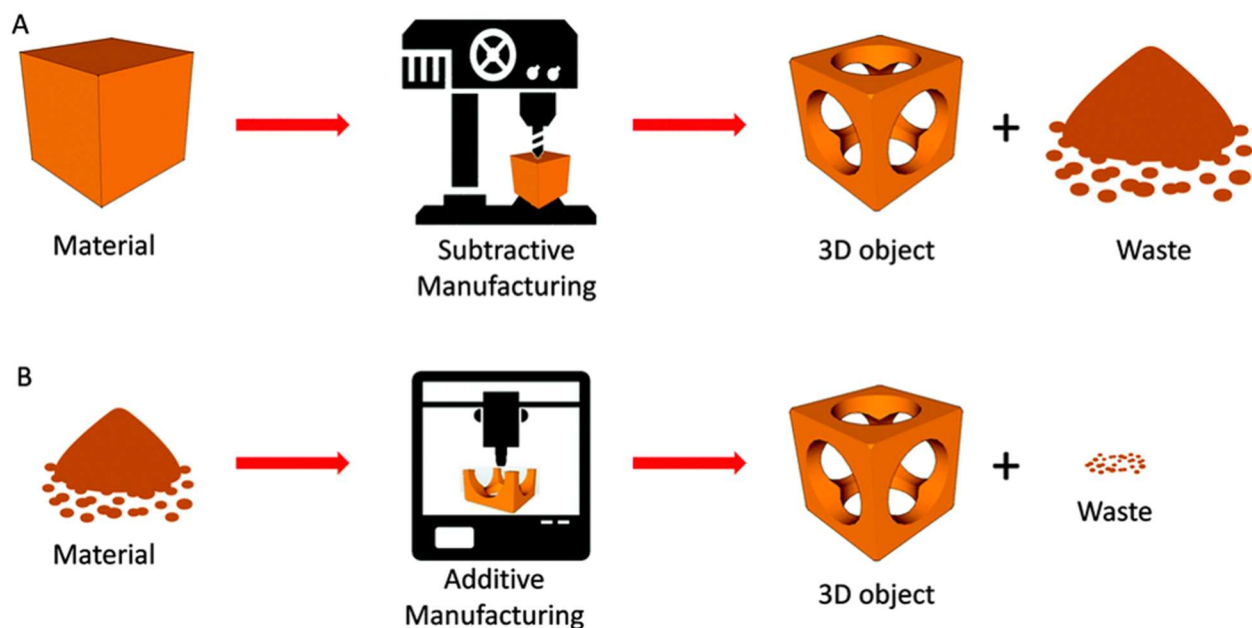


Design for Industry 4.0 – Additive Manufacturing



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MSc Industry 4.0 Advanced Manufacturing.

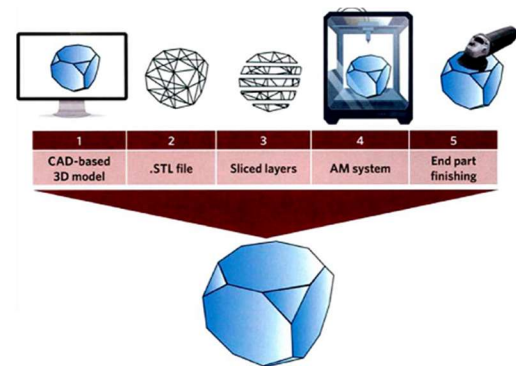
Abstract.

Additive manufacturing (AM), or 3D printing, is an alternative approach to production that optimizes the creation of lighter, stronger parts and systems.

It is an advancement connected to the I4.0 movement to digitalization.

Developments in I4.0 including simulation, communications, imaging, big data, AR and the merging of traditional subtractive techniques with AM can provide considerable flexibility and efficiency (GE, 2021).

CAD software and/or 3D object scanners generate designs, slicing models for printing, layering material to produce 3 dimensional objects that cannot be made with conventional processes. As its name implies, additive manufacturing adds material to create an object. As alluded to earlier traditional machining methods revolve around removing material to create the product using milling, drilling, broaching, shaping, turning, tapping etc. Whereas AM is additive, building up or adding layers which results in much less material waste.



AM or 3D printing has its roots as far back as 1945 but the practical development, with the first 3D metal recorder patented by Johannes F Gottwald in 1971, early AM equipment was then developed in the 1980s (Giovachino, 2020). Developing rapidly through the 90's and to current day where AM is now a feasible alternative to traditional production techniques and not just for rapid prototyping. Enhancing performance, able to generate complex geometries and simplifying fabrication for today's rapidly changing world.

