properties

Source: Weng. T., et al., '3D bioprinting for skin tissue engineering: Current status and perspectives', Journal of Tissue Engineering, vol. 12, 2021, doi: 10.1177/2041731421 1028574.
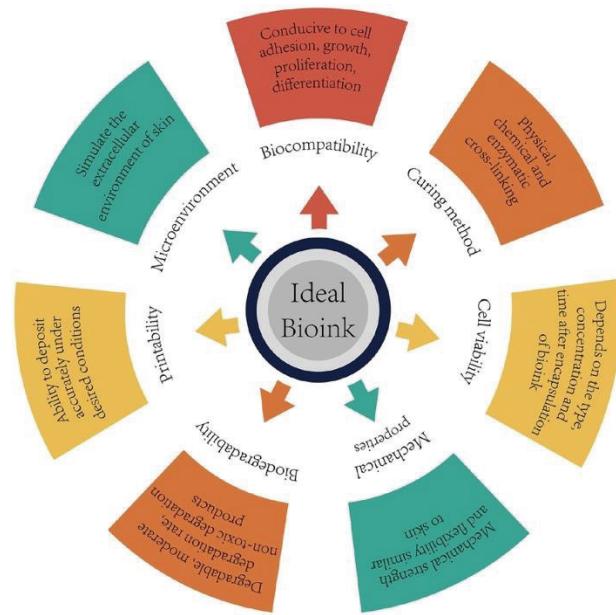
5.2 Drug discovery

Drug discovery is a long, expensive, difficult, and essential process to bring potentially breakthrough drugs to patients. The traditional

126 Khoeini, R., et al., 'Natural and Synthetic Bioinks for 3D Bioprinting', Advanced NanoBiomed Research, March 2021, doi: 10.1002/anbr.202000097.
127 Ibid.
128 Ibid.
129 Weng. T., et al., '3D bioprinting for skin tissue engineering: Current status and perspectives', Journal of Tissue Engineering, vol. 12, 2021, doi: 10.1177/20417314211028574.
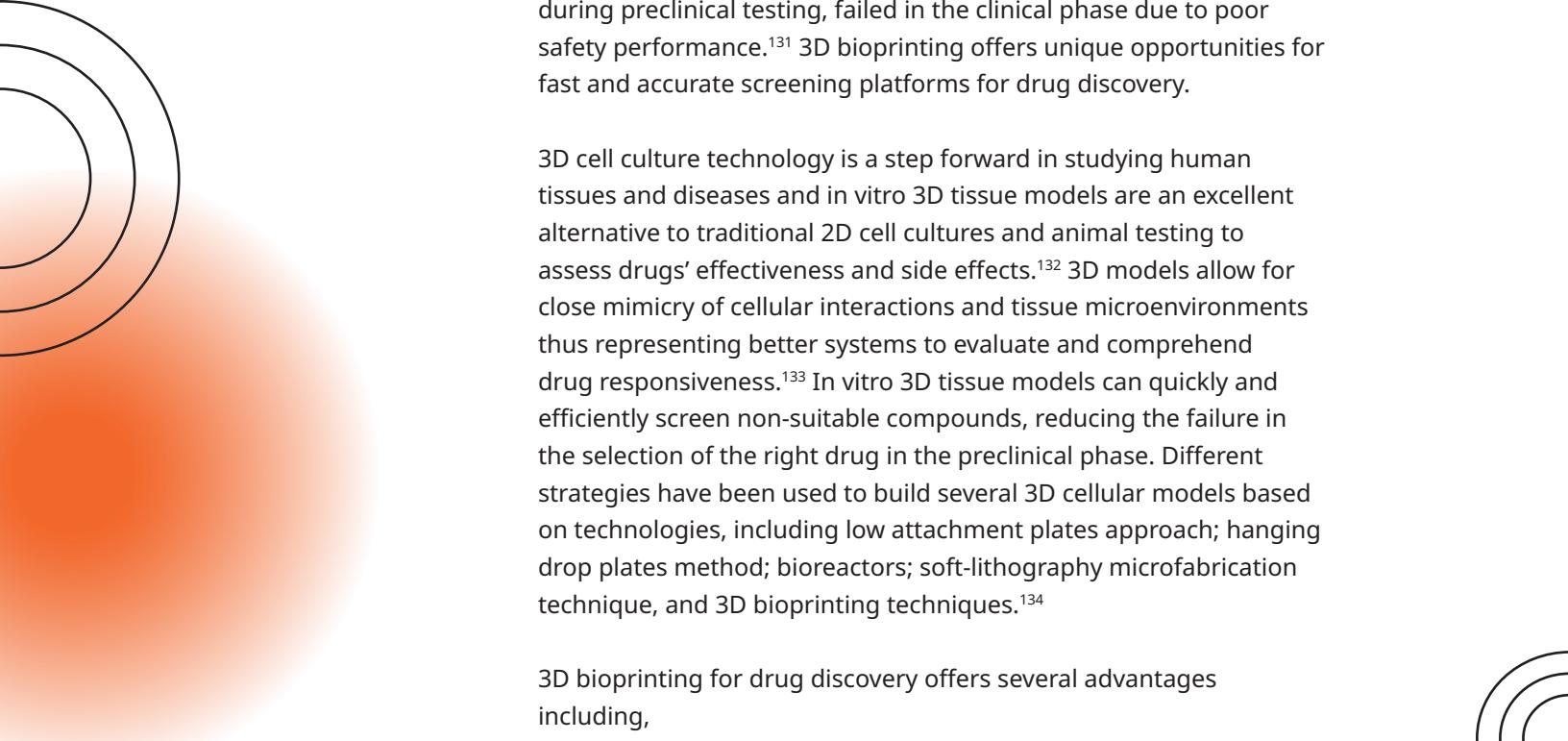
process usually takes 10 -15 years to develop an effective and safe drug because it involves putting thousands of compounds through numerous screening stages before clinical trials during drug discovery and only one compound finally becomes approved.[130]

At least 75 per cent of the novel drugs that demonstrated efficacy during preclinical testing, failed in the clinical phase due to poor safety performance.[131] 3D bioprinting offers unique opportunities for fast and accurate screening platforms for drug discovery.

3D cell culture technology is a step forward in studying human tissues and diseases and in vitro 3D tissue models are an excellent alternative to traditional 2D cell cultures and animal testing to assess drugs' effectiveness and side effects.[132] 3D models allow for close mimicry of cellular interactions and tissue microenvironments thus representing better systems to evaluate and comprehend drug responsiveness.[133] In vitro 3D tissue models can quickly and efficiently screen non-suitable compounds, reducing the failure in the selection of the right drug in the preclinical phase. Different strategies have been used to build several 3D cellular models based on technologies, including low attachment plates approach; hanging drop plates method; bioreactors; soft-lithography microfabrication technique, and 3D bioprinting techniques.[134]

3D bioprinting for drug discovery offers several advantages including,
- improve disease modelling, avoiding errors in translating the results from animal studies across to human physiology,[135]
- amenable to high level of automation and scaling up for high throughput,[136]
- can be accomplished under physiologically amenable conditions (e.g., temperature, humidity and pH)[137], and
- cells can be bioprinted with other sensitive biological

130 Yi, H. G., et al. 'Application of 3D bioprinting in the prevention and the therapy for human diseases', Signal transduction and targeted therapy vol. 6,1 177, 2021, doi: 10.1038/s41392-021-00566-8.
131 Xie, R., et al., 'A comprehensive review on 3D tissue models: Biofabrication technologies and preclinical applications', Biomaterials, vol 304, 122408, Jan 2024, doi: 10.1016/j.biomaterials.2023.122408.
132 Pagnotta, G., et al., 'Progress towards 3D bioprinting of tissue models for advanced drug screening: In vitro evaluation of drug toxicity and drug metabolism', Bioprinting, vol 27, e00218, 2022, doi: 10.1016/j.bprint.2022.e00218.
133 Ibid.
134 Ibid.
135 Satpathy, A., et al., 'Developments with 3D bioprinting for novel drug discovery', Expert opinion on drug discovery, vol. 13, no. 12, 2018, doi: 10.1080/17460441.2018.1542427.
136 Ibid.
137 Ibid.

components including genes and proteins to modulate cellular behaviour.[138]

3D bioprinted models can be designed to reproduce human-like tissues, such as pancreatic ductal adenocarcinoma models, cardiac tissue models, and cancer models.[139] 3D bioprinting technologies allows for rapid development of vaccines to address the emergence of new pathogens and infectious diseases because they provide a method for developing highly biomimetic and reliable in vitro models for infectious disease research.[140] Extensive research is also being carried out to expand the capabilities to build 3D organ models to screen drug candidates for toxicity and study drug metabolism.[141]
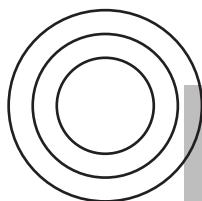
Inventia Life Science, a biotechnology company, is revolutionizing biomedical research, drug discovery and regenerative medicine with 3D bioprinting.[142] It has developed the award-winning RASTRUM™ 3D cell culture platform (3D bioprinter) to create advanced cell models which imitate real human tissue structure and behaviour across a range of disease states.

This bioprinting technology is helping to accelerate research on the cause of and novel treatments for diseases such as cancer or neurological disorders.

How it works: The RASTRUM™ 3D cell culture platform rapidly deposits tiny droplets of cells and matrices with high accuracy due to the unique bio-inks which combine on contact without needing thermal stimuli, turning them into 'matrix building blocks' that can be built into configurable tissues.

© Inventia Life Science

138 Ibid.
139 Pagnotta, G., et al., 'Progress towards 3D bioprinting of tissue models for advanced drug screening: In vitro evaluation of drug toxicity and drug metabolism'.
140 Yi, H. G., et al. 'Application of 3D bioprinting in the prevention and the therapy for human diseases'.
141 Pagnotta, G., et al., 'Progress towards 3D bioprinting of tissue models for advanced drug screening: In vitro evaluation of drug toxicity and drug metabolism'.
142 Inventia Life Science, Australian company accelerating the speed of drug discovery wins prestigious Eureka prize, 21 Oct 2021, <https://inventialife-science.medium.com/australian-company-accelerating-the-speed-of-drug-discovery-wins-prestigious-eureka-prize-15050c22798a>, accessed 16 Dec 2023.

Applications of RASTRUM™ include rapid testing of new drug treatments; healthy liver and liver fibrosis modelling; brain and induced pluripotent stem cells, fibroblasts, and immuno-oncology.

Inventia Life Science has also developed a device to print a 3D blend of the patient's own cells and a special matrix of regenerative biomaterials directly into a deep wound, creating a new layer of normal skin with no scarring.

▶ **VIDEO: RASTRUM™ 3D CELL CULTURE PLATFORM - HOW IT WORKS**
▶ **VIDEO: APPLICATION FOR CANCER RESEARCH**

5.3 3D-printed neural tissues

Brain injuries, such as those caused by trauma, stroke and surgery, often result in significant damage to the cerebral cortex and difficulties in cognition, movement and communication.[143] The long-term consequences of brain injuries include an increased risk of neurodegeneration, such as Parkinson's disease and dementia.[144]

The Lancet Neurology Commission documents traumatic brain injury (TBI) as a global public-health problem, which affects 55 million people worldwide, with over 5 million severe or fatal cases, and costs over US$400 billion per year.[145] In low-and middle-income countries (LMICs), TBI is linked to road accidents. In 2021, WHO launched the Global Plan for Decade for Action on Road Safety 2021-2030.[146] Currently, there are no effective treatments for severe brain injuries.

