CHAIN REACTIONS

INNOVATION BRIEF 3

KEY ENABLING TECHNOLOGIES

ADVANCED MANUFACTURING

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ABOUT INNOVATION BRIEFS

CHAIN REACTIONS addresses the challenge for industrial regions to increase regional capacity to absorb new knowledge and turn it into competitiveness edge and business value. There is a strong need to help SMEs to overcome capacity shortages for innovation and integration into transnational value chains.

The project aims at empowering regional ecosystems with the knowledge and tools to help businesses overcome those barriers and generate sustained growth through value chain innovation.

CHAIN REACTIONS focuses thereby on modern approaches considering value chains and their complex developments rather than linear technology transfer approaches. The framework of value chain innovation builds on Porter's 5 forces framework (new entrants, substitutes, customers, suppliers and rivalry) and transversal innovation drivers: key enabling technologies, resource efficiency, digital transformation and service innovation.

During the project lifetime CHAIN REACTIONS will publish about every third month an INNOVATION BRIEF presenting the rationale behind specific innovation drivers and illustrate them with practical examples.

In the context of CHAIN REACTIONS, the most relevant KETs are the ones related to advanced manufacturing systems. We selected the two most relevant ones and describe hereafter their impact on industry in general:

- additive manufacturing
- Industry 4.0

This INNOVATION BRIEF is about the key enabling technology ADVANCED MANUFACTURING.

ADDITIVE MANUFACTURING

Additive manufacturing (AM) encompasses a range of technologies that allows physical components to be made, from virtual 3D models by building the component layer-upon-layer until the part is complete.

In comparison with subtractive manufacturing processes, in which one starts with a block of material and removes any unwanted material (either by carving it by hand, or by using a machine such as a mill, lathe or CNC machine) until one is left with the desired part, additive manufacturing starts with nothing and builds the part one layer at a time by 'printing' each new layer on top of the previous one, until the part is complete. Depending on the particular technology used, the layer thickness ranges from a few microns up to around 0.25 mm per layer, and a range of materials are now available for the different technologies.

The very earliest concepts related to additive manufacturing date back to the end of the 19th century, and early 20th century, with the introduction of layer-based topographical maps as 3D representations of terrain, together with a number of methods for using these topological models to produce 3D maps by, for example, wrapping a paper map over the topological models to produce a 3D model of the terrain.

Photosculpture, which also originated towards the end of the 19th century, and which used a series of different photographs taken from different angles around the object that were then used to carve out the object using each different angled picture as a template, so an initially subtractive process, also had several proposed methods for creating the models using photosensitive materials.

Modern additive manufacturing saw its origins in the mid-20th century with a patent, in 1951, by Otto John Munz which could be considered the origin of the modern stereolithography technique. It consisted, essentially, of a series of layered 2D transparent photographs printed on photosensitive emulsion stacked on top of each other. He developed a system for selectively exposing the transparent photo-emulsion in a layer-wise fashion in which each layer was exposed with a cross-section of an object. Much like a modern stereolithography machine, the build platform on which the part was being built was gradually lowered, and the next layer of photo emulsion and fixing agent was created on top of the previous layer. Once the printing process was finished, the result was a solid transparent cylinder containing a 3D image of the object. A weakness of this system was that the final real threedimensional object had to be manually carved or photo-chemically etched out of the cylinder as a secondary operation.

The following decades saw the development of a succession of new techniques including those of Swainson who, in 1968, proposed a process to directly fabricate a plastic pattern through the selective 3D polymerization of a photosensitive polymer at the intersection of two laser beams (with the patent assigned to the Formigraphic Engine Corporation). Work was also undertaken at Battelle Laboratories, called Photochemical Machining, in which an object was formed by either photochemically crosslinking or degrading a polymer through the simultaneous exposure to intersecting laser beams.

In 1971, Ciraud proposed a powder process that can be considered the father of modern direct deposition AM techniques such as powder bed fusion, and in 1979, Housholder developed the earliest equivalent of a powder-based selective laser sintering process. In his patent, he discussed sequentially depositing planar layers of powder and selectively solidifying portions of each layer. The solidification could be achieved by using heat and either a selected mask or by using a controlled heat scanning process such as a laser.

Other notable early additive manufacturing developments include those of Hideo Kodama, of the Nagoya Municipal Industrial Research Institute in Japan, who developed a number of stereolithography related techniques, and the work of Herbert who, in parallel with Kodama, developed a system that directed a UV laser beam onto a photopolymer layer, by means of a mirror system on an x–y plotter, to scan a layer of the model. The build platform and layer were then lowered by 1 mm into a vat of resin and the process was repeated.