There are 7 main types of AM, Vat-Photopolymerization, Material Jetting, Material Extrusion, Binder Jetting, Power Bed Fusion, Directed Energy Deposition and Sheet Lamination. We will be exploring each of these methods in more depth looking at pros, cons and use cases for each approach.

Keywords: AM, AR, Big Data, 3D Printing, I4.0, CAD

List of Abbreviations.

AM	-	Additive Manufacturing.
AR	-	Augmented Reality.
CAD	-	Computer Aided Design.
CLIP	-	Continuous Liquid Interface Production.
DED	-	Direct Energy Deposition.
DLP	-	Direct Light Processing.
DMLS-		Direct Metal Laser Sintering.
EBM	-	Electron Beam Melting.
FDM	-	Fusion Deposition Modelling.
FEA	-	Finite Element Analysis.
FFF	-	Fused filament fabrication.
LOM	-	Laminated Object Manufacturing.
ME	-	Material Extrusion.
NIR	-	Near InfraRed.
PBF	-	Powder bed Fusion.
PPE	-	Personal Protective Equipment.
SGC	-	Solid Ground Curing.
SHS	-	Selective Heat Sintering
SLA	-	Stereolithography.
SLM	-	Selective Laser Melting.
SLS	-	Selective Laser Sintering.
UC	-	Ultrasonic Consolidation.
UV	-	Ultraviolet.

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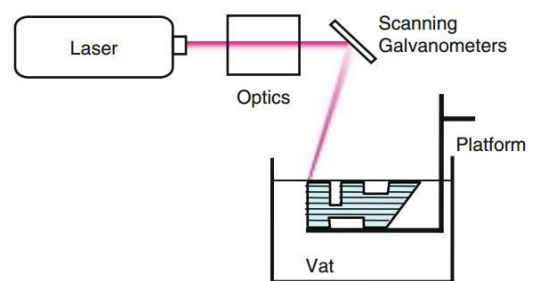
Introduction.

AM is disruptive in the innovation space, impacting design, manufacturing and business models. It is providing a radically new method of production, that enables unique designs to be produced resulting in reduced cost, improved productivity with enhanced sustainability and flexibility.

We will now look at each broad type of AM:

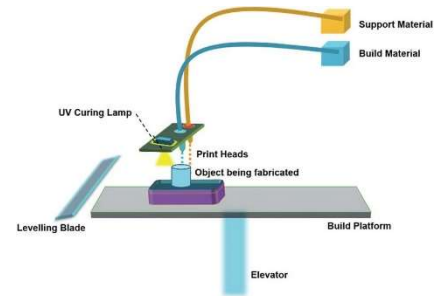
Vat photopolymerization is one method of AM creates 3D objects through selective light stimulation of liquid resin by polymerization. Stereolithography, was the first technique to be patented and marketed and falls into this category. Dating back to the 1980s, vat photopolymerization has increased in popularity to also include CLIP, SGC and DLP (Siemens, 2021).

Vat photopolymerization uses resins called photopolymers as the printing medium. Typically, UV or NIR, liquid photopolymers' molecules bind together and set to a solid state through photopolymerization (Silbernagel, 2018). The liquid photopolymer is held in a vat with a platform partially submerged near the surface of the liquid. Building the 3D object from a CAD file, directing a light source to build the image. The platform is further submerged into the resin and the process is repeats until the 3D image is fully constructed.



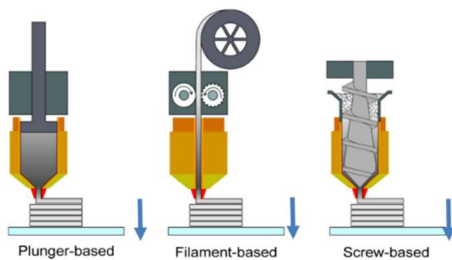
Vat photopolymerization is a fast, accurate process that can be deployed for large models and rapid prototyping, negatively photopolymers are not as robust as some of the other available methods in terms of durability, strength, or stability. Some resins are also toxic and require special PPE to handle parts until they are set. Some geometries also require support structures which can be very complex which lead to extensive post processing.

