University of Zagreb

Faculty of Economics and Business

Managerial Informatics

ADDITIVE MANUFACTURING – DIGITAL TRANSFORMATION IN MANUFACTURING BUSINESS MODELS

Master Thesis

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Zagreb, September 2022.

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Summary:

Additive manufacturing (AM) is a technology that uses a digital 3D model to produce objects in layer-by-layer fashion. Since AM is a completely different from conventional manufacturing techniques, AM requires knowledge of AM process with the importance of AM material and design knowledge. Since the manufacturing industry is steadily in decline, due to the economic shift to service-based business models, manufacturing is in a need of digital transition to adapt to the changing economic environment affected by digital transformation. Digital transformation is sometimes called Industry 4.0, one of the supporting technologies of Industry 4.0 is AM. In this thesis we will give an overview of AM technologies and processes, with the steps for implementation and give examples of AM implementation in different industries.

Keywords: **Additive manufacturing, digital transformation, Industry 4.0, manufacturing, business models**

Contents

1. Introduction

1.1. Topic and Goals of the Thesis

Throughout the master thesis, additive manufacturing (3D printing) will be examined as a new emerging technology that is disrupting current manufacturing processes. Additive manufacturing (AM) is part of on-going digital transforming, where AM technology enables businesses to innovate, create additional value and completely reimagine the product development process. By applying AM technology, businesses and other stakeholders in the economy will move towards more sustainable manufacturing with regards to the principles of circular economy.

Main goals of the thesis are:

- Describing the key characteristics of AM , differentiating the hardware and software aspect of the technology, analyzing materials used in AM and possible implications for the manufacturing industry. Describing current manufacturing practices and possible applications of AM in various industries
- Providing arguments for the AM technology as a fundamental part in the digital transformation of businesses in circular economy
- Showcasing the use-cases of AM technology and exploring the environmental impact of AM. Presetting and analyzing current applications of AM in: aerospace, automotive, healthcare, energy and transportation industries.

1.2. Explanation of Methodology

For confirmation of master thesis objectives, the following methods were used: researching the current literature, collecting primary and secondary data, prescribing the descriptive research, while using graphical representations to explore and compare AM technology to current practices in manufacturing industry.

Literature was obtained from online sources and books, together with the personal experience from the AM industry and other experts and enthusiasts in the field of AM.

1.3. Structure of the Thesis

The thesis is structured as follows: first the reader is introduced to the conceptual framework of AM, where history, technology, materials, and the complete process of AM is explained. Moreover, the introduction is suited for the beginners in the field of AM, and all unfamiliar terms are explained in detail. After the introduction the reader is presented with concepts of digital transformation within business models, industry 4.0 and circular economy. Furthermore, integration of AM in business models is presented, with the focus on bringing together other technologies and practices with AM.

The paper then explains the use-cases of AM and explores the current practices in the manufacturing process. Also, one big aspect of AM - sustainability and environmental impact - is explained to the reader.

Case Study is focused on real-life examples from different companies within their industries. It is structured in a way to present the industries which have the biggest adoption of AM technologies. Furthermore, in the analysis section, the author will analyze the benefits and challenges of specific industry case studies, with the goal of understanding the AM applications in different industries.

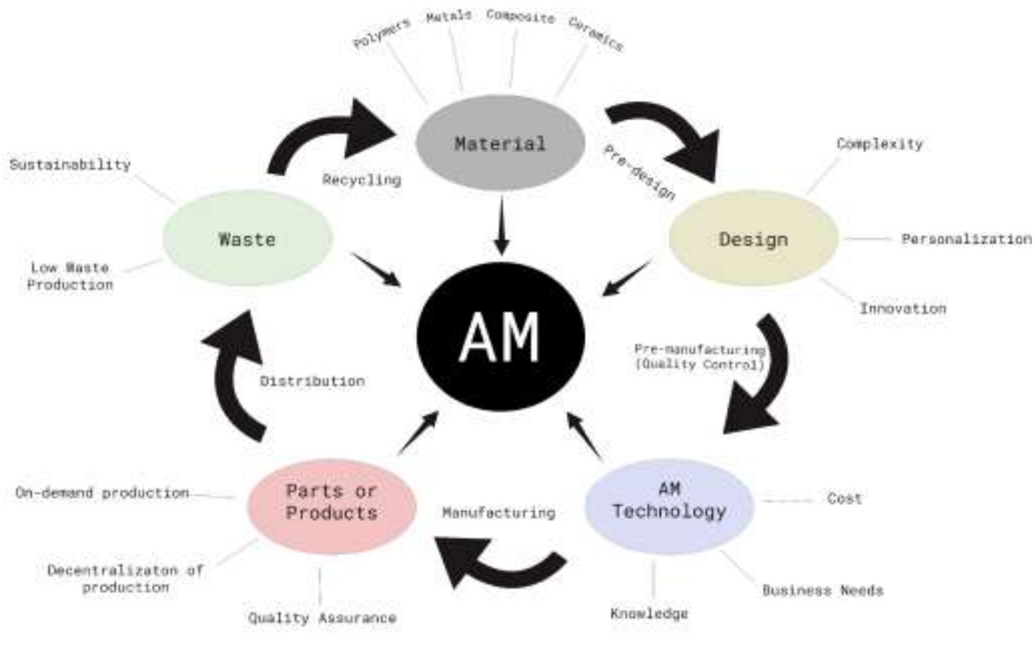
Finally, before concluding, the author will present the innovation within the AM industry and give possible future developments regarding AM and its application in the current manufacturing process.

2. Conceptual Framework of Additive Manufacturing

Additive manufacturing (AM), also known as 3D printing, is a different way of manufacturing physical objects usually by consecutive adding materials in layer-by-layer fashion. Before manufacturing, three-dimensional objects are created with the help of computer aided design (CAD) software. Then, a 3D model of an object is run through slicer software, which generates G-code (numerical control programming language). Finally, G-code is read by the AM system (3D printer), where layers are built in X-Y direction, one on top of the other, ultimately generating Z axis or third dimension[1].

AM utilizes a data-driven approach to manufacturing in every part of the product development process. Thus, disrupting conventional manufacturing processes while following principles of industry 4.0 (Chapter 3.2). AM must be viewed as a data-drive and sustainable alternative or synergism to conventional manufacturing methods like machining, forming, casting or joining. Conceptual framework of AM is represented with the following graphics.

Figure 1.: Conceptual Framework of AM



Source: Made by the author

[1] Zhang, X., Liou, F., (2021.) Introduction to additive manufacturing. In: additive Manufacturing. Elsevier

With AM, businesses can utilize data-driven approach and further optimize their manufacturing processes. This is possible due to the different approach to manufacturing than conventional, formative manufacturing methods. By integrating AM and other new technologies, businesses can have higher quality control throughout the product development process while simultaneously optimizing manufacturing process[2].

This is possible due to new possibilities in AM's material properties, product design, supply chain management and waste management. Therefore, AM is one of the digital technologies which will help manufacturing businesses in achieving industry 4.0 and circular economy standards[3].

Other digital technologies, which will work in synergy with AM are: 1) mobile technologies, 2) social networks, 3) cloud computing, 4) big data analytics and 5) Internet of Things (IoT) systems. On top of these digital technologies, supporting and secondary technologies can be developed. These are: 1) Additive Manufacturing (3D printing), 2) robotics, 3) drones, 4) wearables technologies, 5) holograms, 6) virtual/augmented reality (VR/AR). Together, these digital technologies will completely change work environment and guide businesses into industry 4.0 era[4].

2.1. Historical Overview

2.1.1. Period from 1980s to 1990s

First notable introduction of the 3D system (3D printer) was in 1980 by Dr. Hideo Kodama[5], who filed the patent for rapid-prototyping system. He described the system where a photopolymer i.e. photosensitive resin is polymerized (cured) by an UV light. It was the first time that someone described the building of an object layer-by-layer using photopolymers[6].

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[2] Tian, C., Li, T., Bustillos, J., Bhattacharya, S., Turnham, T., Yeo, J., & Moridi, A. (2021). Data-Driven Approaches Toward Smarter Additive Manufacturing. Advanced Intelligent Systems,

[3] Dilberoglu, U. M., Gharehpapagh, B., Yaman, U., & Dolen, M. (2017). The role of additive manufacturing in the era of industry 4.0. Procedia Manufacturing,

[4] Spremić, M. (2018): Enterprise Information Systems in Digital Economy, Faculty of Economics and Business, 2018.