Commercial additive manufacturing, as we know it today, with the development of commercially available system did not really begin until 1986, with Charles W. Hull’s stereolithography patent. The patent was originally owned by UVP Inc. and the company licensed the technology to their former employee, Charles Hull, who used it to found the start-up 3D Systems. This development saw the first commercial SLA machine appearing in 1988 and, since then, almost every year has seen an exponential rise in available systems, technologies and materials.

Even the terminology relating to additive manufacturing has changed a lot over the last three decades. For most of the 1990s, the principal term used to describe the layer-upon-layer manufacturing technologies was rapid prototyping (RP), because the principal use of the various available technologies was to make concept models and pre-production prototypes. Some other terms that have also been used over the years include Solid Freeform Fabrication (SFF) and Layer Manufacturing.

In early 2009, however, the ASTM International Committee F42 on Additive Manufacturing Technologies tried to standardize the terminology used by the industry and, after a meeting in which many industry experts debated the best terminology to use arrived at the term 'Additive Manufacturing' which, today, is considered the standard terminology used by industry.

In their ASTM F2792 10e1 Standard Terminology for Additive Manufacturing Technologies document they defined additive manufacturing as: the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining.

Unlike subtractive manufacturing, where the material is removed from a larger block of material until the final product is achieved, most additive manufacturing processes do not yield excessive waste material. If a part is properly 'designed for AM', and one is comparing it to a single part produced through conventional manufacturing, it also typically may not require the large amounts of time needed to remove unwanted material thus, potentially, reducing time and costs, and producing relatively little waste. This, however, should not be misconstrued as AM being able to always make cheaper parts than conventional manufacturing. In many cases it is, in fact, the opposite, because AM is a relatively slow and expensive technology. But this depends very much on the AM technology in use and the many possible design parameters that can be used.

It should be noted, however, that while industry has, generally, adopted the additive manufacturing term, much of the popular press and media continues to refer to additive manufacturing as 3D printing, as this is a term more easily understood by the general public. Some consider the term 3D printing to be focussed on lower-cost hobby desktop 3D printers, and additive manufacturing focussed on higher-end industrial production systems. In CHAIN REACTIONS we use the two terms interchangeably

The Additive Manufacturing Value Chain

All additive manufacturing begins with the creation of a virtual 3D CAD model. Almost any 3D computer-aided design (CAD) software can be used. This CAD model must, however, be in the form of a fully enclosed "watertight" volume (which means that a model of a cube, for example, must include all 6 faces, and have no gaps at the seams). If one of the faces of the model is missing, or there are gaps, it represents an infinitely thin surface which cannot be printed (though, depending on how bad the errors are, some AM software can be used to automatically fix the model).

The CAD file is then converted into a file format that can be understood by the AM machine. Typically, today, the most commonly used file format is an STL file (standard triangle language, stereolithography, or standard tessellation language) which is a format that converts the original CAD file into a triangulated file. The higher the resolution of the STL file, the more triangles it contains, so the better the quality of the model.

Some new additive manufacturing file formats, including AMF (Additive Manufacturing File Format) and 3MF (3D Manufacturing Format), have recently been proposed which vastly improve the somewhat antiquated STL format, as they add more information to the file, including colour and material, and allows the use of curved triangles to improve model quality. At the time of publication, 3MF appears to be gaining considerably more traction than the AMF format.

3MF, or 3D Manufacturing Format, is a file format developed and published by the 3MF Consortium. It is an XML-based data format designed specifically for AM, and it includes information about materials, colours, and other information that cannot be represented in the STL format.

The STL file produced by the CAD software is then opened in the AM machine's software, and the model is placed on the software's virtual build platform (the platform on which the part will be printed) in the most suitable orientation for printing. The print orientation can affect both the surface quality and the strength of the final part. Some processes, for example, produce highly anisotropic parts in which there is a weakness between the layers of the part or vertical direction of the print. Other processes use support material to allow overhanging parts to be printed.

The AM machine's software then slices the STL files into thin layers, and some software also let you set the other print parameters including print resolution (layer thickness), material, fill patterns, speed, etc.

Once the software has sent the part build instructions to the machine, it starts to build the part layer upon layer. How it builds each layer, and what material it uses, depends on the particular technology being used.

After the machine has finished printing the part, they are removed from the machine and post-processed. Post-processing almost always includes cleaning the part of left-over powder or resin, removing support material and, in many cases, might include further processing such as machining, if a surface requires a finer finish than the AM machine can provide, infiltration to make the part stronger, heat treatment for metal parts, or colouring and painting if the part needs to be in a colour other than that provided by the AM material.

Current Usage of Additive Manufacturing

Over the past 30 years, AM has grown to be used in an ever-increasing number of application areas. The Wohlers Report, a leading annual 'state of the industry' report, undertakes a yearly survey to find out what AM is being used for.