Material Jetting constructs objects in a similar fashion to traditional 2D ink jet printers. This can be via a continuous process or a drop on demand system. The object is built up layer by layer, material is deposited from an applicator which moves in a horizontal plane across the platform. The complexity of this process varies where the material can be cured/solidified by UV light (University, 2021).



Material Jetting can deliver high accuracy and low waste, enabling the use of different colours and material types but as already stated with a limited range of materials and the requirement for support structures!

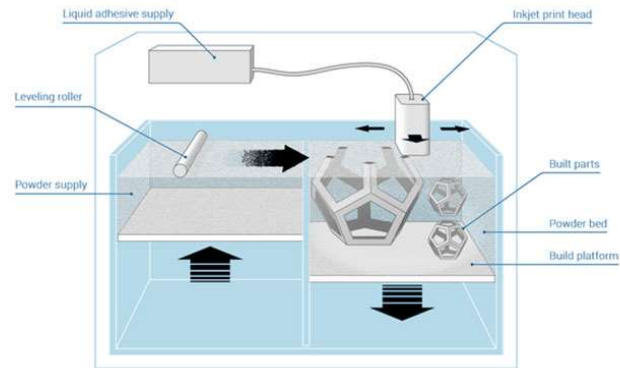
Material Extrusion is another AM system which uses continuous application of material to produce a 3D part. Plastic filament is passed through a nozzle, heated and deposited to build up, layer by layer, the desired object. FDM/FFF are common types of ME and are the most frequently used types of AM ideally suited for general consumer demand and appropriate quality.



There are many advantages related to this process included, but not limited to, broad range of print material, relatively simple technique, easy print material change, low related costs, fast print time for smaller components, tolerance of +/- 0.1mm and the equipment is comparatively small.

ME does suffer from some weaknesses including layer lines, requirement for constantly moving head, support structures are often necessary, plane perpendicular to the application platform is relatively weak, higher resolution and larger components increases print time and as material jetting some materials are toxic and require PPE (Design, 2018).

Binder Jetting uses inkjet-type delivery heads to apply a bonding substance onto powder to form solid, 3D constructs. This process uses a chemical adhesive reaction, this separates binder jetting from fusion methods (Siemens, 2021).



The binder jetting process works like 2D ink jet printer but utilizes adhesive, not ink and powder as opposed to paper. The application plan is generated from a CAD file, sliced for sending to the 3D printer then the application head traverses the platform, applying adhesive to selectively bond sections of powder. The platform height changes, and the process is repeated until the 3D object has been constructed.

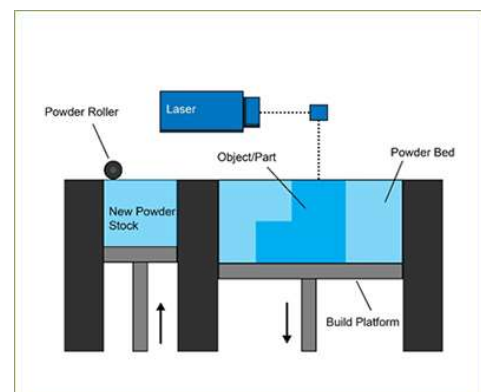
This process can be used with a wide array of materials and bonding agents. The use of different dyes also allows for printing multicolored objects making it suitable for architectural models or decorative pieces (Alexandrea, 2019). Due to the weak structure and limited density this process is not suitable for applications handling mechanical load stresses.



Positively it is fast and cost effective however parts can require significant post processing which adds to cost and time considerations.

Power Bed Fusion - Multiple techniques come under this type of printing, DMLS, EBM, SHS, SLM and SLS.

PBF uses a laser or electron beam to melt and fuse powder. EBM needs a vacuum and can be used metals and alloys in the construction of components, it's a layer-by-layer powder method. The powder delivery can be done with a roller or blade, with hoppers providing material supply. DMLS is a similar principle to SLS, using metals as opposed to plastics. The process sinters the



powder, layer by layer. Fresh powder is applied by roller/blade and the component platform is lowered in a similar method to other techniques (University, 2021).

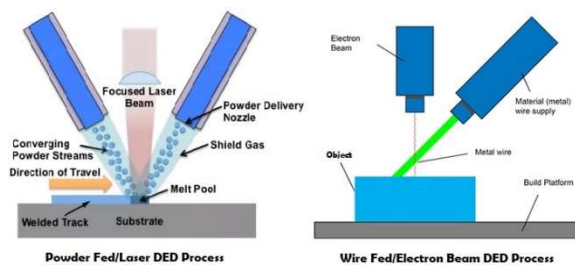
Many justifications for use including its cost effectiveness, use for models and prototypes, small scale of equipment, powder used as a support structure and broad range of material possible.