[5] ASME (2016.) ASME Historic Mechanical Engineering Landmark, retrieved: https://www.asme.org/wwwasmeorg/media/resourcefiles/aboutasme/who%20we%20are/engineering%20history/landmarks/261-stereolithography.pdf

[6] Wohlers, T., & Gornet, T. (2014). History of additive manufacturing. Wohlers report,

Biggest milestone happened in 1984. Charles Hull[7], filed a patent for a stereolithographic (SLA) system, based on photo polymerization technology previously described by Dr. Kodama. Also, Hull was the first who commercialized the system by launching 3D System Inc. Furthermore, he developed the STL file formatting and digital slicing process which is still key characteristic of AM process today.

After the introduction of the SLA method, a new technological method was developed in 1988. by Carl Deckard. He filed a patent for new technology where powder grains are fused together by a laser, later on this method developed into selective laser sintering (SLS)[8].

The same year, in 1988., company Stratasys filed a patent for the new AM technology called fused deposition modeling (FDM). This method uses plastics and extruders to deposit layers on top of the print bed. Today, this is most used technology in AM industry[9].

Since all the major technological breakthroughs were during the 1980s, the decade of 1990s was marked with the rise of the new 3D printer manufacturers and first AM service providers. This brought new, low-cost 3D printers to the market and paved the way for the new-generation machines which dominated 2000s period[10].

2.1.2. Period from 2000s to 2010s

Since 3D printers became more affordable, the AM industry expanded in the space of low-cost desktop printers. In the first part of 2000s Dale Dougherty founded Make magazine and Maker faire, which started the „Maker Movement". There is no standard definition of „Maker Movement", but it can be best described as the cultural and social phenomenon with the goal of accelerating innovation and promoting individuals' ability to create, learn, share the knowledge with the community and adopt principles of do-it-yourself (DIY)[11]. As the movement grew, so did 3D printing adoption in „maker" communities.

Besides individual users adopting AM technology, the 2000s were the period of the big milestones in the applicable use-cases and adoption of AM technology in various industries.

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[7] Bandyopadhyay, A., & Bose, S. (Eds.). (2019). Additive manufacturing. CRC press.
[8] Mendis, D. (2019). 3D Printer. In C. Op den Kamp & D. Hunter (Eds.), A History of Intellectual Property in 50 Objects (pp. 352-359). Cambridge: Cambridge University Press.
[9] Korpela, M., Riikonen, N., Piili, H., Salminen, A., & Nyrhilä, O. (2020). Additive manufacturing—Past, present, and the future. In Technical, Economic and Societal Effects of Manufacturing 4. Palgrave Macmillan, Cham.
[10] Wohlers, T., & Gornet, T. (2014). History of additive manufacturing. Wohlers report, 24(2014), 118.
[11] Dougherty, D. (2012). The maker movement. Innovations: Technology, governance, globalization, The MIT Press

As previously mentioned, prototyping was the first use-case of AM. Automotive, medical and aerospace industries were the first industry to adopt AM prototyping and production. First industry movers, started with the integration of AM in their business models with the goal of developing solutions for further optimization of the manufacturing processes, the increase in productivity, reduction in cost per part and offering new features and materials[12].

Also during the late 2000s, all the patents established during the 80s and 90s started becoming part of the public domain. In 2009. a patent for FDM became available for public use, which started the new cycle of development and commercialization of AM technology. Period of 2010s was the time when „maker" 3D printers started to really take off, and industry started to produce high-quality, low-cost 3D printers.

2.2. Additive Manufacturing Technologies and Materials

AM can be used throughout the whole product development process. All depending on the familiarity with the AM technology and requirements of the part or product. If an object requires geometry complexity or personalized characteristics, AM may be considered the most optimal technology. While mass produced parts or products may leverage AM in specific parts of product development process[13].

Furthermore, one big difference between AM and conventional manufacturing is the relation between material and technology. AM designers and engineers must understand the interaction between technology and material. Since there is no material stability i.e. there is no block of material or cast where material is injected, during the AM process, material properties depend on the AM process parameters set up by the engineers. Thus, this is one of the biggest challenges unique to the AM, but also an opportunity. By controlling the material properties during the manufacturing process, engineers can intentionally create porosity, flexibility or stiffness. The main types of material in AM are: polymers (thermoplastics or resins), metals, composites (blend of materials) and ceramics.[14].

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[12] Bandyopadhyay, A., & Bose, S. (Eds.). (2019). Additive manufacturing. CRC press..

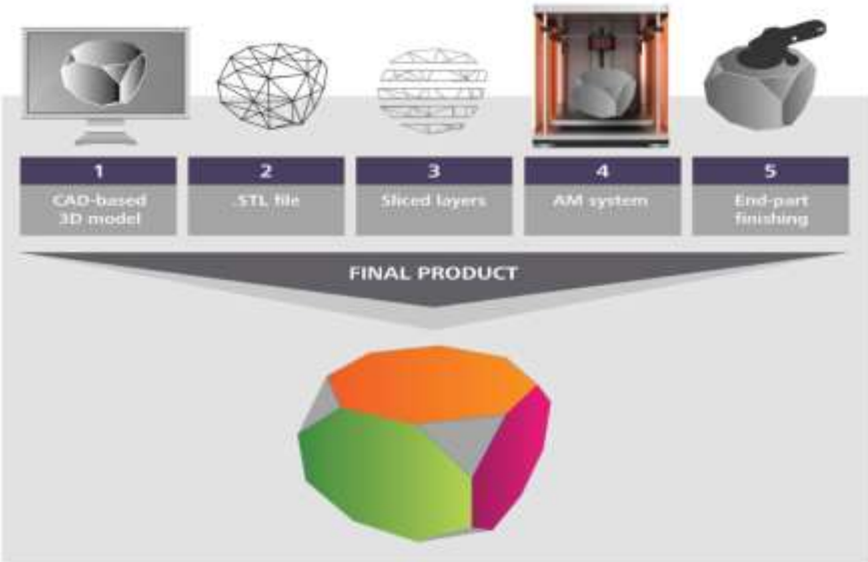
[13] Gibson, I., Rosen, D. W., Stucker, B., Khorasani, M., Rosen, D., Stucker, B., & Khorasani, M. (2021). Additive manufacturing technologies (Vol. 17). Cham, Switzerland: Springer.

[14] Singh, S., Ramakrishna, S., & Singh, R. (2017). Material issues in additive manufacturing: A review. Journal of Manufacturing Processes

2.2.1. Additive Manufacturing Process

Each of AM technologies produce final parts in very different ways but there are 5 steps common in all of them . Following graphics represent each 5 steps.

Figure 2: Generic AM process in 5 steps



Source: Cotteleer M, Holdowsy J., Mahto M. (2014.), The 3D opportunity primer: The basics of additive manufacturing, Deloitte Insight

1. **CAD 3D model** – first input in AM process is CAD 3D model. Digital representation of objects allows designers to test, refine and manipulate the object before production. Furthermore, the CAD model describes objects' borders, geometries and tolerance. During this part defining material is not required, but it can be included.
2. **.STL file** – CAD model is converted into a file format which can be read by a 3D printer. This format is the stereolithographic (STL) file. This is the most used type of a file, but printers can interpret other file types like OBJ or 3DP but they are less common. Main function of STL file is to simplify the CAD model and produce description of 3D model's surface geometry[15].

[15] Redwood, B., Schöffer, F., & Garret, B. (2017). The 3D printing handbook: technologies, design and

3. **Sliced layers -** when an STL file is generated, it becomes an input in the „slicing“ software, which slices the 3D model into the layers that will be used in building the object. Slicing is the most important step in AM process, this is where concept of layer-by-layer is visualized and where new information about each layer is generated. Moreover, this is the step where knowledge of mechanics i.e. technology of AM becomes the biggest determinant in successfully producing the final part. Final product of „slicing“ is generated G-code, which is a numerical control programming language in computer aided manufacturing (CAM) used to control automated machines like computer numerical control (CNC) machines or 3D printers.
4. **AM system** – when G-code is generated, file is ready for transfer to the AM system (3D printer). AM system incorporate hardware part and firmware part, firmware processes the G-code and gives output to the hardware parts (stepping motors, heaters, displays etc..). During the printing process, most AM system have displays where engineers can change parameters (previously set in slicing software) to further optimize the printing process. For example, changes in temperature, speed or Z axis during the printing process can have big impact on the final structure of an object.
5. **End-part processing** – Depending on the AM technology, post-processing is sometimes required. When printing is finished, there are different post-processing options that can range from machining to surface sanding or temperature processing. This part is also the biggest waste producer in the AM process and should be minimized during the designing phase in CAD environment[16].