The Oxford Martin programme on 3D Printing for Brain Repair is pioneering a new approach in which the brain is repaired with 3D-printed neural tissues.[147] Until now, tissue engineering approaches cannot produce structures of the cerebral cortex, which has a layered cellular architecture composed of layer-specific neurons organised into vertical columns that delivers higher cognition through intricately wired neural circuits.[148] The research

143 Lancet Neurology Commission, 'Traumatic brain injury: progress and chal-lenges in prevention, clinical care, and research', Lancet Neurology, Sep 2022, doi: 10.1016/S1474-4422(22)00309-X.
144 Ibid.
145 Ibid.
146 World Health Organization, Global Plan for the Decade of Action for Road Safety 2021-2030, Safety and Mobility, World Health Organization, Geneva, Oct 2021. CC BY-NC-SA 3.0 IGO
147 The Oxford Martin School Programme on 3D printing for Brain Repair, <https://www.oxfordmartin.ox.ac.uk/brain-repair>, accessed 15 Dec 2023.
148 Jin, Y., et al., 'Integration of 3D-printed cerebral cortical tissue into an ex vivo lesioned brain slice', Nature Communications, vol. 14, 5986, Oct 2023, doi:

team is experimenting with personalized neural implants produced by 3D printing with the patient's own stem cells which mimic the architecture of the brain.[149] The aim is to create cortical tissue by generating neurons and support cells from human stem cells, "pre-organising" the cells in three dimensions and then culturing the cells in-vitro to prepare them for implantation, initially in animal models.[150]

So far, the team used a droplet printing technique to fabricate a two-layered brain tissue by 3D printing human neural stem cells[151] (Figure 18).

Figure 20: Flowchart of the droplet-based 3D bioprinting process.

Source: Jin, Y. et. al., Supplementary Information. Integration of 3D-Printed Cerebral Cortical Tissue into an ex vivo Lesioned Brain Slice. Nature Communications, vol. 14, 5986, Oct 2023, doi: 10.1038/s41467-023-41356-w.
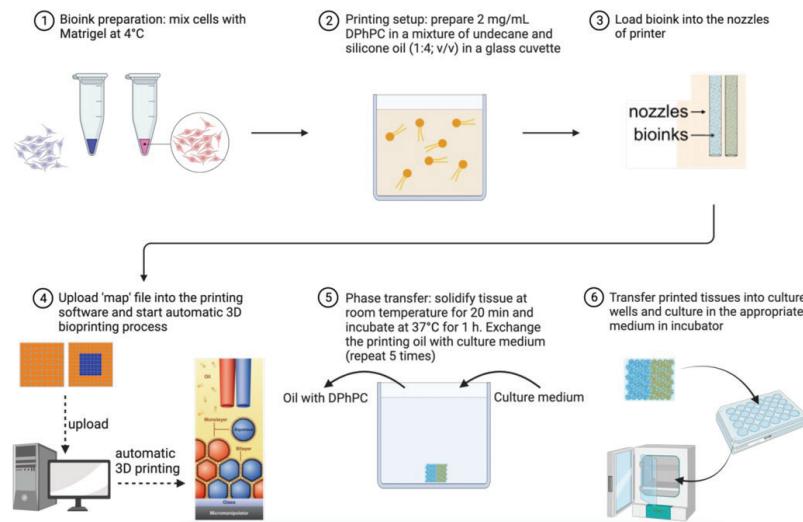
When the printed tissues were implanted into mouse brain slices, the researcher found strong integration as demonstrated by the projection of neural processes and the migration of neurons across the implant-host boundary.[152] The implanted cells also showed signaling activity that correlated with that of the host cells.[153] The findings indicate functional as well as structural integration as the human and mouse cells were communicating with each other.[154] Based on these preliminary results, the team will refine the droplet printing technique to create complex multi-layered cerebral cortex tissues that more realistically mimic the architecture of a human brain.

10.1038/s41467-023-41356-w.

149 The Oxford Martin School Programme on 3D printing for Brain Repair, <https://www.oxfordmartin.ox.ac.uk/brain-repair>, accessed 15 Dec 2023.

150 Ibid.

151 Jin, Y., et al., 'Integration of 3D-printed cerebral cortical tissue into an ex vivo lesioned brain slice'.

152 Ibid.

153 Ibid.

154 Ibid.

5.4 Bone tissue engineering

Bone tissue has limited regenerative properties. Bone healing after trauma may occur only when bone fragments are tightly connected or on callus formation, followed by the new bone formation through intramembranous and endochondral ossifications.[155] If these methods fail, surgical bone replacement is an option but this is restrained by natural graft accessibility.[156]

Bioprinting provides promising and alternative ways of manufacturing of tissue constructs for bone replacement because it allows for easy production of tailored products with a significant architectural control.[157] The application of additive manufacturing in bone tissue engineering changes the way scaffolds are being fabricated and has spurred extensive investment in research and development in the field of orthopaedics and cranioplasty.[158] Table 5 identifies some of the potential benefits of additive manufacturing for bone tissue engineering.

Table 5: Potential benefits of additive manufacturing for bone tissue engineering.

Variability	High variability of designing a targeted degradability and improved biocompatibility
Formability	Can be processed into various shapes, volumes and microstructures
Practicability	Mass-produced or properties can be tailored for patient-specific applications
Controllability	Control over chemical and physically structural properties, degradation rate and mechanical properties
Applicability	Allow exact engineering of matrix configuration, satisfying the biophysical limitations of mass transfer

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155 Semba, J. A., Mieloch, A. A., and Rybka, J. D., 'Introduction to the state-of-the-art 3D bioprinting methods, design, and applications in orthopedics', Bioprinting, vol. 18, e00070, 2020, doi: 10.1016/j.bprint.2019.e00070.

156 Ibid.

157 Henkel, J., et al., Bone Regeneration Based on Tissue Engineering Conceptions - A 21st Century Perspective', Bone Research, vol. 1, 216–248 (2013). doi: 10.4248/BR201303002.

158 R. Vaishya, R., et al., 'Publication trends and knowledge mapping in 3D printing in orthopaedics', Journal of Clinical Orthopaedics & Trauma, vol. 9, 2018, doi: 10.1016/j.jcot.2018.07.006, and Lal, H. and Patralekh, M. K., '3D printing and its applications in orthopaedic trauma: A technological marvel', Journal of Clinical Orthopaedics & Trauma, vol. 9, 2018, doi: 10.1016/j.jcot.2018.07.022.

Flexibility	Flexibility to alter the physical properties and potentially facilitate reproducibility and scale-up, to manipulate the configuration of matrix to vary the surface area available for cell attachments, and to optimize the exposure of attached cells to nutrients and allow transport of waste products.
Surface properties	The ratio of surface area to mass can be altered or the porosity, pore size and pore size distribution of the differing configurations can be altered to increase or decrease the mechanical properties of the scaffold.

Adapted from Henkel, J., et al., 'Bone Regeneration Based on Tissue Engineering Conceptions - A 21st Century Perspective', Bone Research, vol. 1, 2013, doi: 10.4248/BR201303002.

How it works

The tissue constructs are printed with bioink comprised of viable cells, biomaterials, and additional biological substances.[159] These artificial, cell-laden scaffolds promote and support new tissue formation by providing a suitable environment for cell migration, proliferation, differentiation, and ensure a proper extracellular matrix (ECM) secretion[160] (Figure 19).

Bone-tissue engineering requires not only an understanding of the composition and structure of native bone tissue, it also requires deep knowledge of material science to ensure appropriate selection of biomimetic natural or tunable biomaterials, such as polymers, bioceramics, metals and composites.[161] The latest research is experimenting with 3D-printed novel calcium phosphate graphene scaffolds for bone regeneration that supports tissue regeneration at the defect site, and which possesses properties such as biological safety, a long shelf-life, and reasonable production costs.[162]

159 Semba, J. A., Mieloch, A. A., and Rybka, J. D., 'Introduction to the state-of-the-art 3D bioprinting methods, design, and applications in orthopedics'.
160 Ibid.
161 Koons, G.L., Diba, M., and Mikos, A.G., 'Materials design for bone-tissue engineering', Nature Review Material, vol. 5, 2020, doi: 10.1038/s41578-020-0204-2.
162 Daneshmandi, L., et al., 'Ultra-low binder content 3D printed calcium phos-

5.5 Implants

Additive manufacturing for medical care has evolved and progressed over the last 20 years in laboratories for fundamental research and for clinical care.[163] Recent advances in the field allow the development of complex medical implants, the use of different materials and the optimization of implants' surface.[164] 3D printing allows for the design of implants for conditions that are considered difficult to treat, or implants with additional features, such as pre-planned screw trajectories or conformities and has been used in cardiothoracic surgery, dentistry and oral surgery, orthopaedics, neurosurgery, cranioplasty and spinal surgery, just to name a few.[165]

The advantages of additive manufacturing for medical implant over conventional manufacturing techniques include:
- enabling complicated and detailed internal structures in implant design;[166]
- enabling personalization according to a patient's unique anatomy and medical requirements, leading to better functionality and compatibility within the patient's body;[167]
- improving the implants' biocompatibility because of the layer-by-layer fabrication method, fostering better integration with the surrounding tissues;[168]
- accelerating the development and improvement of implants through rapid prototyping,[169] and
- offering cost-effectiveness by streamlining the manufacturing process, lowering tooling and setup costs, and possibly lowering overall patient healthcare costs.[170]

phate graphene scaffolds as resorbable, osteoinductive matrices that support bone formation in vivo', Scientific Report, vol. 12, 2022, doi: 10.1038/s41598-022-10603-3.

163 Aimar, A., et al., 'The Role of 3D Printing in Medical Applications: A State of the Art', Journal of healthcare engineering, 5340616, 2019, doi: 10.1155/2019/5340616.

164 Ibid.

165 Huang, S., Wei, H., and Li, D., 'Additive manufacturing technologies in the oral implant clinic: A review of current applications and progress', Frontier in Bioengineering and Biotechnology, vol.11, 2023, doi: 10.3389/fbioe.2023.1100155, and Raheem, A. A., et al., 'A Review on Development of Bio-Inspired Implants Using 3D Printing', Biomimetics, vol. 6, no. 4, 65, 2021, doi: 10.3390/biomimetics6040065.

166 Mobarak, H. M., et al., 'Recent advances of additive manufacturing in implant fabrication - A review', Applied Surface Science Advances, vol. 18, 2023, doi: 10.1016/j.apsadv.2023.100462.

167 Nagarajan, N., et al., 'Enabling personalized implant and controllable biosystem development through 3D printing', Biotechnology advances, vol. 36, no.2, 2018, doi: 10.1016/j.biotechadv.2018.02.004.

168 Mobarak, H. M., et al., 'Recent advances of additive manufacturing in implant fabrication - A review'.

169 Ibid.

170 Ibid.

Materials

Implants can be made from various materials, including metals, polymers, and ceramics (and a variety of biocompatible ceramics), each with unique properties tailored to the needs of individual patients and medical conditions.[171] The ability to 3D print in high resolution with these materials is important, as they possess the properties needed for successful implants: biocompatibility and excellent thermal and chemical stability.[172] Scientists are focusing on biodegradable materials rather than relying solely on steel and polymers.[173] Table 6 summarizes the AM methods and materials technologies for 3D-printed implantable devices, including prosthetic devices, orthopaedic implants, bone plates, and spinal rods.

Table 6: AM methods and materials for 3D printed implantable devices.

Source: Mobarak, H. M., et al., 'Recent advances of additive manufacturing in implant fabrication - A review', Applied Surface Science Advances, vol. 18, 2023, doi: 10.1016/j.apsadv.2023.100462.