Drawbacks include relatively slow operation, size constraints, power requirements and finish is reliant on the powder granularity.

Directed Energy Deposition process uses the application of a thermal device, often a laser, this fuses particles as they are deposited (Molitch-Hou, 2018). Mobility of this method leads to its use in 4/5 axis machines due to its ability to apply material at an angle.

Material can be printed onto existing metal surfaces and is used frequently in the Aerospace and Automotive industry.

DED can be used to repair existing parts or construct new objects using a combination of AM and subtractive methods. There are many solutions that enable design, 3D printing and finish processing all in one package!



DED is extensively used for the following reasons - fast process rates, minimal post processing, metal addition for repairs, multi-material options, scales size of parts, material feed system is easily changed and reduced waste.

The DED systems do however require a large initial investment, have a low build resolution requiring post processing and it is generally not possible to use support structures!

Sheet Lamination is a technique where thin sheets of material are bonded together to form a mass which is then cut into the desired object. LOM and UC are both types of sheet lamination. A range of materials can be used from paper to metal but require different methods for the binding process.

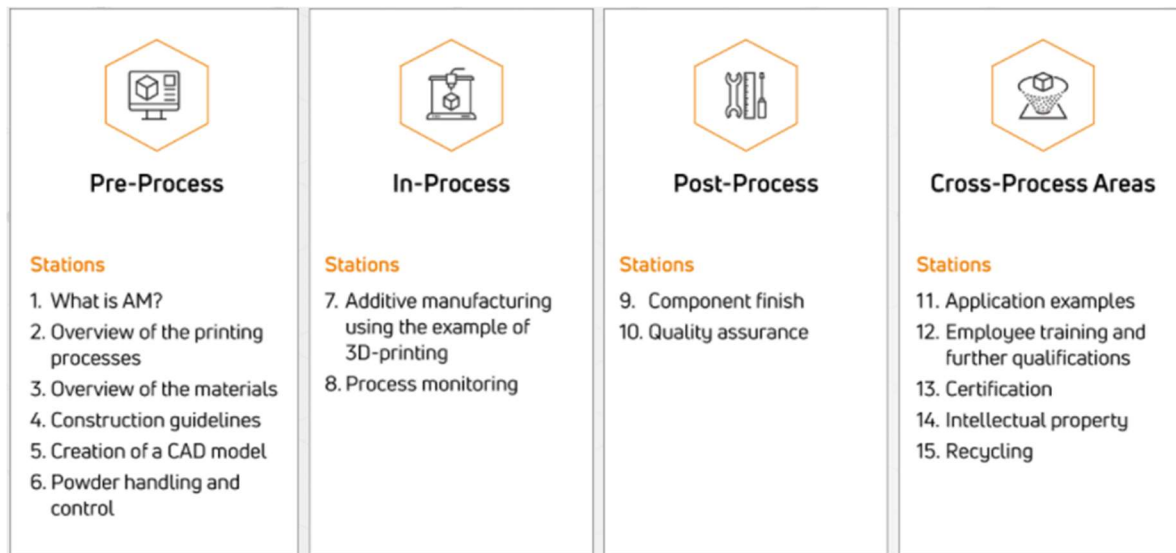
This technique is low cost and fast but less accurate than some other methods and suitable for only nonfunctional prototyping and other simple designs (Siemens, 2021).

A summary of various AM types are shown in the table below:

Technology	AM Process	Typical Materials	Advantages	Disadvantages
Stereolithography	Vat-Polymerisation	Liquid polymers Composites	Complex Geometries, Detailed parts, Smooth finish	Post-curing, relatively weak. Support Structures
Digital Light Processing	Vat-Polymerisation	Liquid polymers	Concurrent production Complex shapes and sizes High precision	Limited product thickness Limited range of materials
Multi-Jet Modeling	Material jetting	Photopolymers Wax	Good accuracy and finish Multiple materials, easy to remove supports	Limited range of materials slow build process, support structures
FDM	Material extrusion	Thermoplastics	Strong components	Poor surface finish, slower than SLA PPE requirements sometimes.
Powder bed and InJet head printing	Binder jetting	Ceramic powders Metal laminates Acrylic, Sand, Composites	Full colour models cheap Fast production	Limited accuracy Poor surface finish
Plaster based 3D printing	Binder jetting	Bonded Plaster Plaster composites	Cheap, Colour print, Fast, Reusable materials, Complex Geometries	fragile product limited range of materials
Electron beam modelling	Powder bed fusion	Titanium powder Cobalt, Chrome	Speed, low distortion, less waste	post processing, X-ray system difficult to clean equipment
SLS	Powder bed fusion	Paper, plastic, Metal, glass, ceramic, composites	No support structures heat and chemical resistant	Accuracy limited to powder particle size, poor surface finish.
Selective Heat Sintering	Powder bed fusion	Thermoplastic Powder	Lower cost than SLS, Complex geometries No support structures	Limited historic info.
Direct Metal laser Sintering	Powder bed fusion	Stainless steel, nickel alloy cobalt, chrome	Dense structures Complex geometries	needs post processing unsuitable for larger components
Laser metal deposition	DED	Metals and alloys	multi-material printing possible, large parts possible, production flexibility	Relatively high cost support structures, post processing
LOM	Sheet Lamination	Paper, Plastic, Metal laminates Ceramics, Composites.	Relatively cheap Non toxic, large parts possible	Low accuracy
Ultrasonic consolidation	Sheet Lamination	Metals and alloys	very fast to make big parts Non toxic, relatively cheap	Low accuracy and inconsistent quality, needs post processing.

Steps in the Design Process

We will now examine some of the considerations when producing additive manufacturing products, see the image below for a basic outline:



Requirements of original design - Many considerations need to be made on the printing method such as fine features, smooth finish, precision and accuracy, but also isotropy, is the design watertight, and versatility of the material.

FDM is known to generate designs with anisotropy due to the application process and thermal effects, SLA does not suffer from these issues and is preferred for a wide range of solutions.

SLA produces components with isotropy, are watertight, given predictable mechanical properties suitable for multiple end use applications such as automotive, aerospace, medical and household (FormLabs, 2019).

The accuracy required will depend on the application, medical will require high accuracy, post processing and SLA can control multiple variables through construction at low/room temperatures.

Surface finish is highly desirable in many applications, some 3D print techniques can approach and even surpass traditional processes such as milling, drilling etc. The image shows the



comparison between the same component printed with FDM and SLA at 100-micron accuracy!

Material choice is critical with a wide range available that can be hard, soft, structurally strong and able to handle large forces.

Generative Design – this is a tool for suggesting designs or improving existing designs. Where constraints, objectives, limitations and designer experience are all fused to generate potential solutions. Suggested designs can be optimized for weight, rigidity etc. which will clearly have an impact on the rest of the design process. Software packages, such as Fusion360, facilitate this GD process but it is essential the designer uses real world variables to produce a realistic set of designs (Briard, 2020).

Topology optimization – various methods exist such as lattice infill or meta blending for optimization but TO is the most popular method. The objective is to optimize the design space in terms of weight, rigidity etc. within the constraints of the original design. Mathematical algorithms are used in some methods to remove low stress areas and bolster high stress areas of as design.

Discrete methods face challenges in optimization depending on the mesh options used and the checkerboard issue. There are modified methods address these issues such as MMC (Moveable Morphable Component), it is not a discrete method where it searches for an optimal solution using a range of building blocks.



Light Weighting – there are 3 basic method for reducing the weight of a 3D printed product (Kauppila, 2021):

Materials substitution - substituting parts of an object with alternative materials with similar properties but is lighter e.g., replacing steel automotive parts with carbon fibre. With the invention of new materials this is becoming increasingly relevant.

Material reduction - as the name suggests this is reducing the amount of material used to an optimum. TO covered above is a fundamental part of the reduction process. Possibilities include modifying solid geometries in hollow ones, introducing lattice structure to provide required strength with less material.

Part consolidation - the merging of several discrete components into one whole or improves functionality. The process of light weighting is only possible through 3D printing as subtractive manufacturing is not capable of removing complex shapes such as lattice structures!

Validate process and product simulation – simulation is used extensively in I4.0 and AM is no exception. Simulation can identify critical aspects of a design by adjusting component or the printing process. Simulation of designs can eliminate inefficient options, and produce complex CAD solutions, saving time and cost. Optimizing DfAM through simulation will reduce development and production cost (CADFEM, 2021).