2.2.2. Vat Photopolymerization

Photopolymerization methods use liquid, more specifically radiation-curable resins as their primary material. These liquid materials react to the radiation from UV light or other visible light sources. Upon contact between the light source and liquid material, photopolymerization happens i.e. liquid materials undergo chemical reaction to become solid. Whole process is happening inside a small barrel or tank where liquid material is

applications. 3D Hubs.

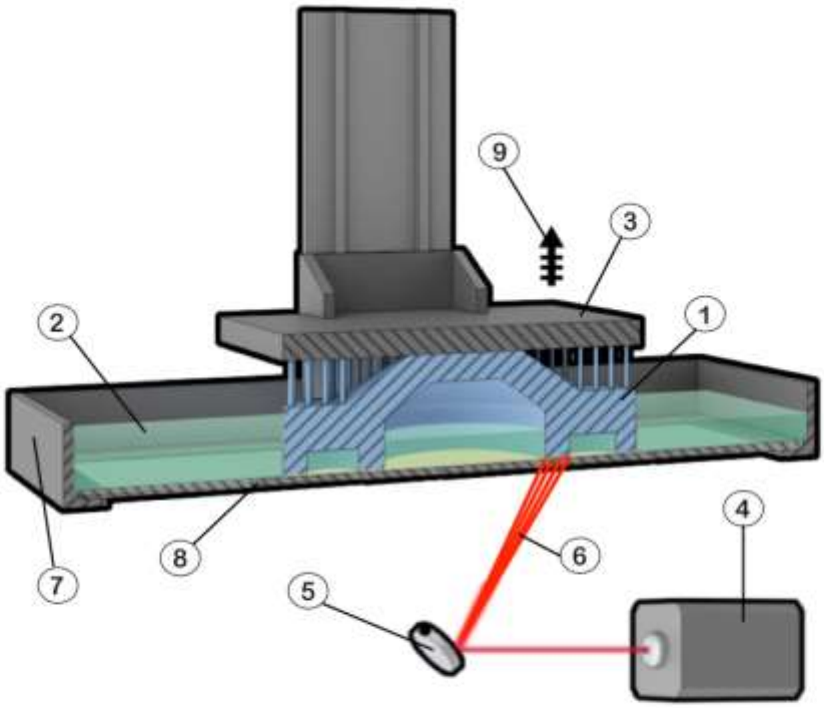
[16] Chiu, B. W. (2020). Additive manufacturing applications and implementation in aerospace (Doctoral dissertation, Massachusetts Institute of Technology).

stored. We will examine two most common methods of vat photopolymerization – SLA and DLP methods[17].

Stereolithography (SLA)

As we previously mentioned, SLA was first AM developed technology, and it uses UV-curable materials, solid state laser light and mirrors known as galvanometers (one on the x-axis and one on the y-axis) to rapidly aim a laser beam across a vat to cure and solidify resin in layer-by-layer style. Following graphic (Figure 3.) is representation of the SLA system and explanation of each part.

Figure 3: Components of a SLA system: 1- printed part, 2- liquid resin, 3- building platform, 4- UV laser source, 5- XY scanning mirror, 6- laser beam, 7- vat, 8- screen, and 9- layer-by-layer elevator



Source: https://www.manufacturingguide.com/en/stereolithography-sla

Direct Light Processing (DLP)

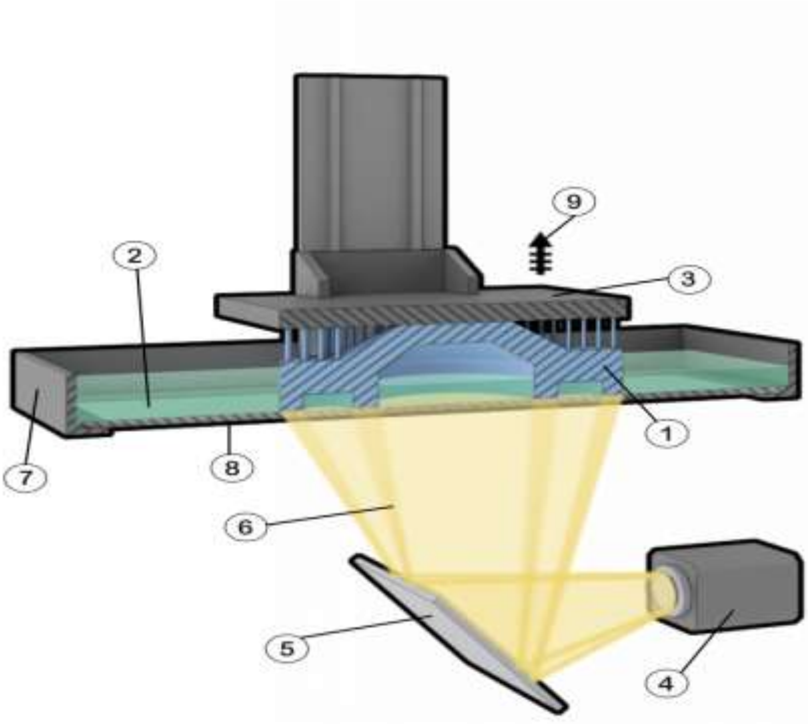
The DLP method is different from SLA only in the part of curing the resin. Instead of a mirror, DLP uses digital projection which flashes the light onto the whole layer all at once. Thus, making it faster than SLA because each layer is completely exposed to the light. Also

[17] Gardan, J. (2017). Additive manufacturing technologies: state of the art and trends. Additive Manufacturing Handbook.

because of the digital screen projector, the image of each layer is composed of pixels resulting in layer formation from small bricks called voxels. During the DLP process, light is projected onto the resin using light emitting diode (LED) screens or a UV light source. (lamp) that is exposed to the layer via digital micromirror device (DMD) which is a small device with micro-mirrors that control where light is projected on the layer.[18].

The following graphic (Figure 4.) is representation of the DLP system and explanation of each part.

Figure 4: Components of a DLP system: 1- printed part, 2- liquid resin, 3- building platform, 4- light source, 5- digital projector, 6- light beam, 7- vat, 8- screen, and 9- layer-by-layer elevation



Source: https://www.manufacturingguide.com/en/digital-light-processing-dlp

Common Applications

Most suitable application of DLP or SLA technology is visualization and prototyping, where a smooth surface and high detailing is needed. Most common application are[19]:

[18] Redwood, B., Schöffer, F., & Garret, B. (2017). The 3D printing handbook: technologies, design and applications. 3D Hubs

[19] Redwood, B., Schöffer, F., & Garret, B. (2017). The 3D printing handbook: technologies, design and applications. 3D Hubs

- **Injection mold-like prototypes** – the smooth surface is desirable for the prototypes for injection molding (formative manufacturing technique). Allowing quick prototype print without need for expensive tooling.
- **Jewelry (Investment Casting)** – investment casting is a casting process in which an expendable pattern is surrounded by an investment compound and then baked so that the investment is hardened to form a mold and the pattern material may be melted and run off. SLA is used for investment casting due to the 25% less weight than conventional casting molds
- **Dental Applications** – dental industry is hugely adopted SLA/DLP technology. It is used to produce dental molds, surgical guides, crowns and bridges. Because of high accuracy and detail with a number of materials capable of working with, AM has become a real disrupting technology in the dental industry.
- **Hearing Aids** – hearing aids are the biggest success story regarding SLA/DLP technology. It reduced the cost of manufacturing, while offering personalized, organic and smooth surfaces. Today approximately 97% of hearing aids are made with this technology.