AM methods	Materials	Implant
SLM	Ti powder 200 micrometers and 60 μ	Suggested for dental and bone
SLM	Titanium alloy	Bone
3DP Inkjet	HA powder 2.78 μm	Bone
Proposed	Titaniananoscale tube	Suggested for dental and bon
EBM	Poly (N isopropylacrylamide) (PIPPAm)	Endoscopic transplantation (oral muscular cells)
EBM	Ti alloys (Ti-6Al-4V) 100 μm	Hip stems, tibial knee stems and intramedullary rods
DMLS	Ti (Ti64Al4V-ELI) 30 μm	Facial bone (orbital area)
Poly Jet & SLS	Polymer	Skull bone
DMLS	Titanium (Ti64 ELI)	Bone (Cranial head)
Proposed	HA 100 nm	Suggested for dental and bone
EBM	Silver Nanoparticles-coated Titanium Ti6Al4V	Bone grafting (Hip/Knee)

171 Szymczyk-Ziółkowska, P., et al., 'A review of fabrication polymer scaffolds for biomedical applications using additive manufacturing techniques', Biocybernetics and Biomedical Engineering, vol. 40, no. 2, 2020, doi: 10.1016/j.bbe.2020.01.015.
172 Mobarak, H. M., et al., 'Recent advances of additive manufacturing in implant fabrication - A review', Applied Surface Science Advances, vol. 18, 2023, doi: 10.1016/j.apsadv.2023.100462.
173 Ibid.

SLM	Silver Nanoparticles-coated Titanium Ti6Al4V	Bone
Proposed	Silver nanoparticles (AgNPs)	Orthopedic

Spinal surgery

3D printing of customized spinal implants to treat spinal problems for spinal surgery is a relatively new technique.[174] In order to optimize the potential benefits of this approach to treat complex and previously untreatable surgical problems, an increasing number of hospitals are establishing a 3D printing point-of-care facility in which the opportunities of 3D printing can be fully explored.[175] For example, a 3D lab within one academic hospital printed nylon drill guide, with such accuracy that it can be used for insertion of cervical pedicle screws in very young children.[176] The lab also designed a 3D-printed titanium spinal column prosthesis that was used to treat progressive and severe deformities due to lysis of the anterior column.[177]

3D-printed ribs and sternum implant

A medical team at Salamanca University Hospital in Spain used a 3D printing solution for a 54-year-old man who had his sternum and a portion of his rib cage removed due to a tumour growing on his chest wall.[178] Instead of replacing these bones with a conventional titanium implant, the medical team chose a 3D-printed implant because the sternum and rib cage are extremely difficult to recreate with prosthetics due to the complex geometry and intricate structures involved.[179] A 3D-printed implant would allow for unparalleled personalization and overcome some of the problems associated with conventional flat titanium implant design.

174 Choy, W. J., and Mobbs, R. J., Current state of 3D-printed custom-made spinal implants, The Lancet - Digital Health, vol. 1, no. 4, 2019, doi: 10.1016/S2589-7500(19)30081-0.

175 Willemsen, K., et al., 'Vital Role of In-House 3D Lab to Create Unprecedented Solutions for Challenges in Spinal Surgery', Practical Guidelines and Clinical Case Series. Journal of Personalized Medicine, vol. 12, 2022, doi: 10.3390/jpm12030395.

176 Ibid.

177 Ibid.

178 CSIRO, 'Cancer patient receives 3D printed rib cage', 11 Sep 2015, <https://www.csiro.au/en/research/health-medical/biomedical/Sternum-and-ribs>, accessed 17 Dec 2023.

179 Mendoza, H. R., 3D Printing Gives Cancer Patient New Ribs and Sternum in First-of-Its-Kind Surgery, 11 Sep 2015, <https://3dprint.com/95371/3d-printed-ribs-and-sternum>, accessed 17 Dec 2023.

The team at the metal 3D printing facilities at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) used electron beam melting method to build up layers of titanium power and melt them together to print the implant based on the patient's CT scans.[180] Once the fusing process is complete, extra powder is vacuumed away, leaving the fully formed implant ready to be cleaned and used in surgery[181] (Figure 20). The 3D-printed implant was designed to accommodate the end pieces of the remaining rib bone and be screwed into place. Once the sternum-rib implant was complete it was couriered to Spain.[182] The patient was discharged 12 days after the surgery.[183]

▶ **VIDEO: HOW IT WORKS**

More recently, this technology was applied to create a customized sternum and partial ribcage made from titanium and porous polyethylene material for a 20-year-old American who was diagnosed with a rare bone cancer.[184] The 3D-printed implant provided a 'bone-like' architecture to facilitate tissue integration[185]

(Figure 21).

3D-printed implants with antibiotics

Bone infection following an open fracture or surgery is shockingly

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180 Ibid.
181 Ibid.
182 CSIRO, 'Cancer patient receives 3D printed rib cage'.
183 Ibid.
184 Bindi, T., Australian-made 3D-printed sternum and rib cage implanted into NY patient, ZDNET 18 Oct 2017, <https://www.zdnet.com/article/australian-made-3d-printed-sternum-and-rib-cage-implanted-into-ny-patient>, accessed 17 Dec 2023.
185 Ibid.

frequent. But the removal of infected bone tissue often leaves a hole that is too big for the body to fill via normal bone regeneration.[186] 3D printing has emerged as a very promising approach to personalize implant solutions. Researchers from the Netherlands, Italy and Spain have deployed this technology to develop a novel antibiotic-releasing and biodegradable polymers 3D-printed scaffold implant that is capable of supporting bone regeneration and local delivering antibiotics at the same time[187] (Figure 22). Future research on integrating antibiotics and biodegradable polymers will focus on optimizing implant for bone regeneration.

Figure 21: Additive manufactured scaffolds with antibiotics for bone infection and tissue regenerations.

Source: Cámara-Torres, M., et al., '3D additive manufactured composite scaffolds with antibiotic-loaded lamellar fillers for bone infection prevention and tissue regeneration', Bioactive Materials, vol. 6, no. 4, 2021, doi: 10.1016/j.bioactmat.2020.09.031.
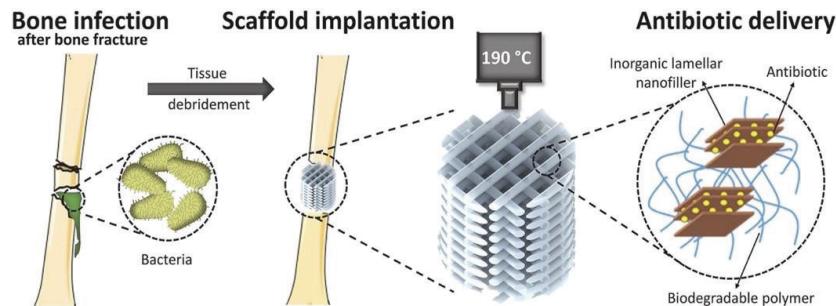
186 Cámara-Torres, M., et al., '3D additive manufactured composite scaffolds with antibiotic-loaded lamellar fillers for bone infection prevention and tissue regeneration', Bioactive Materials, vol. 6, no. 4, 2021, doi: 10.1016/j.bioactmat.2020.09.031.
187 Ibid.

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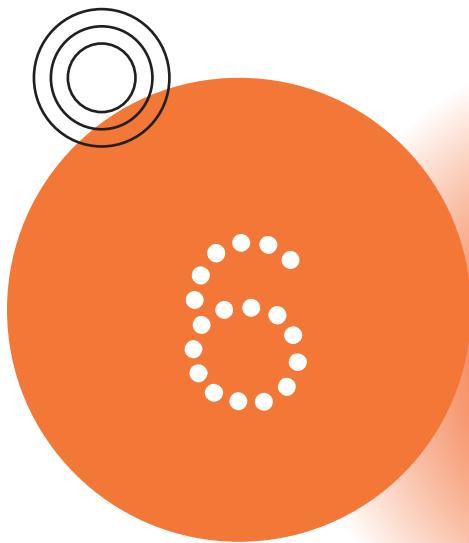
APPLICATION: PEOPLE WITH DISABILITIES

6.1 Rehabilitation

Around 2.4 billion people are currently living with a health condition that may benefit from rehabilitation.[188] The World Health Organization defines rehabilitation as measures to alleviate the conditions of disability and handicap, improve the functioning of the sick, injured and disabled, and make it possible for them to interact with their environment fully.[189] Rehabilitation helps a child, adult or older person to be as independent as possible in everyday activities and enables their participation in education, work, recreation and meaningful life roles.[190] However, rehabilitation is mainly an unmet need. In some LMICs more than 50 per cent of people do not receive the rehabilitation services they need.[191] Humanitarian crises, from conflict to natural disasters, increase the need for rehabilitation. Rehabilitation is highly person-centred and personalized. It includes approaches to address their symptoms, modify their environment to better suit their needs, and use assistive products.

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188 World Health Organization, 'Rehabilitation', Jan 2023, <https://www.who.int/news-room/fact-sheets/detail/rehabilitation>, accessed 26 Dec 2023.
189 Ibid.
190 Ibid.
191 Ibid.
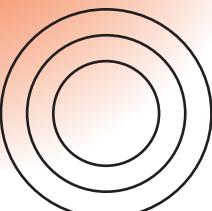
Additive manufacturing is transforming the field of rehabilitation, particularly in prosthetics. According to LIMBS International, only 5 per cent of the approximate 30-40 million amputees in the 'developing world' have access to prosthetic devices or assistance.[192] 3D technologies allow for the design of cheaper and more personalized devices on demand and with shorter manufacturing time than traditional methods.

3D-printed transtibial prosthetic sockets

3D printing has emerged as a potentially viable alternative to traditional fabrication for producing prosthetic sockets. The prosthetic socket absorbs the impact and transfers load from the residual limb to the prosthesis.[193] Manufacturing conventional laminated composite sockets require costly infrastructure, technical specialists, long production times, and limited scope for rapid prototyping to the final product.[194]

3D-printed sockets can potentially resolve these shortcomings. Rapid production of 3D-printed sockets reduces time between amputation and receiving the first prosthesis or modified sockets, which could lead to better rehabilitation outcomes.[195] Rapid production may help patients who require many socket modifications such as children. Moreover, the cost of a 3D printer and 3D printing filament materials is often lower than the costs of conventional manufacturing methods.[196]

A preliminary study on the potential low-cost 3D-printed transtibial prosthetics for rural population in Sierra Leone found all participants were still wearing the prosthesis after six weeks and six of the eight participants reached their personal rehabilitation goals[197] (Figure 23). Table 7 points to some promising data collected from the proof-of-concept stage of product development.[198]

192 LIMBS international, <https://www.limbsinternational.org/why-limbs.html>, 26 Dec 2023.

193 Kim, S., et al., '3D printed transtibial prosthetic sockets: A systematic review', PLoS ONE, vol. 17, no. 10, e0275161, 2022, doi: 10.1371/journal.pone.0275161.

194 van der Stelt, M., et al., 'Pioneering low-cost 3D-printed transtibial prosthetics to serve a rural population in Sierra Leone - an observational cohort study', EClinicalMedicine, vol. 35, 100874, 2021, doi: 10.1016/j.eclinm.2021.100874.

195 Ibid.

196 Ibid.

197 Ibid.

198 Ibid.

Table 7: Proof-of-concept data from study of low-cost 3D-printed transtibial prosthetics for rural population in Sierra Leone.

Manufacturing time	• 15 mins to scan the participant's stump, including preparation of the scanner and clinical inspection. • 20 mins to design of the socket. • 17.5 hours to fabricate a transtibial socket with 4 mm thickness.
Costs	• The material costs of the 3D-printed prosthesis were around 87 USD each. This could come down to around 54 USD if some parts are made locally. • The equipment (computer, 3D scanner, 3D-printer) and running costs were 11.500 USD.
Weight	• A 3D-printed transtibial prosthesis weighed around 1,560 grams, whereas conventional local prostheses weighed around 1,945 grams.

3D-printed socket

Prosthesis with 3D-printed socket

3D-printed prosthesis with aesthetic cover

Manufacturing a low-cost 3D-printed transtibial prosthetic sockets require few tools and materials, though the initial cost of acquiring the equipment is substantial. After the upfront capital investment, it would be possible to create a mobile prosthetic facility to serve remote communities if there is a reliable source of electricity. Long-term follow-up and further clinical research would need to include ensuring compliance with the International Standard for Structural Testing of Lower Limb Prostheses, expanding the trial to a larger and more diverse cohort, and building local capacity for digital design and 3D technology.[199]

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199 Ibid.