It is interesting to note that, although 43.9% of applications are in the rapid prototyping realm (including fit and assembly, functional models, presentation models and visual aids) the use of AM to produce real parts, both directly or indirectly, now represents over 56% of usage. This includes patterns for prototype tooling, patterns for metal casting, tooling components, and direct part production. Wohlers expects this percentage to grow substantially over the next few years as more and more industries adopt AM as part of their growing manufacturing arsenal.

Since its inception, AM has grown on two distinct fronts. The last decade, in particular, has seen good improvements on high-end machines capable of producing excellent quality parts in a number of materials. At the same time, there has been enormous growth in the DIY and desktop 3D printer community with a wide range of entry-level additive manufacturing systems with prices ranging from a few hundred to a few thousand dollars. Entire communities (the reprap, fablab, and makerbot communities, for example) have developed, often with an open-source approach to sharing knowledge on additive manufacturing which has greatly benefitted the industry.

It is only over the last few years that additive manufacturing has improved in quality to the extent that some companies have started to use it as a viable production technology. As new polymer and metal materials are developed and the speed and precision of the machines further increase, more additive manufacturing machines are likely to find their way into mainstream production lines.

Additive manufacturing also has a number of qualities that give it the ability to manufacture parts that cannot be made by traditional manufacturing techniques. Understanding this is vital to understanding when, and when not, to use AM. It is also important to note that AM will never completely replace traditional manufacturing. It is a complementary technology that, if used because of the value it can add, and if the parts it produces are specifically designed for AM, then it can add great value to the company. Some of the advantages AM has over conventional manufacturing are listed below.

The Advantages of Additive Manufacturing

AM can be an expensive process, so in order for its use to be profitable as a production method, it must bring added value to a product. This can either be through reducing life cycle costs for the product or through enabling a higher price to be charged to the customer. This is achievable in a number of ways as described below.

▪ Part Complexity

Additive manufacturing enables the creation of parts and products with complex features, which could not easily have been produced via subtractive or other traditional manufacturing processes. With conventional manufacturing, the more geometrically complex a part becomes the more expensive it becomes to manufacture and, at a certain point, it becomes impossible to manufacture. AM works in the opposite way: The more geometrically complex the part is, the more suitable it is for AM, as it costs no more to produce a complex part than a simple one (there are some exceptions to this, particularly if support material is hard to remove). If a part is very simple, however, AM can become an expensive way of producing the part compared to traditional manufacturing.

With AM, more complex shapes can be created, both for external forms and internal structures. This can result in improved product performance and/or increased aesthetic attraction. The former can be translated into lower running costs and the latter into increased price.

With traditional injection moulded or die-cast parts, for example, the parts must be removable from the die in which they are made and must, therefore, be designed in such a way that this can be done. For simple ‘open and close’ die parts this is not a problem but, as the complexity of the parts increases, a number of ‘moving cores’ becomes necessary which can greatly increase the complexity, and cost, of the tool. And, past a certain level of complexity, the parts cannot be manufactured at all or must be broken down into a number of smaller components that then need to be assembled to make the final component possible. With AM, this is no longer a problem as the complex part can be manufactured directly.

It should be noted that additive manufacturing does not remove all manufacturing restrictions. It, instead, replaces them with a different set of design considerations that designers must take into account if they wish to successfully use the technologies.

A simple example of the type of restrictions that additive manufacturing suffers from is the inability to manufacture entirely enclosed hollow volumes. A completely sealed hollow sphere, for example, is still impossible for current additive manufacturing technologies to make because there is no way of removing the excess resin, powder, or support material, from the inside of the sphere. One must, therefore, leave a hole of a minimum diameter in the part in order to remove the excess material from inside the part.

These new design considerations are, however, much less restrictive than traditional manufacturing technologies, and easier for designers to both understand and comply with without them affecting design intent in a major way.

- **Instant Assemblies**

With additive manufacturing, it is possible to manufacture complex interlocked moving parts in ready-made working assemblies. Though two components may be permanently linked together, they are made as a single component and come out of the machine assembled and ready to work.

There is a foldable guitar stand that was printed using a powder bed fusion technology. The entire guitar stand is, however, manufactured in a single operation with no assembly whatsoever required. If the guitar stand were to be manufactured using traditional manufacturing methods, it would require, at least, sixteen components and an assembly procedure to attach all the separate components together.

To additively manufacture complete assemblies, the designer needs to leave a minimum gap between the moving components. The material in these gaps is not processed by the AM machine so, after the part is finished, can be removed to leave the surrounding components free to move. The size of this gap varies from process to process but is, generally, in the order of a fraction of a millimetre. It is important to understand that the required gap between moving parts is considerable, by engineering standards, so if moving parts with tight engineering fits are required, it is unlikely that AM would be able to print them in an assembled configuration.

- **Part Consolidation**

Part consolidation is when several simpler parts are replaced by a single more complex AM part. This reduces assembly and inventory costs.