2.2.3. Extrusion Based Technology

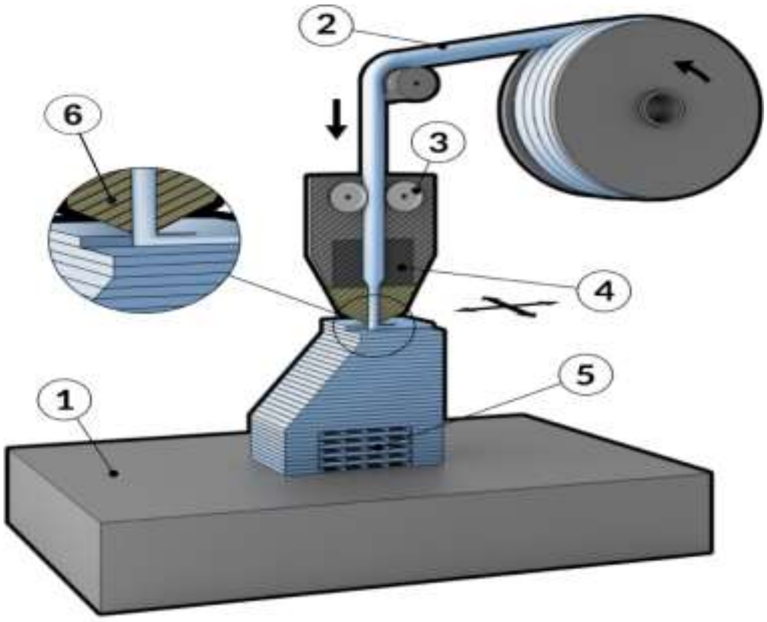
Extrusion based AM technology is currently the most popular on the market, due to the adoption within the „maker" users because of simplicity of use and material selection. Commercial name for extrusion-based technology is fused filament fabrication (FFF) or fused deposition modeling (FDM), we will use FDM as more used abbreviation between the two[20].

FDM method starts when the material (in form of a filament) is fed into the extruder which pushes the filament to the heat element where it liquefies and extrudes through the nozzle onto the print bed in layer-by-layer fashion. The material (usually thermoplastic) that is being extruded must be in a semisolid state when it comes out of the nozzle. Upon leaving the system, it must imminently become solid and bond with the previous layer. The FDM

[20] Freitas, D., Almeida, H. A., Bártolo, H., & Bártolo, P. J. (2016). Sustainability in extrusion-based additive manufacturing technologies. Progress in Additive Manufacturing,

system must control the material extrusion, cooling and position of the nozzle so layers can be produced on the Z-axis forming a 3D object[21].

Figure 5: Components of FDM system: 1- movable print bed, 2- filament, 3- rollers, 4- heating element, 5- support structure, 6- heating nozzle



Source: https://www.manufacturingguide.com/en/fused-deposition-modeling-fdm

Common Applications

FDM is cost-effective prototyping and design technology, it can also create functional parts for mainly non-commercial use. Some of the most common application are[22]:

- **Investment casting pattern** – the low cost of FDM material and the possible geometries makes FDM perfect technology for making investment casting patterns. Because the infill (inner part of the object) can be managed and lowered, the burnout process of casting can be easier.
- **Electronics housing** – this is the most widely spread application of FDM technology, it is great for prototyping and geometry complexity while being much cheaper than conventional manufacturing techniques.

[21] Blažević, N. (2016.) Development of a modular 3D printer (Master Thesis). Retrieved from: https://urn.nsk.hr/urn:nbn:hr:235:073146

[22] Redwood, B., Schöffer, F., & Garret, B. (2017). The 3D printing handbook: technologies, design and applications. 3D Hubs

- **Form and fit testing –** FDM enables creation of curves and organic shapes which are difficult to produce with conventional techniques.
- **Jig and fixtures –** high level of customization and complexity, while offering speed and accuracy of manufacturing, makes FDM ideal technology for jigs and fixtures.

2.2.4. Powder Bed Fusion

There are two types of powder bed fusion systems (PBF), first is selective laser sintering (SLS) which uses polymers as material while second type is metal based PBF systems like: direct metal laser sintering (DMLS), selective laser melting (SLM) and electron beam melting (EBM)[23].

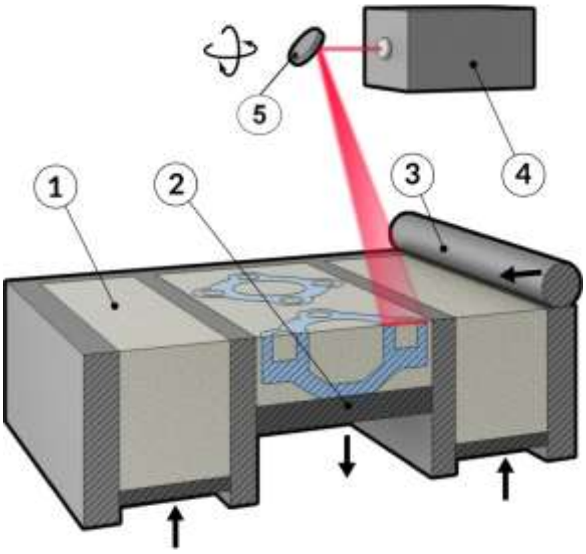
All PBF technologies share a basic set of characteristics. These include one or more thermal sources (lasers or electron beams) that induce fusion between powder particles on a specific point on a powder layer. Also the system has mechanisms for applying and smoothing powder as the object is printed, which leaves the object covered in powder at the end of the process. Furthermore, PBF system have wider selection of materials, from polymers to metals and ceramics, while final objects have better material quality comparing it to other AM technologies[24].

As there are many types of PBF systems, we will use SLS characteristics to visualize the PBF technology. Following graphics (Figure 7.) represents PBF system

[23] Gardan, J. (2017). Additive manufacturing technologies: state of the art and trends. Additive Manufacturing Handbook.

[24] Kumar, S. (2020). *Additive manufacturing processes* (p. 205). Cham: Springer.

Figure 6: Components of SLS system: 1- powder material tank, 2- building platform, 3- roller, 4- laser beam, 5- mirror



Source: https://www.manufacturingguide.com/en/selective-laser-sintering-sls

In SLS systems, powdered material is heated to just below its melting point and then spread out into an even layer over the building platform using a roller. A pulsating laser draws a cross section of a CAD model in the powder, which causes the powder particles to adhere to each other by sintering. The building platform is then lowered on the Z-axis corresponding to a layer thickness, the usual layer thickness is up to 0.1 mm. Advantage of powder bed fusion systems is the lack of needed support material, which is not needed due to powder vat that is filled with unfused powder which holds the object in one place. Also approximately 50% of powder in vat can be recycled without losing mechanical properties[25].

Common Applications

PBF is one of the most used AM technologies in industrial manufacturing. It has a wide range of applications, it offers high complexity and design freedom. We will divide them in two categories 1) polymer (SLS) and 2) Metal (DMLS/SLM)[26].

1) **Polymer SLS Applications**

[25] Gibson, I., Rosen, D. W., Stucker, B., Khorasani, M., Rosen, D., Stucker, B., & Khorasani, M. (2021). Additive manufacturing technologies (Vol. 17). Cham, Switzerland: Springer.

[26] Redwood, B., Schöffer, F., & Garret, B. (2017). The 3D printing handbook: technologies, design and applications. 3D Hubs

- **Functional parts –** SLS can offer a wide range of strong functional parts, it is mostly used for the parts that will be used under heavy load. Same as FDM is offers wide number of complex geometries and material selection
- **Low parts production –** since SLS can produce functional parts, it is also capable of low production. As SLS prints full powder vat, a lot of parts can be manufactured in a small amount of time.
- **Complex ducting (hollow section) –** powder-based technology can create hollow sections, SLS is used for low production of complex ducting and piping. It affect complex geometries as well as functionality.

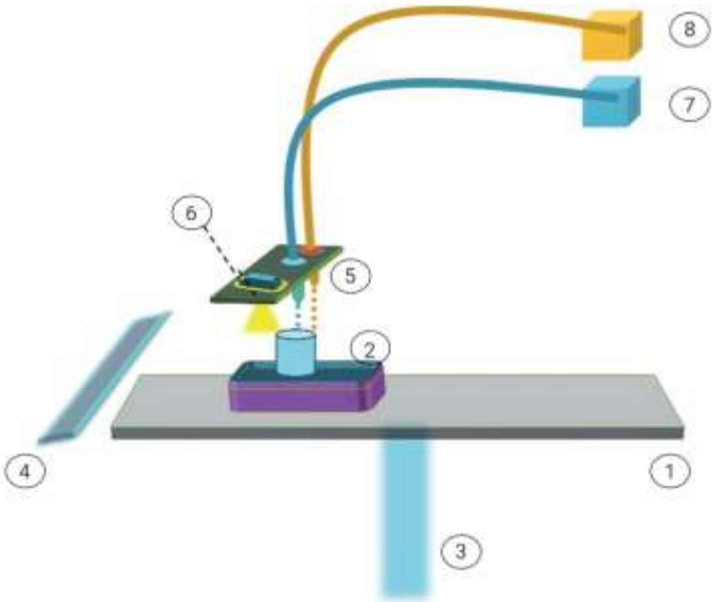
2) **Metal DMLS/SLM Applications**

- **Dental application –** similar to SLA/DLP technology, DMLS/SLM offers unique and personalized parts rather than high volume, low production parts. The lead time is shorter and there is no need for investment casting.
- **Medical application –** since design freedom and part complexity is possible with DMLS/SLM, the possibilities within medical industries are endless. It can fit any anatomy, while offering metals which can be sterilized. As well as dental applications it is used for low production, individual parts.
- **Aerospace and automotive industry –** since DMLS/SLM can produce hollow objects, the application within aerospace and automotive industry is wide. Together with the designer freedom and material selection, it makes it perfect fit for these two industries. It can create high strength parts, with high complexity.