3D-printed bionic prosthetics for children

A US-based startup, Unlimited Tomorrow, has created a lightweight 3D-printed bionic prosthetic arm called TrueLimb™ for youth amputees because standard prosthetics tend to be heavy and uncomfortable, leading many children to abandon their prosthesis[200] (Figure 24). The TrueLimb™ prosthetic arm weighs 1.5 pounds and is available in hundreds of skin tones.[201]

▶ **VIDEO: UNLIMITED TOMORROW IS CHANGING THE WORLD FOR GOOD, ONE PROSTHETIC LIMB AT A TIME.**

The battery-powered prosthetic is designed to be a 3D-printed mirror image of the amputee's opposite arm and is equipped with an array of sensors that attach to the residual limb, where they interpret subtle topographic movements.[202] These movements trigger TrueLimb™ to perform various grips, allowing the user to more easily perform tasks that might be difficult with other types of prosthetics: unscrew a water bottle, roll up sleeves, or take a drink from a cup.[203] The prosthesis provides the wearer haptic feedback, delivered through small vibrations to the residual arm whenever the hand makes contact with an object.[204]

Another example of 3D-printed bionic prosthesis is the Hero Arm™ created by Open Bionics, an UK-based social enterprise (Figure 25). The Hero Arm™ is an advanced, lightweight, breathable 3D-printed bionic arm with multi-grip functionality that has received medical approval

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200 https://www.unlimitedtomorrow.com/changing-the-prosthetics-industry>, Jan 2021, accessed 26 Dec 2023.
201 Ibid.
202 <https://www.unlimitedtomorrow.com/truelimb>, accessed 26 Dec 2023.
203 Ibid.
204 Ibid.

and industry certification. The prosthetic arm is suitable for children as young as 8 years of age.

▶ **VIDEO: HERO ARM™ - THE WORLD'S FIRST CLINICALLY TESTED, MEDICALLY CERTIFIED, AND FDA REGISTERED 3D-PRINTED BIONIC ARM.**

6.2 Hearing

Nearly 2.5 billion people worldwide, or 1 in 4 people, will live with hearing loss by 2050.[205] Nearly 80 per cent of people with disabling hearing loss live in low- and middle-income countries.[206] 'Disabling' hearing loss refers to hearing loss greater than 35 decibels (dB) in the better hearing ear.[207] Hearing loss, when unaddressed, impacts a person's communication and speech, cognition, education, employment, mental health, sense of belonging, and years lived with disability (YLDs) and disability adjusted life years (DALYs).[208]

Additive manufacturing and 3D-printed solutions
Hearing aids are one of the earliest examples of the value of additive manufacturing and 3D printing solutions for people with disabilities. Coupled with 3D scanning technology, additive manufacturing has made it possible to improve the quality of existing products and introduce next generation solutions.

Custom-made In-the-Ear (ITE) and In-the-Canal (ITC) style hearing aids have seen a 3D printing revolution[209] (Figure 26). ITE hearing aids are designed to sit flush against the bowl of your ear, with the speaker and inner workings fitting into a single case that extends slightly into the ear canal.[210]

205 World Health Organization, 'Deafness and hearing loss', 27 February 2023, <https://www.who.int/news-room/fact sheets/detail/deafness-and-hearing-loss>, accessed 20 Dec 2023.
206 World Health Organization, World Report on Hearing Loss, WHO, Geneva, 2021.
207 World Health Organization, 'Deafness and hearing loss'.
208 Ibid. According to WHO, children with hearing loss and deafness in LMICs often do not receive schooling. Adults with hearing loss have a much higher unemployment rate than those hearing. If they are employed, more are in the lower level of employment compared with the general workforce.
209 3dsourced, 'How 3D Printed Hearing Aids Silently Took Over The World', <https://www.3dsourced.com/editors-picks/custom-hearing-aids-3d-printed>, accessed 20 Dec 2023.
210 Ibid.

ITC hearing aids, which as implied sit discretely within the ear canal, share the same production method and benefits that come with a custom fit.[211]

3D scanning and 3D printing technology like the awarding winning Computer-Aided Manufacturing for Individual Shells for Hearing Aids (CAMISHA) create bespoke ITE hearing-aid that fits exactly to each person's unique ear canal.[212] It uses laser technology to make an impression of the hearing aid user's ear canal and turns this data into a 3D computer model.[213] The 3D computer model is used to manufacture individual shells and ear moulds that fit the user's ear canal.[214] These Invisible In-Canal (IIC) hearing aids prevents any noise from leaking out and allow for more sound to be collected naturally by the shape of the ear, and to flow down the ear canal as it would with unassisted hearing, improving the fidelity and range of sound.[215] With further advances in additive manufacturing, it is now possible to fabricate ultra-thin, 26 per cent smaller and durable IIC 3D-printed hearing aids made from titanium for children.[216]

3D-printed implants to reverse hearing loss

Hearing works partly through the transmission of vibrations from the ear drum to the cochlea via three tiny bones in the middle ear known as ossicles.[217] They are the tiniest bones in the human body. Conductive hearing loss occurs due to ossicular abnormalities occurs from many causes, including trauma, infection, cholesteatoma, surgery and congenital anomalies.[218] Hearing can be restored using prosthetic struts that restore bones to their correct places, but these procedures often fail because it is very difficult to make prostheses that fit perfectly when the the ossicles such small structures.[219]

Custom 3D printing an individualized ossicular prosthesis - a transplant of middle-ear bones using 3D-printed components -

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211 Ibid.
212 Maxey, K., '3D Printing For the Hearing Impaired', <https://www.engineering.com/story/3d-printing-for-the-hearing-impaired>, 28 Dec 2023.
213 Widex, CAMISHA, <https://www.widexpro.com/en-au/widex-technology/camisha>, 28 Dec 2023.
214 Ibid.
215 3dsourced, 'How 3D Printed Hearing Aids Silently Took Over The World'.
216 Hendrixson, S., ' SLM Titanium Expands Options for Hearing Aid Wearers', < https://www.additivemanufacturing.media/articles/slm-titanium-expands-options-for-hearing-aid-wearers>, 20 Dec 2023.
217 Matcher, E., 'Doctors Are 3D Printing Ear Bones To Help With Hearing Loss', <https://www.smithsonianmag.com/innovation/doctors-are-3d-printing-ear-bones-to-help-with-hearing-loss-180967560>, accessed 20 Dec 2023.
218 Hirsch, J.D., Vincent, R.L. and Eisenman, D.J., 'Surgical reconstruction of the ossicular chain with custom 3D printed ossicular prosthesis', 3D Printing in Medicine, vol. 3, 7, 2017, doi: 10.1186/s41205-017-0015-2.
219 Ibid.

would be a potential solution to decrease the rate of post-operative prosthesis displacement by increasing the likelihood of a proper fit.[220] By replacing the ossicles that are not functioning properly, the procedure carries less risk, including the potential for facial nerve paralysis, which can occur if the facial nerve that passes through the middle ear space is damaged[221] (Figure 27).

Figure 22: The ossicles without implant (left image) and one with ossicular prothesis implant (right image).

© RSNA
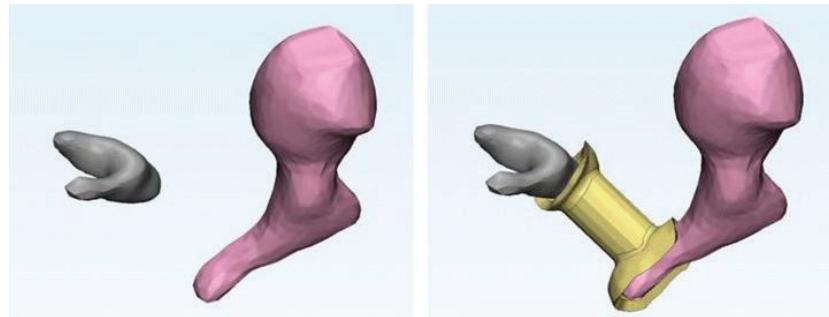
3D-printed Bionic Ears

The ability to three-dimensionally interweave biological tissue with functional electronics could enable the creation of bionic organs possessing enhanced functionalities over their human counterparts.[222] Conventional electronic devices prevent multidimensional integration with synthetic biology, as the processes and materials are very different.[223] Additive manufacturing of biological cells with structural and nanoparticle derived electronic elements can overcome these difficulties.[224]

Researchers from Princeton University and Johns Hopkins University have used additive manufacturing technology to generate a bionic ear via 3D printing of a cell-seeded hydrogel matrix in the precise anatomic geometry of a human ear, along with an intertwined conducting polymer consisting of infused silver nanoparticles.[225] The researchers used a CAD drawing of a human right ear as a blueprint for the printing. The bioink used for the experiment was a combination of cartilage cells in a hydrogel matrix, structural silicone, and silicone infused with silver nanoparticles.[226] The ear was built

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220 Ibid.
221 Petersen, A., 'World's first middle ear transplant facilitated by 3D printing cures deafness'.
222 Mannoor, M. S., et al., '3D printed bionic ears', Nano letters, vol. 13, no. 6, 2013, doi: 10.1021/nl4007744.
223 Ibid.
224 Feiner, R., and Dvir, T., 'Tissue–electronics interfaces: from implantable devices to engineered tissues', Nature Reviews Materials, vol. 3, 17076, 2018, doi: 10.1038/natrevmats.2017.76.
225 Mannoor, M. S., et al., '3D printed bionic ears'.
226 Ibid.

layer by layer with an ordinary 3D printer.[227] The printed ear exhibits enhanced auditory sensing for radio frequency reception, and complementary left and right ears can listen to stereo audio music.[228] This proof-of-principle study shows that tissues and electronics can be combined to form hybrid, bionic organs and suggests a new approach to build and grow the biology up with the electronics synergistically and in a 3D interwoven format[229] (Figure 28).

Figure 23: 3-dimensional interweaving of biology & electronics via additive manufacturing to generate a bionic ear.
A: CAD drawing
B: Materials for 3D printer
C: Illustration of the 3D printed bionic ear

© Mannoor et al. PMC
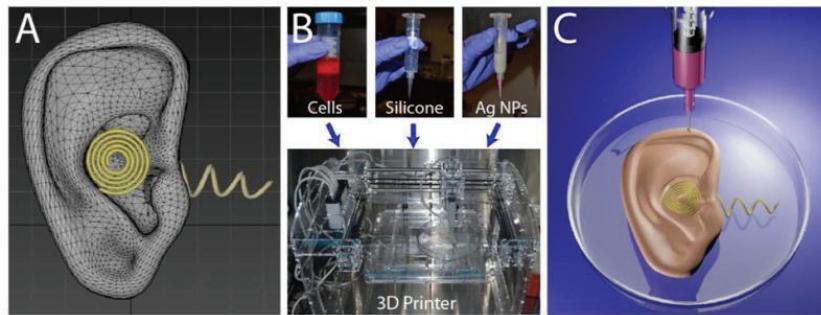
6.3 Vision

At least 2.2 billion people around the world have a vision impairment, of whom at least 1 billion have a vision impairment that could have been prevented or is yet to be addressed.[230] The WHO defines blindness a presenting visual acuity (PVA) of 3/60 or worse and PVA <6/12 as visual impairment.[231] The burden of eye conditions and vision impairment is often far greater among people living in rural areas, people with low incomes, women, older people, people with disabilities, ethnic minorities, and indigenous populations.[232] Blindness is disproportionately prevalent in LMICs.[233] Many eye conditions are triggered by non-modifiable (genetic, ethnicity and aging) and modifiable (lifestyle and environment related) risk factors.[234] 90 per cent of vision loss is preventable or treated with existing, highly cost-effective interventions.[235]

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227 Ibid.
228 Princeton Materials Institute, '3D printed bionic ears', <https://collaborate.princeton.edu/en/publications/3d-printed-bionic-ears>, accessed 20 Dec 2023.
229 Mannoor, M. S., et al., '3D printed bionic ears'.
230 World Health Organization, 'Blindness and vision impairment', 10 August 2023, <https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment>, 20 Dec 2023.
231 World Health Organization, World Report on Vision, WHO, Geneva, 2019, CC BY-NC-SA 3.0 IGO licence.
232 Ibid.
233 Ibid.
234 World Health Organization, World Report on Vision, WHO, Geneva, 2019, CC BY-NC-SA 3.0 IGO licence.
235 Burton, M. J., et al., 'The Lancet Global Health Commission on Global Eye Health: vision beyond 2020, The Lancet Global Health, vol. 9, no. 4, February 16, 2021, doi: 10.1016/S2214-109X(20)30488-5.