- **Mass Customization**

With additive manufacturing parts can be made on-demand, as there is no longer a long lead-time to get tooling produced. The tooling required for conventional mass-manufacturing typically takes from a few weeks to several months to produce. This feature of additive manufacturing has a great impact on new product time-to-market and on the ability to easily produce model changes throughout the life of a product. It also has implications in stock control: As components can be made on the spot, companies may no longer need to hold large stock of spare parts as they simply manufacture the parts when needed. This feature of additive manufacturing is often referred to as 'manufacturing-on-demand'.

From a product design perspective, it also means that every component made can be completely different to the others in a production run without significantly affecting the manufacturing cost or manufacturing time. This opens the door to mass-customization in which, though mass-manufactured, each product can be customized to each individual customer. This is already beginning to happen in industries including hearing aids, dental crowns, implants, medical prostheses, customized orthotic shoe inserts, and the high-end interior design and fashion industries.

For this new way of designing products to be used effectively, the product design and the computer-aided design industries will need to develop new methods for integrating personalized customer data into their designs. This development has already started, particularly in the hearing aid and the dental industries, in which specialized software exists to automate the processes of patient data acquisition. The patient's personalized data is acquired, usually through a laser scanning process, and the software then automates the process of cleaning of the data, shelling the part, inserting mounting points for electronic components, etc. This increased automation in CAD software now needs to be extended to encompass other industries, including consumer product industries.

Freedom of Design

One of the greatest advantages additive manufacturing gives the designer over traditional manufacturing is freedom of design. Because of constraints of traditional manufacturing technologies, a product, which the designer may have originally envisioned as having a certain aesthetic and functionality, may need to be compromised so that it can be cost-effectively made. Most designers are quite accustomed to hearing the response of "it cannot be made like that" from manufacturing engineers. They may then need to compromise their design to the extent that the product loses the essence that truly embodies the designers vision. With additive manufacturing, complexity and geometry often no longer affect manufacturability. Almost anything the designer imagines can be made precisely as the designer conceived it (with the proviso that the parts may require substantially more labour in the post-processing stage).

Though this is directly related to product complexity, discussed above, we are, here, talking about the ability it gives designers and engineers to be less restricted by manufacturing constraints, and thus allows them to innovate in a way that may not have been previously possible.

Light-Weighting

Topology optimisation is a method of removing as much material as possible from a part while maintaining sufficient mechanical properties. It consists in performing a finite element analysis (FEA) and then iteratively removing unnecessary material.

Topology optimisation has been available for a long time, but complex designs could not be manufactured with conventional manufacturing. AM, however, is capable of making most complex designs from topology optimisation. This opens up a whole new engineering area dedicated to making lighter products. In the context of aeronautics, for example, any weight savings can represent large savings in fuel.

On-Demand Manufacturing

The term "on-demand manufacturing" or "manufacturing on-demand" is a manufacturing process in which goods are produced as and when required and, in the context of additive manufacturing, where required. With conventional manufacturing, an assembly line produces large quantities of products, which are then kept in stock until they are ready for shipping to their intended location. With on-demand manufacturing, products are made only once the customer's order comes in, and only as many products as are immediately required are made. If AM is being used, the AM system can be located near where the customer is, and the products can be made locally, rather than shipped around the world.

One can see the potential this has in entirely disrupting our existing supply chains. The benefits of this new supply chain are increasingly evident. It has the potential to lead to:

- Cost savings by eliminating or significantly reducing inventory requirements. Warehouses full of spare parts and stock could become a thing of the past. Instead of a physical inventory of parts, we now switch to keeping a digital inventory of parts and only make the parts physical the moment they are required.
- Digital files also provide the ability to quickly produce new product iterations at little to no additional cost. And as keeping stock of old product is no longer necessary, these changes can be instantly implemented.
- With a single source for a variety of parts, businesses that use 3D printing contract manufacturers deal with less risk, more control and added agility in relation to their product lifecycle.

- Local facilities can 3D print designs on-demand from files sent across the globe, or they can print securely from a nearby supplier.

Prior to the industrial revolution, the supply chain was extremely small. Most production was local to where the products where being sold and transporting products over long distances was often not feasible. The supply chain often began with the end-user making the product for themselves, perhaps with some bartering for parts from local trades-people and, if the product was good, it could then be sold to the rest of the market which, in most cases, was local to the village the maker lived in. In contrast, once mass-production began during the industrial revolution, products began to be mass-manufactured in a location, and then transported to the end-user somewhere in the world, through a complex supply chain of middle-men. Each of these middle-men adds a percentage cost to the product to make their margins, and the environmental footprint caused by all the transport and storage of the products can now be seen to be having an impact on the world we live in.

Additive Manufacturing in CHAIN REACTIONS

Innovative uses of additive manufacturing in different value chains will be explored within CHAIN REACTIONS in the framework of our transnational pilots.