2.2.5. Material Jetting

Material jetting (MJ) is AM technology which is closely compared to the 2D inkjet printers. It has a similar process of printing, it uses photopolymer (resin) droplets that cure when exposed to the light in layer-by-layer fashion. This technology allows many materials to be printed at the same time by using multiple printheads. Therefore, this is one of the fastest technologies in AM while also offering multi-color printing. Because of multiple materials and fast printing time, MJ requires support material printhead which generates support material that is taken off during the post-processing phase[27]. Following graphic (Figure 9) visualizes the material jetting system.

Figure 7: Components of MJ system: 1- build platform, 2- object, 3- elevator, 4- levelling blade, 5- print heads, 6- UV curing light, 7- building material, 8- support material



Source: Sireesha, M., Lee, J., Kiran, A. S. K., Babu, V. J., Kee, B. B., & Ramakrishna, S. (2018). A review on additive manufacturing and its way into the oil and gas industry. RSC advances

Material Jetting Application

Material Jetting is used to generate incredibly realistic prototypes that look like the genuine component because of its smooth surface, excellent precision, and varied range of available materials[28].

- **Full color visual prototypes**

  As has been seen throughout this chapter, one of the most significant benefits offered by Material Jetting is the capacity to print high-detail, full-color models that are an accurate representation of a finished component. Because of this, designers and

[27] Gülcan, O., Günaydın, K., & Tamer, A. (2021). The state of the art of material jetting—A critical review. *Polymers*

[28] Redwood, B., Schöffer, F., & Garret, B. (2017). The 3D printing handbook: technologies, design and applications. 3D Hubs

prototypes are able to gain a distinct understanding of how a finished product will seem.

- **Medical models**

  The manufacturing of medical models by means of Material Jetting is experiencing tremendous expansion as a technique. Parts printed using Material Jetting offer clinicians a unique perspective on the anatomy of their patients since they use data that is individual to each patient. In the process of teaching and preparing physicians for medical procedures, medical models play a vital role. However, these models are not employed as functioning elements; rather, they are used for visual or instructional purposes.

- **Injection mold-like prototypes**

  Material Jetting is frequently used as a method for checking the designs of injection molded parts because of its ability to provide a surface that is both smooth and highly detailed. It is possible to print parts fast, which provides designers with the opportunity to test clearance, fit, assembly, and shape prior to making an expensive investment in tooling.

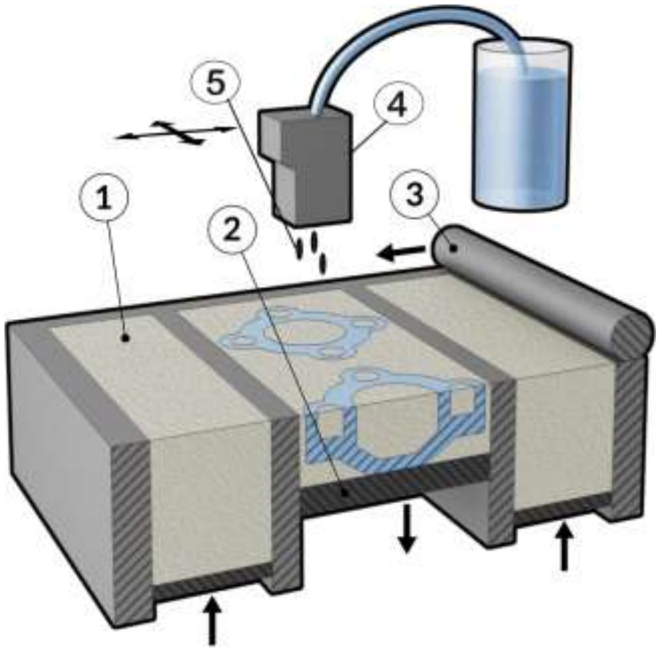
- **Low-run injection molds**

  When making injection molds for low-volume manufacturing runs, simulated ABS is a material that is frequently employed. Because of Material Jetting's capacity to accurately generate complex geometries as well as its endurance to high temperatures, the industry of injection molding is increasingly adopting this technique.

2.2.6. Binder Jetting

Binder jetting (BJ) technology is similar to SLS, it requires powder-based material. But in comparison to SLS which uses lasers to fuse powder material together, binder jetting uses binder droplets (80 µm in diameter) that bind powder material together. Rest of the process is the same as SLS. After the binding of the layer is finished, the building platform is lowered and another layer of powder is applied. Following graphics (Figure 10.) visualizes binder jetting systems.

Figure 8: Components of BJ system: 1- powder material, 2- building platform, 3- roller, 4- inkjet head, 5- binder droplets



Source: https://www.manufacturingguide.com/en/binder-jetting

Since the inkjet head has various nozzles, BJ process is fast, but not faster than HJ due to the needed application of powder layer via roller. However, the BJ process does not require support material due to the same reason as SLS, because the object is placed in the powder vat which holds it in place. Most used materials in BJ are: metals (stainless steel), polymers, ceramics and most interestly sand[29].

Binder Jetting Application

- **Full color models**

  Even while parts printed in full color by Binder Jetting are typically not functional, the ability to print in full color paves the way for a wide variety of new applications in the real world. The use of full color makes it possible to create realistic prototypes, which can display the appearance of a finished part prior to the investment in its manufacture. In addition, components can be used to

[29] Gibson, I., Rosen, D. W., Stucker, B., Khorasani, M., Rosen, D., Stucker, B., & Khorasani, M. (2021). Additive manufacturing technologies (Vol. 17). Cham, Switzerland: Springer.

demonstrate areas that are subjected to stress gradients, which provides designers with a novel insight into the performance of a component.

- **Sand casting**

  Binder Jetting is used for a wide variety of applications, but one of the most prevalent ones is the fabrication of massive sand-casting patterns. Because of the low cost and the speed of the process, it is an ideal alternative for producing intricate pattern designs, which would be extremely difficult to generate using conventional methods, if it were even possible at all.

- **Functional metal parts**

  The manufacture of functional metal parts is made possible by the secondary processes—specifically, sintering and infiltration—that are performed in conjunction with binder jetting. Binder Jetting is a potential alternative for designs that would be highly expensive and difficult to construct using traditional methods due to the wide variety of metals that can be used in the process and the ability to form intricate shapes.

3. Digital Transformation and Industry 4.0

Digital transformation is organizational and operational change of businesses and industries through integration of digital technologies, where human-centric design drives innovation and change in a constantly changing business environment. Final goal of digital transformation is creation of a digital business model.

Industry 4.0 represent the digital transformation with the goal of creating smart products and services, where synergy between digital technologies create integration between production facilities, supply chains and service systems enabling establishment of data-centric environment

3.1. Digital Transformation

Since the 1980s, the digital revolution has completely transformed our economy and society. First it was the internet technology and broadband networks which accelerated the information sharing and connected all participants in the economy. As technology progressed, the digital platforms created digital spaces for exchange of goods and services, and now we are progressing into a completely digitized data-driven economy that is based on integration and interoperability between all digital technologies.

With the development of new digital technologies like: fifth-generation (5G) mobile network, internet of things (IoT), cloud computing, artificial intelligence (AI), big data analysis, robotics, blockchain etc.. economy is moving from connected economy to digitalized economies and societies[30].

Digital transformation refers to the change in the business models by integrating these developing digital technologies. This leads to the development of new products and services, shift in organizational structures, change in a way how people work while also changing business culture and values[31].