Low-cost additive manufacturing techniques have been used to fabricate educational tools for visually impaired and blind students such as tactile artefacts, braille labels and interactive maps to convey abstract information through haptic sensory experience.[236] Researchers at Oxford University are developing glasses whose frames can be 3D printed and then equipped with various sensors and electronic components to enable people with severely impaired sight to use their remaining vision to detect obstacles[237] (Figure 29). Another use case of 3D printing is to make 'data for all' a reality for people with blindness have been historically discouraged from learning chemistry and excluded from laboratories.[238]

Preventing blindness

A potentially ground-breaking use of additive manufacturing is corneal tissue engineering to prevent blindness.[239] Over 12 million people worldwide suffer from corneal blindness.[240] Corneal blindness refers to a group of eye disorders that change the corneal transparency, causing corneal scarring and blindness.[241] The cornea can heal from minor injuries but major injury or disease leads to scarring that blocks light, blurs images, and can lead to blindness.[242] Corneal transplants can restore sight but a shortage of tissue donors and the economic and in some cases, cultural barriers to harvesting,

236 Serrano-Mira, J., et al., 'Use of additive manufacturing to obtain moulds to thermoform tactile graphics for people with visual impairment', Procedia Manufacturing, vol. 13, 2017, doi: 10.1016/j.promfg.2017.09.113

237 Skinner, K., Oxford start-up OXSIGHT launches smart glasses for visually impaired, The Business Magazine, August 2021, <https://thebusinessmagazine.co.uk/technology-innovation/oxford-start-up-oxsight-launches-smart-glasses-for-visually-impaired>, accessed 21 Dec 2023.

238 Koone, J. C., et al., 'Data for all: Tactile graphics that light up with picture-perfect resolution', Science Advances, vol.8, no. 33, 2022, doi: 10.1126/sciadv.abq2640. See also, Wedler, H. B., et al., 'Nobody can see atoms: Science camps highlighting approaches for making chemistry accessible to blind and visually impaired students', Journal of Chemistry Education, vol. 91, no. 2, 2014, doi: 10.1021/ed300600p.

239 Sill, K., '3D bioprinting to eliminate corneal blindness', <https://med.stanford.edu/ophthalmology/news-and-media/annualreport_2021/3D-bioprint.html?tab=proxy>, accessed 21 Dec 2023.

240 Tidke, S. C., and Tidake, P., 'A Review of Corneal Blindness: Causes and Management', Cureus, vol. 14, no. 10, 2022, doi: 10.7759/cureus.30097.
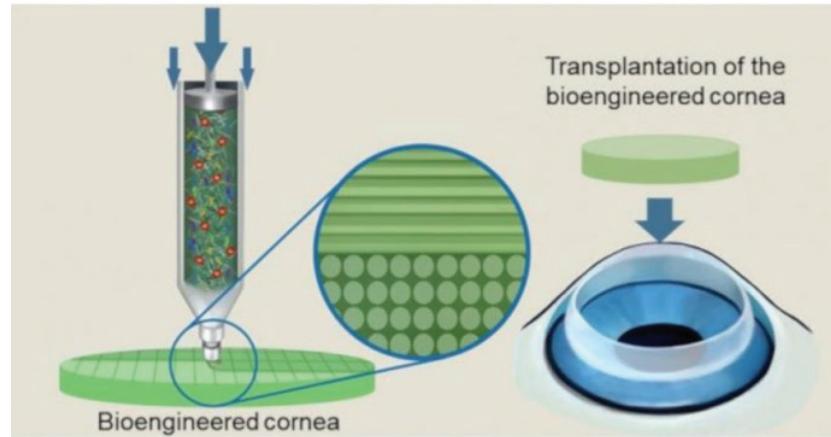
241 Ibid.

242 Sill, K., '3D bioprinting to eliminate corneal blindness'.

screening, and delivery, means that less than 2 per cent of patients have access to this surgery globally.[243]

Figure 24: 3D printing to fabricate an artificial cornea.

© Pohang University of Science and Technology

An alternative solution is to use 3D bioprinting technology to produce artificial corneal tissue engineering to replace traditional corneal transplant.[244] The advantage of choosing 3D bioprinting is the induction of the natural process during embryogenetic tissue formation and imitation[245] (Figure 30).

This method can potentially generate a supply of engineered tissue needed to meet the world's demand for transplantable corneas. Research teams around the world are focused on analyzing various biomaterials and fabrication methods for corneal tissue regeneration. For example, an interdisciplinary team at Stanford University is creating a biosynthetic alternative to donor tissues by using 3D bioprinting technology to fabricate and grow cornea tissue in the lab.[246] The team is printing engineered corneal tissue of the same dimensions of human donor corneas which has about the same material volume as a drop of water using their unique UNIversal Orthogonal Network (UNION) bioinks, which has been engineered to encapsulate and print corneal stem cells in the lab using a modified 3D printer.[247]

There is still room for progress in mimicking the native corneal properties. The behavior of corneal cells in tissue engineering

243 Ibid.
244 Jia, S., et al., 'Advances in 3D bioprinting technology for functional corneal reconstruction and regeneration', Frontiers in bioengineering and biotechnology, vol.10, 2023, doi: 10.3389/fbioe.2022.1065460.
245 Orash Mahmoud Salehi, A., et al., 'Bioprinted Membranes for Corneal Tissue Engineering: A Review', Pharmaceutics, vol. 14, no. 12, 2022, doi: 10.3390/pharmaceutics14122797.
246 Sill, K., '3D bioprinting to eliminate corneal blindness'.
247 Ibid.

constructions in corneal injury has been proven in vitro. The next step is to conduct in vivo proof-of-concept investigations.

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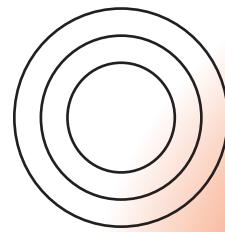
FUTURE OF ADDITIVE MANUFACTURING

7.1 4D printing - intelligent additive manufacturing

The idea of 4D printing represents a significant development in additive manufacturing smart techniques. 4D printing introduces time as the 4th dimension.[248] Whereas 3D printing produces static objects, 4D printing enables an object to become 'alive', changing its design or functionality over time in response to environmental factors, as well as the ability to self-repair when damaged.[249] Shape morphing following printing is the key distinguishing feature of 4D printing. 4D printing technology reconstructs the shape of an object with the use of smart materials which can change their properties or shapes in response to external stimuli, such as mechanical, chemical, thermal or electrical, over time.[250] Table 8 compares 3D and 4D printing technology.

248 Vasiliadis, A.V., Koukoulias, N., and Katakalos, K., 'From Three-Dimensional (3D)- to 6D-Printing Technology in Orthopedics: Science Fiction or Scientific Reality?', Journal of Functional Biomaterials, vol. 13, 2022, doi: 10.3390/jfb13030101.
249 Joharji, L., et al., '4D printing: A detailed review of materials, techniques, and applications', Microelectronic Engineering, vol. 265, 2022, doi: 10.1016/j.mee.2022.111874.
250 Vasiliadis, A.V., Koukoulias, N., and Katakalos, K., 'From Three-Dimensional (3D)- to 6D-Printing Technology in Orthopedics: Science Fiction or Scientific Reality?'.

Table 8: Comparison between 3D and 4D printing technology

	3D printing technology	4D printing technology
Printing method	Printing repeats a 2D structure lay by lay from bottom to top	Printing is the extension of 3D printing
Printer type	3D printer	Smart/multi-material 4D printer
Materials	Thermoplastics, ceramics, metals, paper, food, polymers, nanomaterial and biomaterials	Smart material, multi-material, self-assembled, self-actuating, and self-sensing material, shape memory polymers and advanced material
Design concept	The 3D digital object - drawing/scanning	3D digital object with deformation feature
Product flexibility	No	Yes, after printing in shape, colour, various functions, and other conditions
Product state	Static structure	Smart, dynamic structure
Equipment cost & market outlook	Low cost and medium market outlook	High cost and med-high market outlook

Source: Quanjin, M., et al., 'Recent 3D and 4D intelligent printing technologies: A comparative review and future perspective', Procedia Computer Science, vol. 167, 2020, doi: 10.1016/j.procs.2020.03.434.

▶ **VIDEO: WHAT IS 4D PRINTING?**

The core element of 4D printing technology is smart or intelligent material because these are capable of changing their properties with time and when responding to specific stimuli.[251] Intelligent materials include shape memory polymers (SMPs) and their composites, shape memory alloys (SMAs), liquid crystal elastomers (LCEs), dielectric elastomers, and hydrogels as well as conventional sensing materials such as piezoelectric materials.[252] Shape memory is governed by chemical composition, the processing methods and material layout.[253] SMPs have many advantages over SMAs, such as a high strain recovery, low density, cost, simple processing, biocompatibility and biodegradability. Figure 31 is an overview of the key features of 4D printing.

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251 Quanjin, M., et al., 'Recent 3D and 4D intelligent printing technologies: A comparative review and future perspective', Procedia Computer Science, vol. 167, 2020, doi: 10.1016/j.procs.2020.03.434.

252 McLellan, K., Sun, Y-C., and Naguib, H.E., 'A review of 4D printing: Materials, structures, and designs towards the printing of biomedical wearable devices', Bioprinting, vol. 27, 2022, doi:

253 Ibid.

Figure 25: 4D printing - key characteristics.

Adapted from: Ahmed, A., et al., '4D printing: Fundamentals, materials, applications & challenges', Polymer, vol. 228, 2021, doi: 10.1016/j.polymer.2021.123926.

FDM: Fused Deposition Modeling — DED: Direct energy deposition
SLA: Stereolithography apparatus — DIW: Direct-Ink-Writing
SLM: Selective laser melting — PµSL: Projection Micro-Stereolithography
SLS: Selective laser sintering

Applications

Despite being a novel technology, 4D printing technology has attracted growing interest from a wide range of industries that includes medical engineering, automobile, electronics, textiles, aerospace engineering, and defence.[254] In particular, 4D bioprinting presents enormous potential for personalized medicine, pharmaceuticals, drug delivery, biosensors, bioactuators, biorobotics and tissue engineering.[255]

In orthopaedics, 4D bioprinting technologies can be applied to manufacture specific tools and devices, intelligent tissue-engineered scaffolds that release drugs or/and cells, and smart orthopaedics implants which can change their shape after being implanted in the patient's body.[256] The shape memory of these smart implants can be used for spinal deformities, fracture fixation, joint replacement, bone tissue engineering.[257] One of the major challenges in orthopaedics is developing artificial bones and implants that can grow as the child grows and develops, 4D-printed implants offer potential solutions as they can react to different stimuli and change their structure with the passage of time.[258]

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254 Agarwal, N., et al., '4-Dimensional printing: exploring current and future capabilities in biomedical and healthcare systems - a Concise review', Frontiers in Bioengineering and Biotechnology, vol. 11, 2023, doi: 10.3389/fbioe.2023.1251425.
255 Ibid.
256 Vasiliadis, A.V., Koukoulias, N., and Katakalos, K., 'From Three-Dimensional (3D)- to 6D-Printing Technology in Orthopedics: Science Fiction or Scientific Reality?'.
257 Wan, Z., et al., 'Four-dimensional bioprinting: Current developments and applications in bone tissue engineering', Acta Biomaterialia, vol. 101, 2020, doi: 10.1016/j.actbio.2019.10.038.
258 Vasiliadis, A.V., Koukoulias, N., and Katakalos, K., 'From Three-Dimensional (3D)- to 6D-Printing Technology in Orthopedics: Science Fiction or Scientific Reality?'.