Pre-Printing, Printing & Monitoring – Many considerations are needed for the preparation and the printing process. Depending on the method used we must consider location is the printing space, orientation of the printed part, support structures required for features like overhangs, distortion from thermal effects, stresses of the process. These issues can be planned for/uncovered by simulating the printing process before producing a sliced 2D layered model (CADFEM, 2021).

Where possible it is advisable to use existing process parameters from historical applications to further optimise the process.

Post Processing – is an extremely important step in production, preprocesses to this step should be optimized to ensure that the total process is viable and does not compromise structural integrity e.g., does not introduce porosity into fusion methods. Whether removing support structure or fine finishing components it all adds to the production complexity.

There are multiple postprocessing method from depowering, shot peening, dyeing, painting, chemical smoothing, galvanization and many more. One post processing method of particular interest is CNC machining.

Post processing through CNC machining can improve the aesthetics as well as mechanical properties, tensile strength can be enhanced through heat treatment which can balance a products toughness, hardness and ductility (Shi, 2021).

Heat treatment of metal components will markedly affect the way the final product performs, and this concept of hybrid manufacturing is being used extensively in the automotive and aerospace industries to gain competitive advantage.

AM has already shown it can replace traditional casting, now the fusion of CNC and AM technologies looks to open the next generation of mass-manufacturing in an attempt to bring down manufacturing cost and time. For some exciting examples of this check the links out below:

<https://www.youtube.com/watch?v=fx5dWHBut2Y>

<https://www.youtube.com/watch?v=1TwVkAuvGwM>

Final Finished part – with the range of applications every increasing the final part requirements are quite diverse depending on the application whether its aerospace, automotive, medical or product development.

These techniques reduce the time, cost, weight, re-engineering cycles and gift the ability to produce organic designs that were impossible to achieve before.

It is crucial in many applications to quality control the density, surface roughness and dimensional accuracy of the components and the various post processing techniques help to achieve this (Minetola, 2019). Shown are some complex examples of finished parts:



Conclusion

The advancements in Industry 4.0, and AM in particular, has brought about a revolution in manufacturing from design for manufacture, design for assembly and

creating radical new design that were previously impossible to produce with conventional means.

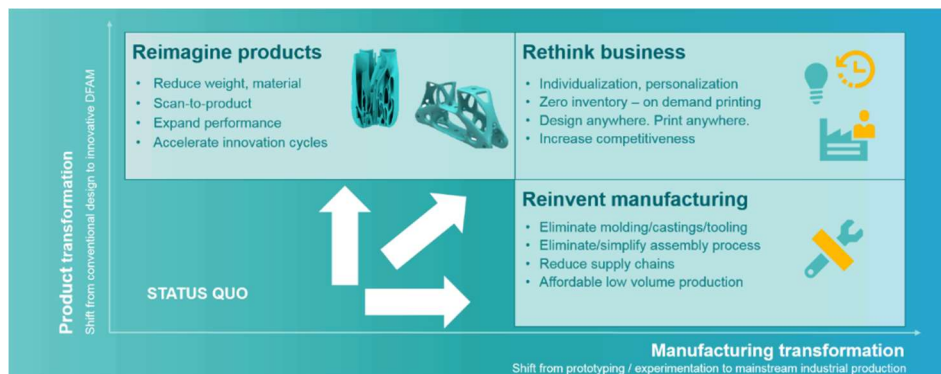
Advancing the lean methodology, removing waste from processes, avoiding duplication, enhancing how we manufacture products. Using AM to eliminate anything that adds complexity, cost and time that ultimately doesn't add value for the customer.

The flexibility to take advantage of new information and design, flow with rapidly changing markets and to produce in a batch of one scenario where facilities and investment can be optimized more than ever before.

Exceeding customer expectations in design and delivery, moving closer to zero waste and zero defects. Improving OEE using enhanced components, lowering MTTR through rapid repairs and deployment (Key, 2021).

Sustainability considers economic, social effects are optimized, environmental effects but wider industry effects should be considered (Alfaify, 2020):

Do cost and lead time for outsourcing AM promote bringing 3D printing in house? How is this handled? How does this affect the current/traditional manufacturing landscape? What happens to the traditional toolroom and its skilled employees? Can these skilled craftsmen be upskilled into I4.0 or are the necessary skills coming through the current educational systems? What about the support chain for traditional manufacturing process, specialist manufacturers could be effectively wiped out overnight!? What impact will this inexorable drive to new technologies have on employment and employability? Is there a clear pathway to embrace I4.0?



The image shown will stimulate the various questions, challenges & opportunities open to businesses.

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