In recent years we saw acceleration in digital transformation, due to the COVID-19 pandemic which created great uncertainties in regular economic activities. It disrupted global supply chains and forced businesses to explore new ways of maintaining their operations.

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[30] CEPAL, N. (2021). Digital technologies for a new future. United Nations

[31] Spremic M., (2018.) Enterprise Information System in Digital Economy. Sveučilište u Zagrebu, Ekonomski Fakultet

Some businesses had no other choice than to digitized and explore digital tools, platforms and technologies. While new businesses were created due to the change in customers behavior, needs and increase in usage of digital technologies[32].

In such a turbulent scenario, businesses, particularly small and medium-sized enterprises, are required to dynamically respond to this environment by undergoing a strategic transformation. This transformation entails alterations in the organizational structure, and it is accomplished by utilizing the appropriate digital interface and mechanisms for the purpose of capturing value and developing qualitative relationships with customers. Leadership, people-centered management, continual improvements, management based on facts, and a persistent emphasis on the needs of customers are the pillars on which long-term business success is built. Since pandemic period is still underway and evolving, businesses are addressing current and positional risks by adopting digital technologies for achieving sustainable business excellence in unpredictable economy[33].

Furthermore, innovation and idea generation are two key contributors for digital transformation. With innovation, businesses are changing their everyday operations and create new strategic outlook while new ideas serve as generation of ongoing digital transformation. Diverse innovation management strategies are implemented in businesses in order to develop such ideas. Several steps comprise the innovation process: 1) idea creation (also known as ideation), 2) idea management and collecting, 3) concept selection; and 4) innovation execution. Changes in a business model because of the innovation implementation phase might have varying degrees of disruption. Business models may be reinvented on an operational and strategic scale[34].

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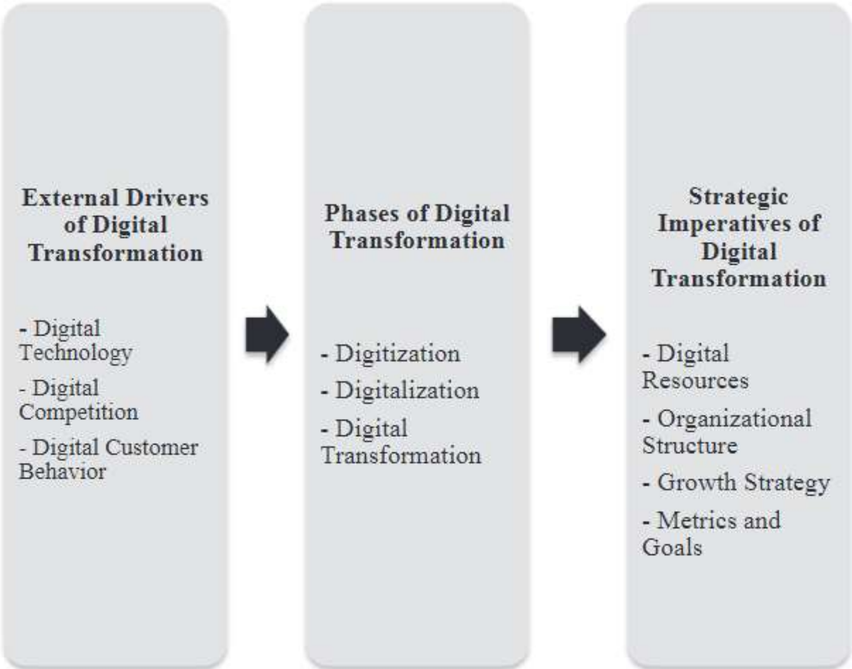
[32] Priyono, A., Moin, A., & Putri, V. N. A. O. (2020). Identifying digital transformation paths in the business model of SMEs during the COVID-19 pandemic. *Journal of Open Innovation: Technology, Market, and Complexity*, *6*(4), 104.

[33] Savastano, M., Zentner, H., Spremić, M., & Cucari, N. (2022). Assessing the relationship between digital transformation and sustainable business excellence in a turbulent scenario. *Total Quality Management & Business Excellence*, 1-22.

[34] Spremić, M., Ivancic, L., & Vukšić, V. B. (2020). Fostering innovation and value creation through ecosystems: case of digital business models and digital platforms. In *Leadership, Management, and Adoption Techniques for Digital Service Innovation* (pp. 25-44). IGI Global.

With the following flow model (Figure 9.) We will demonstrate the process of digital transformation and each factor for successful transition.

Figure 9. Flow model of digital transformation



Source: Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Dong, J. Q., Fabian, N., & Haenlein, M. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research*

1. **External Drives of Digital Transformation**

Digital Technology can be divided into primary and secondary technologies. Primary technologies are well established and currently in use in businesses, these are: mobile technologies, social networks, cloud computing, big data analysis, IoT.

Secondary technologies are: additive manufacturing (AM), robotics, drones, virtual reality (VR), augmented reality (AV), these technologies are still in development but have potential of future use[35].

[35] Spremic M., (2018.) Enterprise Information System in Digital Economy. Sveučilište u Zagrebu Ekonomski Fakultet

Digital Competition is becoming global, with big technology-oriented companies like Amazon, Alphabet, Apple, Facebook and Microsoft dominating industries and giving small companies platforms and market reach to cause further disruption to conventional business.

Digital Customer Behavior is shifting towards online platforms and stores, where the concept of customer journey is affecting online and offline sales. Customers have become more knowledgeable, connected, and demanding where new technologies can easily spread among customers and create demand in a short amount of time. In digital space, customer perceived value is key in successfully acquiring and retaining customer[36].

2. **Phases of Digital Transformation**

Digitization refers to taking analog information and encoding in into the computer system. It is a process of changing analog to digital form, eliminating „paper-trail“ and moving it in digital space.

Digitalization is a broader term than digitization, it goes one step further, it involves digital technologies and information systems to transform business operations. By automating tasks it increases process efficiency and improves data transparency. It essentially moves business processes into digital space.

Digital Transformation goes further than business processes, it's not implemented like a project to improve efficiency of operations. It is a strategic change in all segments of the business model. First we digitize information, then we digitize processes and we digitally transform business strategy by putting customer in the center of the change[37].

Most used framework for designing new business models is digital business model canvas. It visualizes all key aspects of digital transformation, it consists of nine components: key partners, key activities, value proposition, key resources, customer relationship, channels, customer segments, cost structure and revenue streams.

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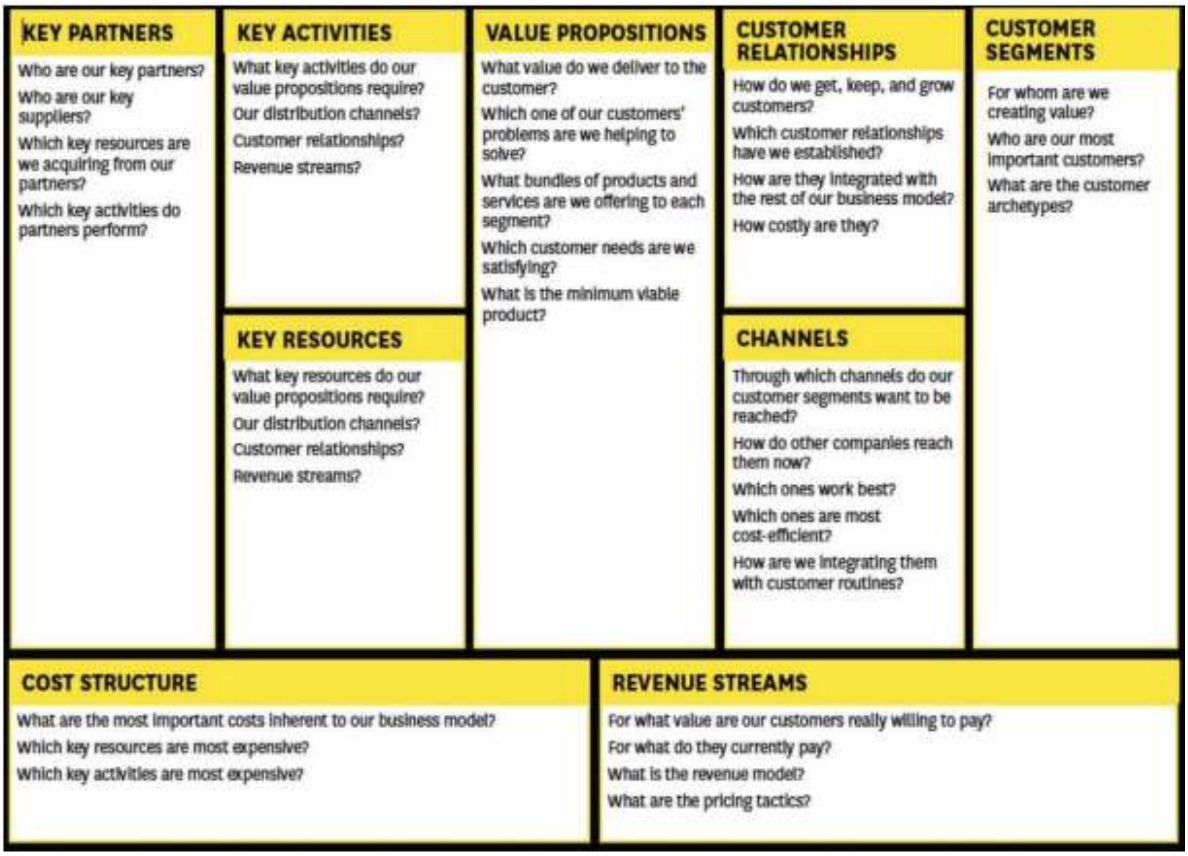
[36] Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Dong, J. Q., Fabian, N., & Haenlein, M. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research*