4D additive manufacturing is at the proof-of-concept stage. Figure 26 is a SWOT analysis that highlights the strengths, weaknesses, opportunities, and threats of emerging technology.

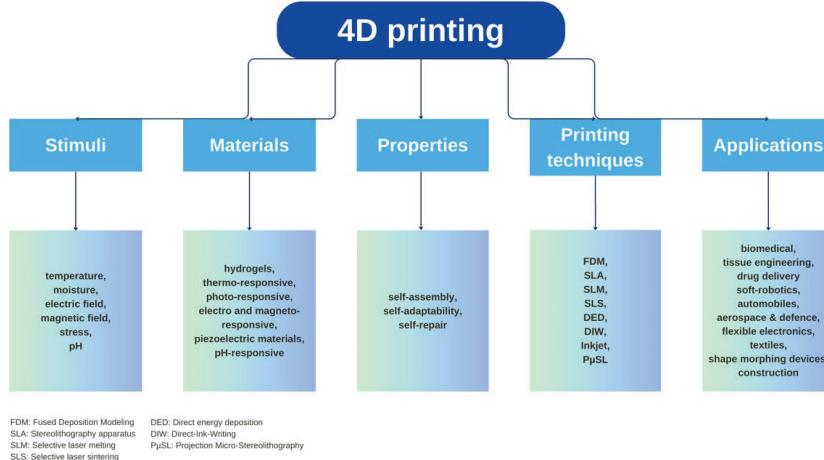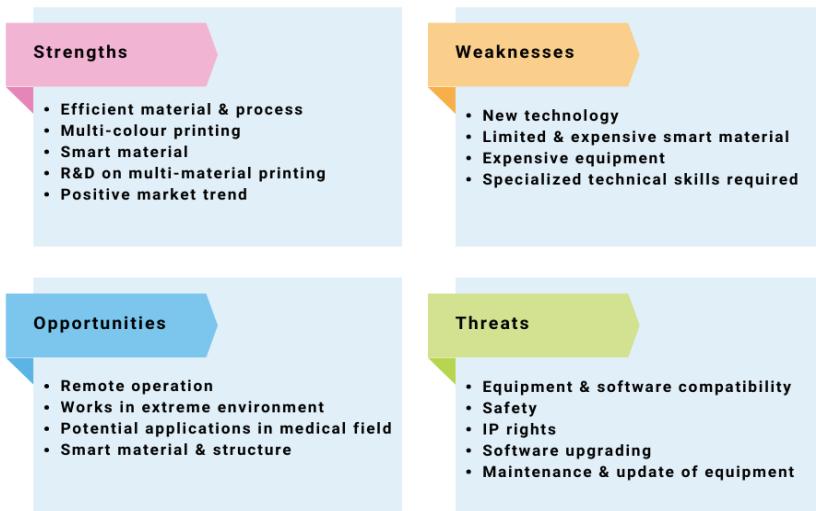**Figure 26: SWOT analysis of 4D additive manufacturing.**

Adapted from: Quanjin, M., et al., 'Recent 3D and 4D intelligent printing technologies: A comparative review and future perspective', Procedia Computer Science, vol. 167, 2020, doi: 10.1016/j.procs.2020.03.434.

Strengths
• Efficient material & process
• Multi-colour printing
• Smart material
• R&D on multi-material printing
• Positive market trend

Weaknesses
• New technology
• Limited & expensive smart material
• Expensive equipment
• Specialized technical skills required

Opportunities
• Remote operation
• Works in extreme environment
• Potential applications in medical field
• Smart material & structure

Threats
• Equipment & software compatibility
• Safety
• IP rights
• Software upgrading
• Maintenance & update of equipment

7.2 Sustainability and circularity

AM is a promising sustainable manufacturing method that is attracting growing interest from diverse fields including international development.[259] For example, cement-based additive manufacturing construction is an emerging technology that, while omitted from many roadmaps for decarbonizing the cement sector, has a potential of becoming a climate solution for the cement sector.[260] The cement industry is a key driver of climate change currently contributes to approximately 8 per cent of global CO_2 emissions ever year - double that of air travel.[261] Beyond the construction sector, the potential of AM in facilitating carbon neutrality has demonstrated usefulness for the energy sector and carbon capture and storage technologies (Chapter 3), and industrial manufacturing such as lightweight aircraft components.

Life cycle assessment of additive manufacturing

Life cycle assessment (LCA) is a comprehensive analysis tool that

259 Taddese, G., Durieux, S., and Duc, E., 'Sustainability performance indicators for additive manufacturing: a literature review based on product life cycle studies', International Journal of Advance Manufacturing Technology, vol. 107, no. 7, 2020, doi: 10.1007/s00170-020- 05249-2.
260 Habert, G., et al., 'Environmental impacts and decarbonization strategies in the cement and concrete industries', Nature Reviews. Earth & Environment 1, 2020, doi: 10.1038/s43017-020-0093-3.
261 Cheng, D., et al., 'Projecting future carbon emissions from cement production in developing countries', Nature Communications, vol. 14, Dec 2023, doi: 10.1038/s41467-023-43660-x.

evaluates the potential environmental impact a product over the whole life cycle, namely: (i) Design; (ii) Material preparation; (iii) Production; (iv) Post processing; (v) Use, and (vi) End of Life treatment, including recycling and final disposal.[262] Figure 32 is a schematic illustration of the inputs, outputs and stages of the life cycle of an additive manufactured product.[263]

Figure 27: The inputs, outputs and stages of the life cycle of an additive manufactured product.

Source: Kokare, S., Oliveira, J. P., and Godina, R., 'Life cycle assessment of additive manufacturing processes: A review', Journal of Manufacturing Systems, vol. 68, 2023, doi: 10.1016/j.jmsy.2023.05.007.
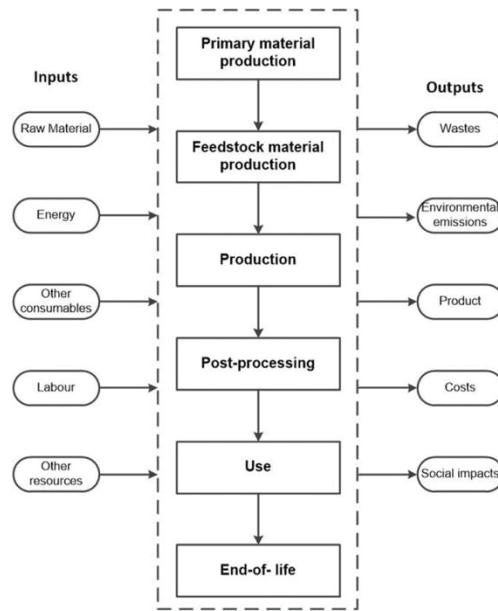
Another way to use the life cycle assessment for AM is as a tool for a 'cradle-to-grave' analysis to identify sources of negative environmental impacts as well as opportunities or intervention points to improve sustainability along the entire product value chain or life cycle.[264] The six intervention points are: (Figure 34)

a. design of products and processes
b. manufacturing system configuration
c. business model
d. efficiency in use phase
e. product life extension
f. losing the loop

262 International Organization for Standardization, ISO 14040:2006/Amd 1:2020 Environmental management - Life cycle assessment - Principles and framework, 2020, Geneva, Switzerland.

263 Kokare, S., Oliveira, J. P., and Godina, R., 'Life cycle assessment of additive manufacturing processes: A review', Journal of Manufacturing Systems, vol. 68, 2023, doi: 10.1016/j.jmsy.2023.05.007.

264   Saade, M., Yahia, A. and Amor, B., 'How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies', Journal of Cleaner Production, vol. 244, no. 11, 2019, doi: 10.1016/j.jclepro.2019.118803.

Figure 28: Six areas of opportunity to advance sustainability with additive manufacturing across a product's life cycle.

Source: Despeisse, M., et al., 'Sustainable Value Roadmapping Framework for Additive Manufacturing', Procedia CIRP, vol. 61, doi: 10.1016/j.procir.2016.11.186.

a Design of products and processes for efficiency

b Manufacturing system configuration

c Business model

d Efficiency in use

Product & process design

Material extraction & processing

Component & product manufacturing

Use & Service

Other waste/by-products

Upcycle, recycle, downcycle

Remanufacture, refurbish

Repair, reuse

f Closing the loop

e Product life extension

This model shows resources flow in a circular manner and hints at the potential of additive manufacturing to contribute to the creation of a circular economy that radically improve resource efficiency by eliminating the concept of waste and shifting away from the linear take-make-waste model to a closed-loop resource model.[265] For example, 3D printing can improve resource recovery, even perishable food wastes. A recent study in India demonstrated the 3D printability of banana peel powder with guar gum for customized and biodegradable food packaging casings.[266]

Emerging research suggests that the adoption of AM processes can potentially lead to sustainability gains such as waste reduction due to the nature of *additive* process as opposed to subtractive process which starts with a substantial piece of material; optimization of on-demand production - reducing the need to warehouse spare parts and products, and reduction in carbon footprint and embodied energy.[267] But more research is needed to increase our understanding of the enablers and barriers for AM to reach its full potential for a circular economy, particularly in the areas of material choice in the design stage and developing new opportunities in waste streams. We also need tools to quantify the circularity of a product and measure the sustainability of various AM processes so we can compare their sustainability merits.

265 Despeisse, M., et al., 'Unlocking value for a circular economy through 3D printing: A research agenda', Technological Forecasting and Social Change, vol. 115, 2017, doi:10.1016/j.techfore.2016.09.021.

266 Nida, S., Moses, J. A. and Anandharamakrishnan, C., 'Converting fruit waste to 3D printed food package casings: The case of banana peel', Circular Economy, vol. 2, 2023, doi: 10.1016/j.cec.2022.100023.

267 Agnusdei, L. And Del Prete, A., 'Additive manufacturing for sustainability: A systematic literature review', Sustainable Futures, vol. 4, 2022, doi: 10.1016/j.sftr.2022.100098.

7.3 Peace and security risks

Additive technologies have opened a largely under-regulated pathway to the private manufacture of operational weapons within an otherwise highly regulated environment in most countries. Without serial numbers, such guns are untraceable. They pose serious a threat for community safety, social cohesion and critical infrastructure when these weapons are hard to detect with traditional screening technologies because they are made mostly from plastics.[268] 3D-printed guns have gained traction among extremists and paramilitary groups as demonstrated by a surge in searching for, downloading, sharing, and manufacturing 3D-printed gun designs.[269] Finnish prosecutors recently convicted three men who made semi-automatic weapons using a 3D printer with the intent to launch the attacks on ethnic and religious minorities, key infrastructure and perceived political opponents.[270]

While fully 3D-printed designs are generally considered unreliable as weapons, several factors make 3D-printed guns highly attractive and accessible. Additive manufacturing and 3D printing technologies are improving rapidly. 3D printers are relatively inexpensive. Tried and tested designs are freely posted online, with step-by-step instructions on printing, assembling, and testing the guns.[271] Open source, decentralized, and dispersed networks of individuals around the world can incubate, accelerate and amplify the rapid evolution of design and manufacturing solutions. For example, DEFCAD is the world's largest repository for small arms technical data.[272] Their aim is to ensure the world's 2D and 3D firearms reference files and blueprints are permanently available in the public domain and to organize open-source collections for the benefit of the American rifleman and gunsmith.[273] Although the technical data is only available to people in the US, it is easy to evade this restriction with the use of a Virtual Private Network (VNP) service (Figure 34).

268 Daly, A., and Mann, M., 3D printing, policing and crime, QUT Crime, Justice and Social Democracy Research Centre, Australia, Briefing Paper 1, 2018.

269 Basra, R., 'The Future is Now: The Use of 3D-Printed Guns by Extremists and Terrorists', Global Network on Extremism and Terrorism, June 2022, <https://gnet-research.org/2022/06/23/the-future-is-now-the-use-of-3d-printed-guns-by-extremists-and-terrorists>, accessed 02 Jan 2024.

270 Finnish neo-Nazis used 3D printer to make guns in preparation for 'race war', The Guardian, 1 Nov 2023, <https://www.theguardian.com/world/2023/oct/31/finland-neo-nazis-convicted-crimes-with-terrorist-intent-3d-printer-guns>, accessed 02 Jan 2024.

271 Basra, R., 'The Future is Now: The Use of 3D-Printed Guns by Extremists and Terrorists'.

272 DEFCAD, <www.defcad.com>, accessed 02 Jan 2024.

273 Ibid.
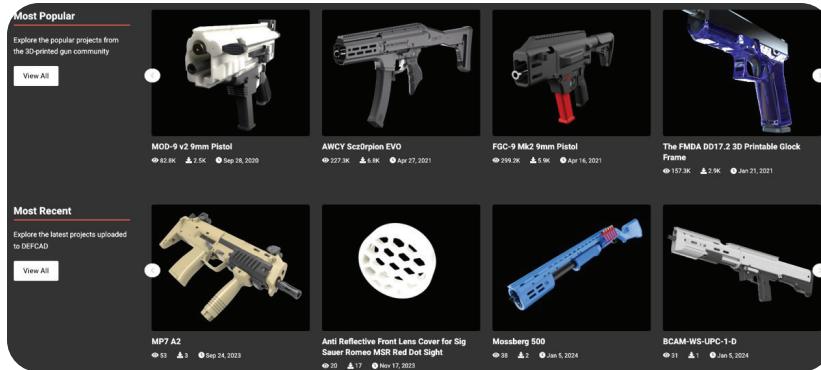
In response to this public safety issue, the 3D-printed Gun Safety Act of 2023 has been introduced into US Congress on June 6, 2023.[274] This bill is in the first stage of the legislative process. The aim of the Bill is to prohibit the distribution of 3D printer plans for the printing of firearms, and for other purposes.[275]

Legislative responses to 3D firearms have varied internationally and are evolving given the dynamic nature of the problem. International responses to 3D-printed guns include:

- criminalizing the manufacture of 3D-printed firearms,[276]
- licensing or registration schemes for 3D-printed firearms,[277] and
- introducing new offences for possession of digital design files for 3D-printed firearms.[278]

International peace and security

The military and defence industry are investors in and users of additive manufacturing. 3D printing applications in military contexts include weapon prototyping and development, spare parts production, Unmanned Aerial Vehicles (UAVs), robotics, body armour and protective gear, camouflage and concealment, military vehicle components, specialized ammunition, field medical devices, communication and sensor equipment, satellite and space technology base, infrastructure and shelters, military training and simulation tools, electronic warfare equipment, landmine clearance and explosive disposal equipment, and lightweight components for aerial reconnaissance and mapping drones.[279]

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274 Senator Edward J. Markey introduced S.1819 - 3D Printed Gun Safety Act of 2023 - 118th Congress (2023-2024), <https://www.govtrack.us/congress/bills/118/s1819/text>, accessed 02 Jan 2024.

275 Ibid.

276 Daly, A., and Mann, M., *3D printing, policing and crime.*

277 Ibid.

278 Ibid.

279 Colorado, H. A., et al., 'Additive manufacturing in armour and military applications: research, materials, processing technologies, perspectives, and challenges', *Journal of Materials Research and Technology*, vol. 27, 2023, doi:

3D and 4D printing, like other emerging technologies, could have a significant impact on the future of warfare as they all have the potential to fundamentally change the way force is applied and questions of accountability and agency.[280] Such technologies require a re-examination of current legal concepts and of what have been unequivocal concepts in international law such as weapon and armed conflict.[281] Current regulations attempts to address general additive manufacturing standards but lack specific directives for military contexts. The United Nations Arms Trade Treaty includes 3D-printed weapons as light arms and firearm components but it does not cover the dissemination or possession of 3D design files.[282]

7.4 International development and effective localisation

Despite the benefits of design flexibility, versatility, highly customizable capacity offered by additive manufacturing, several challenges prevent the widespread adoption of AM technologies in many industries, and the international development and humanitarian sectors are no exception. Critical studies on additive manufacturing have documented the limitations and challenges, including:

- Education and capacity building[283]
- Limited material suitability[284]
- Set-up cost, from equipment to novel materials[285]
- Poor surface finishing[286]
- Security concerns[287]
- Weak standardization and regulatory framework[288]
- Speed of production for some objects[289]

10.1016/j.jmrt.2023.11.030.

280 Bruun, L., Marta, B., and Goussac, N., Compliance with International Humanitarian Law in the development and use of autonomous weapon systems, Stockholm International Peace Research Institute, Stockholm, 2023.

281 Boulanin, V. and Verbruggen, M., *Article 36 Reviews: Dealing with the challenges posed by emerging technologies*, Stockholm International Peace Research Institute, Stockholm, 2017.

282 *United Nations Arms Trade Treaty* (adopted 2 April 2013, entered into force on 24 December 2014).

283 Ribeiro, I., et al., 'Framework for Life Cycle Sustainability Assessment of Additive Manufacturing', Sustainability, vol. 12, no. 3, 2020, doi: 10.3390/su12030929.

284 Ford, S. and Despeisse, M., 'Additive manufacturing and sustainability: An exploratory study of the advantages and challenges', Journal of Cleaner Production, vol. 137, 2016, doi: 10.1016/j.jclepro.2016.04.150.

285 Ribeiro, I., et al., 'Framework for Life Cycle Sustainability Assessment of Additive Manufacturing'.

286 Ibid.

287 Ibid.

288 Ibid.

289 Ibid.

- Higher energy consumption in specific fabrications[290]
- Quality control[291]
- Repeatability and scalability[292]

Although these studies do not directly address the international development context, some of the limitations and challenges are highly relevant.

1. Knowledge and skills deficit
- Highly specialized skills and interdisciplinary knowledge are needed to go from design to product.
- Although designers and engineers may have an overview of AM techniques, they often do not have experience-based knowledge and hands-on experience.

2. Cost
- The initial set-up cost of equipment and training is substantial.
- AM is best suited for low volume and hard to get/make or expensive parts.
- It should be noted that many studies on the cost of AM tend to look at the production of single parts and do not examine supply chain effects such as reduced inventory and transportation costs along with decreased risk to supply disruption.[293]
- Metal powder material and advanced composite materials are expensive

3. Materials
- The variety of material suitable for AM is very limited when compared with the range of materials that are available for conventional manufacturing.
- The lack of materials available for AM either inhibits the manufacture of certain parts or requires them to be redesigned for different materials.
- Developing a new material for AM is costly, involving R&D, quality control and standardization of new material, and compatibility with various AM technologies.

4. Finishing

290 Ibid.
291 Thomas-Seale, L. E. J. et al., 'The barriers to the progression of additive man-ufacture: perspectives from UK industry', International Journal of Production Economics, vol. 198, 2018, doi: 10.1016/j.ijpe.2018.02.003.
292 Ibid.
293 Thomas, D. S. and Gilbert, G. W., Costs and Cost Effectiveness of Additive Manufacturing. A Literature Review and Discussion, National Institute of Standards and Technology, U.S. Department of Commerce, Washington D.C., 2014.

- Post-processing requirements are often needed before an object can be used. These additional steps can add to the overall cost and time required for the manufacturing process.

5. Quality control

- There is a need to address the challenges of quality control so that AM technologies deliver results in a predictive and replicable manner.
- It is necessary to establish effective processes for validation of the mechanical and thermal properties of AM materials, particularly for newer or proprietary materials due to the lack of knowledge of the material properties.[294]

6. Governance and standards

- Innovation moves faster than government. Regulations have not kept pace with the rapid change in this field. Governance frameworks are often weak or lacking.
- Efforts to develop effective technical guidance, policy directives and oversight on 3D-printed medical devices, implants, drugs, and 3D bioprinting started less than 10 years ago. For some, these instruments are piecemeal and ambiguous, particularly for governing non-traditional manufacturers like medical facilities and academic institutions that create 3D-printed personalized devices.[295]

Towards a hybrid approach

A most promising way to maximize the value of AM is to adopt a hybrid approach and integrate AM with conventional subtractive manufacturing processes, if applicable, with other advanced technologies. Technologies can often be complementary, where two technologies are adopted alongside each other and the benefits are greater than if they were adopted individually.[296] Research on AM finds it is cost effective for manufacturing small batches alongside centralized manufacturing.[297] At the same time, increase adoption of additive manufacturing may lead to a reduction in raw material cost through economies of scale.[298] AM will continue to evolve as adoption

294 Flood, A., et al., 'Searching for Unknown Material Properties for AM Simulations', Metals, vol. 13, no.11: 1798, 2023, doi: 10.3390/met13111798.
295 Pew, 'DA's Regulatory Framework for 3D Printing Of Medical Devices at the Point of Care Needs More Clarity', July 2022, <https://www.pewtrusts.org/en/research-and-analysis/issue-briefs/2022/07/fdas-regulatory-framework-for-3d-printing-of-medical-devices-needs-more-clarity>, accessed 04 Jan 2024.
296 Thomas, D. S. and Gilbert, G. W., *Costs and Cost Effectiveness of Additive Manufacturing. A Literature Review and Discussion.*
297 Ibid.
298 Ibid.

increases and the technology improves, and used in combination with artificial intelligence and other advanced technologies.

Effective localisation

Gerstle et al. stated that 50% of all globally manufactured goods will be printed using additive manufacturing technology by 2060 if the current investment in additive manufacturing continues.[299]

In low-income or disaster-prone regions, supply-chain expenses regularly absorb 60-80 percent of humanitarian budgets, making the localization of AM logistically advantageous.[300]

Research conducted by George Washington University School of Business has shown that localisation of additive manufacturing (AM) requires the alignment of four critical pillars: industry readiness, financing mechanisms, human capital development and regulatory environment. Each of these components must be considered to ensure AM's sustainable adoption and integration in local contexts.

Industry Readiness

To determine the most appropriate industries and sectors, six criteria should be considered:

- Existing capabilities and resources: examines the technological infrastructure, technical expertise, and institutional resources present in a given context.
- Local supply chain maturity: assesses the availability and accessibility of materials and logistical infrastructure necessary to support AM operations.
- Local needs and market demand: explores the demand for customized products, the existence of localized challenges that could be addressed through AM, and the potential to substitute imports with locally manufactured goods.
- Social impact on youth: emphasizes the role of AM in fostering opportunities for young people.
- Sustainability: evaluates the economic and environmental sustainability, and the resilience-related aspects of AM implementation
- Scalability: assesses the potential for expansion and replication

299 Gerstle, T.L. Ibrahim, A.M.S. Kim, P.S. A plastic surgery application in evolution: three-dimensional printing Plast. Reconstr. Surg. 2014; 133:446-451
300 Stumpf, J., Besiou, M. and Wakolbinger, T. (2023), "Assessing the value of supply chain management in the humanitarian context – An evidence-based research approach", Journal of Humanitarian Logistics and Supply Chain Management, Vol. 13 No. 1, pp. 1-9.

of successful AM models.

Financing mechanisms

Field interviews, literature review, and case studies show a clear pattern: localization of AM succeeds fastest, reaches more children, and costs less when non-governmental organizations (NGOs) and private sector, profit-driven firms pool their assets.

NGOs bring last-mile knowledge and donor credibility, while private companies can supply design libraries, quality control, and scale capital.

Four financing pathways are found to be effective in marrying social impact with commercial viability.