[37] Bloomberg, J. (2018). Digitization, digitalization, and digital transformation: confuse them at your peril. *Forbes. Retrieved on August, 28,* 2019.

Figure 10: Business model canvas



Source: Spremic M., (2018.) Enterprise Information System in Digital Economy. Sveučilište u Zagrebu, Ekonomski Fakultet

3. Strategic Imperatives of Digital Transformation

Digital Resources are instruments for digital change, they consist of digital assets, digital agility and digital networking. Digital assets are intellectual property, information and communication systems, where the biggest asset is data and data analysis as a tool for effective decision making. Digital agility represents a dynamic view of the markets by adapting to the changes in customer needs while also adapting to the competition in the unpredictable marketplace. Digital networking is a way of engaging and connecting with the customers by content creation and personalized touch, while also networking with other businesses in co-creation of value adding products or services to the same customers[38].

[38] Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Dong, J. Q., Fabian, N., & Haenlein, M. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research*

Organization Structure is a flexible and non-hierarchical view of organization, with focus on strong leadership, cutting of bureaucracy and non-value-added reporting while creating IT infrastructure and processes for a dynamic unpredictable environment.

Growth Strategy is unique for each business and industry, but with integration of digital technologies and growing number of platforms, businesses can use digital tools and different channels for wider market reach and offer products or services to the global market. Businesses that offer non-digital goods or services can incorporate e-commerce for wider market reach and explore different channels for customer acquisition, while continuously searching for new opportunities for growth and value creation like new product development.

Metrics and Goals are used for measuring and understanding the scope of digital transformation. Most used metrics in the business environment are key performance indicators (KPIs) which facilitate learning and improving business models. KPIs may differ in each phase of digital transformation, growth KPIs may be important for start-ups and small companies, but financial KPIs must be prioritized since growth cannot become more important than profitability[39].

3.2. Industry 4.0

In current economy, challenges imposed by advancements in both technology and society require manufacturing businesses to increase their flexibility and responsiveness in order to achieve the ability to manage the whole value chain. As a result, companies need the support including both virtual and physical technologies in order to conduct their businesses and operations in a manner that is cooperative and extremely adaptable[40].

It can be said that concept of industry 4.0 is implementation of digital transformation in every industry, but especially manufacturing. By applying all the core principles of digital transformation, manufacturing businesses can achieve industry 4.0 objectives and become a part of new connected, data-driven environment. Some call this transition fourth industrial revolution.

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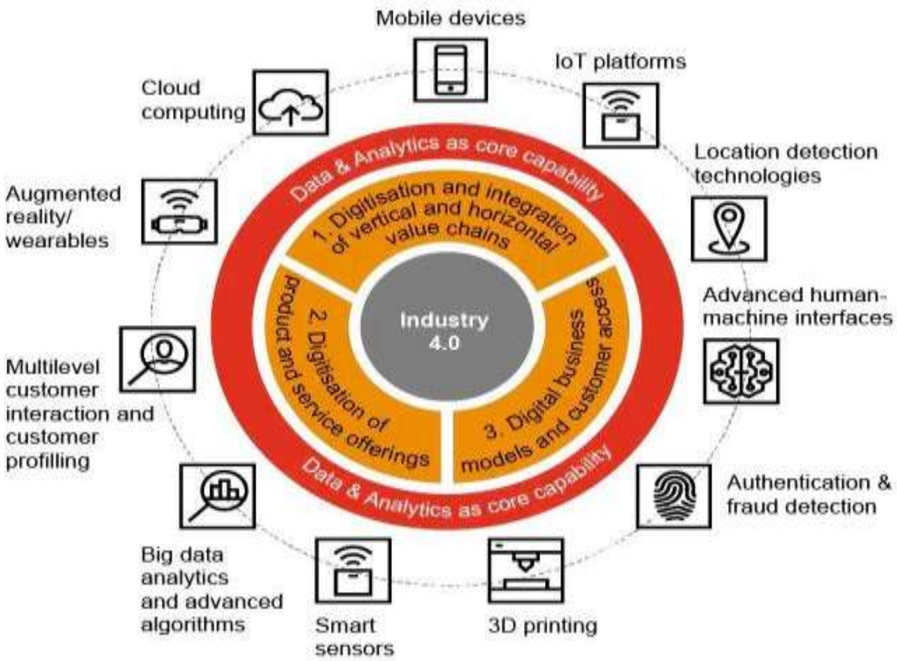
[39] Brosseau, D., Ebrahim, S., Handscomb, C., & Thaker, S. (2019). The journey to an agile organization. *McKinsey & Company*, *May*, *10*.

[40] Ustundag, A., & Cevikcan, E. (2017). *Industry 4.0: managing the digital transformation*. Springer.

Both manufacturing businesses and service providers have shown a significant amount of interest in the Industry 4.0 effort. On the other hand, there is no agreed-upon definition of "Industry 4.0," and there is also no agreed-upon way to use newly developing technology to launch the transition into "Industry 4.0." Integration of manufacturing facilities, supply chains, and service systems to allow the formation of value-added networks is the primary focus of Industry 4.0. For this reason, up-and-coming technologies such as big data analytics, autonomous AI and human-machine interface, cyber physical infrastructure, simulation, horizontal and vertical integration, Industrial Internet, cloud systems, additive manufacturing, and augmented reality are required for a successful adaptation. The broad use of the Industrial Internet and the use of alternative connections to accomplish the networking of globally distributed machines is the single most essential factor. To fully conceptualize Industry 4.0, the following framework can be a good starting point.

Figure 11. Framework for Industry 4.0



Source: Reinhard, G., Jesper, V. & Stefan, S. 2016. Industry 4.0: Building the digital enterprise. 2016 Global Industry 4.0 Survey

Key concepts of Industry 4.0 are related to data and analytics as core principles in 1) digitization and integration of vertical and horizontal value chains, 2) digitization of products and services (smart products and services) and 3) creation of digital business models which are customer-centric[41].

Smart products and services can only be created by integrating data-centric organizations which harness the power of intelligent data management, data collection, data analytics and data processing. They represent the communication and networking core technologies which are supported by a number of other technologies.

On the basis of the core technologies, supporting technologies like adaptive robotics and human-machine interfaces, embedded systems, and AM (3D printing) may be developed. For example, the autonomous character of Industry 4.0 may be enhanced by the construction of integrated devices along with the incorporation of physical systems comprising of sensors and authenticators. In addition to this, AM makes it possible to create digital models via the use of an additive process. AM offers agile manufacturing which we will discuss in the following chapter. As a result, the adaptation of core technologies needs to be adequately managed before the implementation of supporting technologies.

As a result of advancements in digital technologies, there has been an uptick in the number of emerging business models, which include remote services and decentralized manufacturing processes. For instance, a growing number of businesses have begun marketing their goods in the form of a service, which creates a win-win situation for both the businesses and their customers[42].