- In *public-private partnerships (PPP)*, 3DP companies can give access to specialised equipment, training, and ongoing maintenance, while NGOs can provide on-the-ground knowledge and firsthand connections to community needs to help private-sector partners tailor their solutions.
- In *blended finance structures*, where donor grants and private investment are combined, NGOs can leverage philanthropic capital to de-risk early-stage AM projects and attract commercial financing for long-term expansion. This also aligns the incentives of diverse stakeholders behind a unified objective.
- In *thematic donor engagement*, 3DP can be framed as a strategic tool for achieving the SDGs to help NGOs attract donors such as governments and multilateral institutions.
- *Pooled funds or challenge models* allow resources pooling from multiple donors. By inviting NGOs, startups, and universities to apply, this model directly spurs innovation and creativity from local stakeholders who understand the region's unique challenges.

An assessment conducted to select the most suited financing methods based on potential impact, simplicity of execution, scalability, risk profile, and long-term sustainability found that PPPs and blended finance structures provide the strongest all-round profiles for AM projects, while pooled funds and thematic grants are valuable for early-stage experimentation or mission-specific gaps.

Human capital development

Unlike traditional manufacturing, AM demands a fundamentally different set of skills, such as robotics, 3D design, and systems

management. These technologies are complex and evolving, requiring continual learning and adaptability.

As AM is complex and evolving, reliance on foreign expertise to operate and scale AM would lead to high cost, delays implementation and reduced ownership of innovation. This is not sustainable.

AM empowers youth as it offers a new frontier for youth to acquire cross-industries and cross functional skills, explore diverse career paths with enhanced earning potential, and address pressing social and economic needs through locally driven manufacturing solutions.

To bridge the skills gaps in AM, a fundamental transformation of education systems is required, including:
- Providing AM-related development opportunities for educators as a critical first step.
- Creating spaces in schools, libraries, and community centers to foster hands-on learning and encourage innovation.
- Strong collaboration between academia and industry to facilitate knowledge transfer and best practices.
- Integration of AM concepts into educational programs from an early stage is essential.[301]

Research suggests coupling every project with a human-capital track. Dedicated training modules in CAD, printer maintenance, and quality control - delivered through local universities or maker spaces - are essential for durable results and youth employment. Offer certificates co-branded with industry partners to improve graduates' job prospects.[302]

Regulatory environment

For regulatory analysis, an assessment of the context has been carried out with two focuses: regulation in the AM space and regulation on a national/regional level.

In the AM space, the primary themes for regulation are industry

301 To, T. T., Al Mahmud, A., & Ranscombe, C. (2024). Opportunities and challenges of 3-D printing integration into engineering education in developing countries. Emerging Technologies and Society, 27(4), Article RP11. https://doi.org/10.30191/ETS.202410 27(4).RP11

302 Kirchain, R., Moore, E., & Field, F. (2022). Preparing the advanced manufacturing workforce: A study of occupation and skills demand in the 3-D/additive manufacturing industry. Center for Advanced Manufacturing, Massachusetts Technology Collaborative. https://cam.masstech.org/sites/default/files/2024-07/Preparing%20the%20Advanc ed%20Manufacturing%20Workforce%20A%20Study%20of%20Occupation%20a nd%20Skills%20Demand%20in%20the%203DAdditive%20Manufacturing%20In dustry.pdf

specific standards and certifications, material and process standards, intellectual property, and environmental and safety.

- Key organizations in developing industry standards consist of ASTM International, ISO, the European Federation for Welding (EFW)[303] and Additive Manufacturer Green Trade Association (AMGTA).[304]
- The current AM regulations include FAA (U.S.)[305] and EASA (EU)[306] on aviation, FDA (U.S.)[307] on medical device, ISO/ASTM 52910, ISO 10993 on materials and processes[308], EPA (U.S.)[309] and REACH (EU)[310] on emission, etc.
- There are other resources for regulatory development, such as Worldwide governance indicators[311], ICT Regulatory Tracker[312], World Economic Forum's Executive Opinion Survey[313] and Global Cyberlaw Tracker.[314]

The regulations for countries and regions rely on the analysis of the local context. Three indexes were selected to provide a comprehensive view of this regulatory environment including:

- The Index of Economic Freedom gives an in-depth analysis of a country's political and economic context, giving insights on how conducive the regulatory environment is to implementing AM.[315]
- The Global Innovation Index gives information on how the environment is in terms of innovation capabilities, technology adoption or R&D investment, giving insights on how likely the country is to have strong policies supporting tech adoption and innovation.[316]
- The Network Readiness Index measures a country's preparedness to leverage information and communication technology (ICT), digital infrastructure, and tech integration in business/government, reflecting on how well a country embraces

303 https://www.ewf.be/

304 https://amgta.org/

305 https://www.faa.gov/

306 https://www.easa.europa.eu/en

307 https://www.fda.gov/

308 https://www.iso.org/standard/67289.html

309 https://www.epa.gov/

310 https://echa.europa.eu/home

311 https://www.worldbank.org/en/publication/worldwide-governance-indicators

312 https://app.gen5.digital/tracker/about

313 https://centres.weforum.org/centre-for-new-economy-and-society/execu-tive-opinion-survey

314 https://unctad.org/topic/ecommerce-and-digital-economy/ecom-merce-law-reform/summary-adoption-e-commerce-legislation-worldwide

315 Miller, T., Kim, A. B., Roberts, J. M., & Tyrrell, P. (2024). 2024 index of economic freedom. The Heritage Foundation. https://www.heritage.org/index/pages/report

316 World Intellectual Property Organization. (2024). Global Innovation Index 2024. https://www.wipo.int/web-publications/global-innovation-index-2024/en/

digital transformation, critical for localising AM.[317]

Engaging regulators and standards bodies from day one is important. Early dialogue with ministries, ASTM, ISO, and health- or building-safety agencies will speed approvals and avert later compliance shocks.

Prioritisation

Each of these components should be considered to ensure AM's sustainable adoption and integration in local contexts. Targeting countries with the right enabling conditions first will expedite success. Starting where hurdles are lower will shorten time-to-impact and create reference sites for more challenging environments. When these pillars align, AM becomes a tool for accelerating child-centered development at scale.

7.5 Call to action

The potential use of AM and more specifically, 3D printing in the humanitarian and development sectors has been an ongoing topic since 2000. But the range of possible applications for the sector remains under explored. As additive manufacturing technologies continually evolve and develop, new opportunities and new applications will emerge that will help address humanitarian and development challenges. To unlock these opportunities, this Insight Report concludes with a call to action to support broader and deeper exploration of and experiments in additive manufacturing for international development that would demonstrate impact and in the long term deliver more sustainable outcomes for every child.

Research & Development
- Studies related to material compositions and printing protocols should include improvement to recyclability and biodegradability and development of low-carbon printable materials.
- Commission demonstration projects on the long-term performance of 3D-printed objects and products to increase trust and the uptake in the humanitarian and development sector.

Sustainability and environmental impact
- While early studies indicate that additive manufacturing holds promise for a circular economy, to truly understand the environmental impact we need develop predictive environmental

317 Portulans Institute. (2024). The network readiness index.https://networkread-inessindex.org/

frameworks, cost models and sound methodologies to quantify the circularity of a product and the sustainability of different manufacturing processes for comparative analysis.

- Extend the scope of Life Cycle Assessments to include post-manufacture stages of AM products.
- Conduct environmental assessments and LCA studies in the demonstration projects to test and showcase the value and in particular the environmental gains of 3D printing compared to current 'business as usual' approach.

Social and economic impacts
- Existing research on AM has largely neglected the social and economic impacts of the technologies have been largely neglected.
- Two areas that should receive further attention are: (i) the impact on labour market in emerging economies and (ii) how might we leverage potential social and economic opportunities along the value chain.

Knowledge dissemination and exchange
- Establish open-source data repositories for industry and academia to share data on reliable materials manufacturing and printing protocols.
- Encourage reporting and sharing of data on LCA studies and other environmental metrics within the open-source repositories.

Capacity-building
- Ensure gender equity in AM courses and training and access to FabLab facilities, developing multiple entry points and new pathways.
- Integrate courses on sustainability and the social, economic and environmental impacts of AM and 3DP printing into existing teaching and training programmes.

Standards and codes of practice
- Develop standards and codes of practice that set out technical specifications, procedures and guidelines to help ensure a common approach and repeatable outcome in the design and development of products, particularly for new applications in health and for addressing potential risks such as small arms production. The ISO has published a general document on additive manufacturing but more work needs to be done.[318] Standards helps ensure products are safe, secure, consistent,

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318 International Organization for Standardization, Additive Manufacturing (ISO/ASTM 52900:2021), 2021, <https://www.iso.org/obp/ui/#iso:std:iso-ast-m:52900:ed-2:v1:en>, accessed 04 Jan 2024.

and reliable, and documents good practices, which helps accelerate the adoption of new technologies.

- Develop manufacturing standards to ensure the strength and durability of 3D printable cementitious materials.
- Standards promote compatibility and interoperability with other technologies and innovations, innovation adoption, and efficient scalability.

Partnerships

- To fully realize the potential of AM to address complex global challenges, we need to bring together skills and resources from partners from a range of sectors and disciplines at local, national and international level. This also means collaborative relationships between partners from the global south and global north.

APPENDIX A: TYPES OF BIOINK, ADVANTAGES, DISADVANTAGES AND APPLICATIONS

Figure 35: Types of bioinks

Natural	Synthetic	Hybrid (natural + synthetic)
• Alginate • Agarose • Cellulose • Collagen • Chitosan • Decellularized Extracellular Matrix (dECM) • Gelatin • Hyaluronic acid (HA) • Fibrin • Silk • Matrigel • Gellan gum	• Pluronic • Poly(ethylene glycol) (PEG) • Polycaprolactone (PCL) • Polyvinylpyrrolidone (PVP) • Poly(L-Lactic) Acid (PLA) • Poly(Lactic-Co-Glycolic) Acid (PLGA) • Polyethylene (glycol)-diacrylate (PEGDA) • Poly (ethylene glycol) - methacrylate/dimethacrylate (PEGDMA)	• Gelatin-methacrylate (GeIMA) hydrogel • Poly(ethylene glycol) - Alginate • Hyaluronic acid methacrylate (HAMA) • HA-PEG • HA-PCL • HAMA-GELMA

Source: Ghosh, S., and Yi, H-G., 'A Review on Bioinks and their Application in Plant Bioprinting', International Journal of Bioprinting, vol. 8, no. 4, 2022, doi: 10.18063/ijb.v8i4.612.

Figure 36: Advantages, disadvantages and applications of different types of bioink

Types of bioink	Advantages	Disadvantages	Bioink	Applications
Melt-cure polymers	Mechanically robust and durable, and can serve as structural supporting scaffolds	Require high temperature or toxic solvents, low cytocompatibility	PCL	• Cartilage • Bone • Muscle • Liver-on-a-chip
			PLA	• Heart-on-a-chip
			PU	• Nervous tissue • Muscle

Types of bioink	Advantages	Disadvantages	Bioink	Applications
Naturally derived hydrogels	Naturally cell-adherent and can provide native ECM-like environments	Generally low mechanical strengths and difficult to modify	Collagen	• Liver-on-a-chip • Cartilage
			HA	• Cartilage
			Alginate	• Cartilage • Vascular constructs
			Gelatin	• Liver-on-a-chip
			Agarose	• Vascular network
			Chitosan	• Cartilage & bone • Skin
			Fibrin	• Skin • Muscle
Synthetically derived hydrogels	Mechanical properties easy to manipulate and features such as temperature sensitivity	The contradiction between bioactivity and processability	GelMA	• Vascular networks • Liver-on-a-chip
			PEG	• Cartilage • Vascular network
			Pluronic	• Vascular network
			F-127	• Cartilage & bone • Muscle
dECM	Retain ECM components that induce tissue formation	Inferior post-printing shape fidelity	-	• Muscle • Bone
Cell spheroids and tissue strands	High cell density High cell density No need for delivering medium or support materials	The process, which includes generating and loading spheroids, deposition, and construct handling is time-consuming	-	• Cartilage • Vascular networks • Nerve grafts

HA: hyaluronic acid; GelMA: methacrylated gelatin; PEG: polyethene glycol