Fundamental infrastructure for adopting principles of Industry 4.0 is big data analysis, IoT systems and cloud systems. On these foundations other digital technology can be effectively integrated. Final goal in adopting Industry 4.0 related technologies is the creation of smart products and smart services. More specifically, smart products require well established fundamental infrastructure, smarter supply-chains, and smart working which can all be summed up as smart manufacturing. All these concepts are achievable only with integration of core and supporting digital technologies regarding specific technology in each part[43].

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[41] Reinhard, G., Jesper, V. & Stefan, S. 2016. Industry 4.0: Building the digital enterprise. 2016 Global Industry 4.0 Survey

[42] Ustundag, A., & Cevikcan, E. (2017). *Industry 4.0: managing the digital transformation*. Springer.

[43] Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, *210*, 15-26.

3.3. Digital Transformation in Manufacturing Business Models

Traditional manufacturing business model consist of well-established supply chains where manufacturing process, storage and retailers are big parts in creating and bringing value to the end-customer. There are two parts of value-creating in this business model, 1) procurement of raw materials or parts and manufacturing a product and 2) finished product that is supplied to the end-customer.

There are two types of business models, 1) business-to-business (B2B) and 2) business-to-customer (B2C). With manufacturing businesses, the B2B model is more applicable since sales is often outsourced to other retailers and businesses.

As we established previously, digital transformation of our economy is progressing in a way of Industry 4.0, which integrates new digital technologies based on data-driven approach and customer-centric business models that create new value by innovation and appliance of digital technologies.

As data capturing and data analysis can greatly improve and optimize the manufacturing process, businesses have realized an opportunity in implementing core technology of Industry 4.0. Where most used technologies are: IoT systems, cloud computing, big data analysis and robotics. More precisely, these digital technologies are used in following manufacturing cases: 1) machine learning and AI, 2) manufacturing analytics, 3) radio frequency identifiers (RFID), 4) condition monitoring systems, 4) predictive maintenance, 5) automated guidance vehicle (AGVs) 6) cobots and 7) drones[44].

Furthermore, there are other factors that play a role in determining successful digital transformation. These are: 1) an overall organizational structure that supports a digital culture and associated adjustments; 2) and operational process excellence with efficient integrated information systems in the background; and 3) a digital culture. Change management, innovation management, and the cultivation of talent are three aspects of digital transformation that need special attention. In the end, having a digital mentality as well as having abilities in the digital realm has the potential to become a crucial mediating competence in deciding the success of digital transformation[45].

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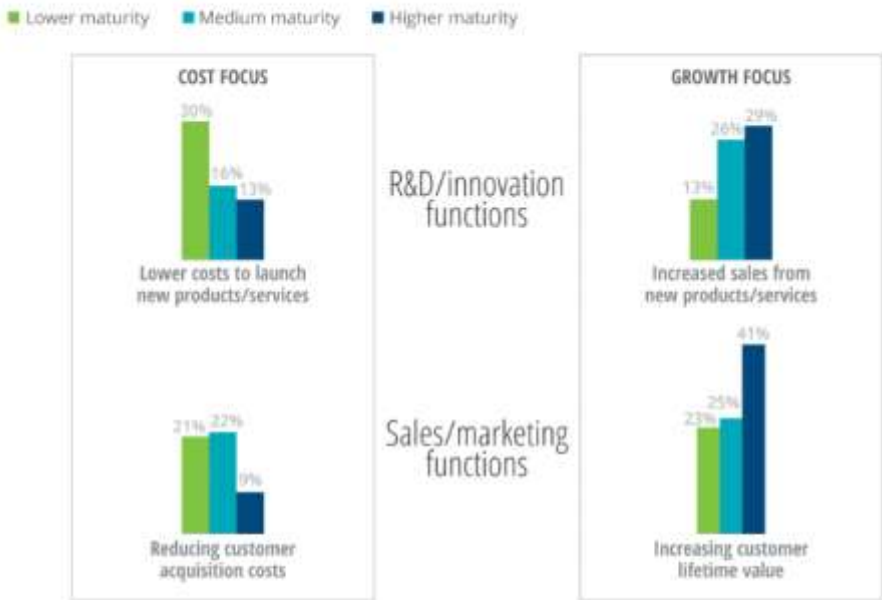
[44] Maw T. (2022.): Your Guide to Digital Transformation in the Manufacturing Industry [Based on 2022 Survey Data], retrieved from https://www.l2l.com/blog/digital-transformation-in-manufacturing-industry

[45] Ivančić, L., Vukšić, V. B., & Spremić, M. (2019). Mastering the digital transformation process: Business practices and lessons learned. Technology Innovation Management Review, 9(2).

Manufacturing businesses that have adopted core digital technologies together with the other supporting technologies, are naturally more digitally mature than those that didn't. There is a link between digital maturity and financial performance. With digital maturity there is increase in operation efficiency, revenue growth, product/service quality, customer satisfaction and employee engagement. Also rate of innovation was higher, while the following graphics represent the effect of digital maturity on four functions[46].

Figure 12.: How digital maturity affects four functions: 1) lower costs to launch new products/services 2) reducing customer acquisition costs 3) increase sales from new products/services 4) increase customer lifetime value



Source: Gurumurthy R., Schatsky D., Camhi J. (2020). Uncovering the connection between digital maturity and financial performance. Deloitte

Simply said, manufacturers that have successfully embraced digital transformation methods have a distinct advantage over their competitors in terms of operational efficacy. This efficiency may be created by improved cross-organizational cooperation, increased worker productivity, or asset uptime. In the end, it doesn't matter how efficiency is acquired; it may be used as a leverage point to either boost income or cut expenses. These enhanced business outcomes, in turn, enable organizations to be more agile in their respective markets, offer

[46] Gurumurthy R., Schatsky D., Camhi J. (2020). Uncovering the connection between digital maturity and financial performance. Deloitte

better products/services to their customers and attract more favorable attention from investors[47].

To establish digital maturity there must be digital transformation strategy by businesses. The power of a digital transformation strategy lies in its scope and objectives. Organizations with a lower level of digital maturity have a higher tendency to concentrate on specific technologies and develop strategies with a emphasis on business operations. When a company reaches a certain level of maturity, its digital strategies are established with a view on altering the business.

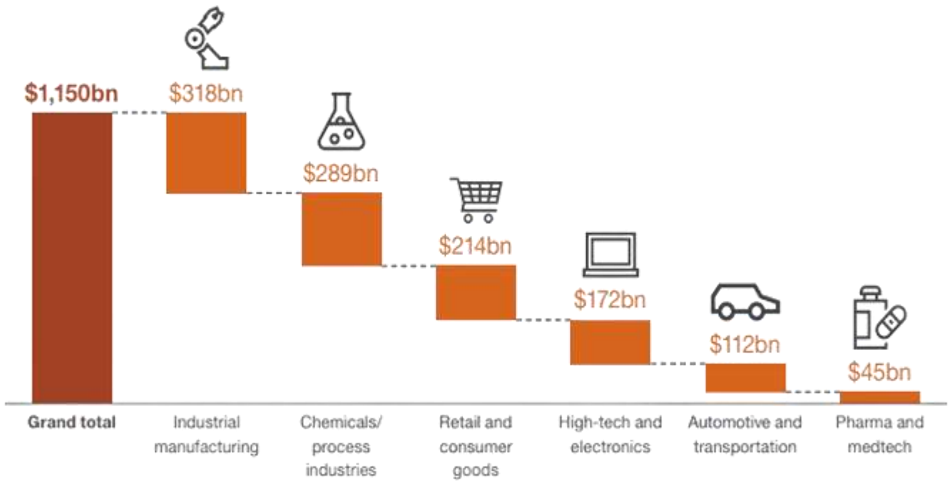
In order to foster greater levels of cooperation and encourage individuals to take more risks, many firms will need to undergo a shift in their cultural beliefs. The leaders of businesses had to additionally consider the question of whether or not various digital technologies or methods may assist in bringing about such shift. In addition to this, they need to have an understanding of which components of the existing culture have the potential to promote further digital transformation development[48].

With technological advancement, which reduces the cost of technology, the investment in digital transformation will be present in more businesses, not just big corporations that have financial and operational capabilities to undergo transformation. Following graphic represent the investment in specific industries, where average investment per annum is 1.8% of net revenue with the biggest investment in industrial manufacturing industry ($318bn).

[47] Hastings W. (2021.) A guide to digital transformation in manufacturing. PTC

[48] Kane, G. C., Palmer, D., Phillips, A. N., Kiron, D., & Buckley, N. (2015). Strategy, not technology, drives digital transformation. *MIT Sloan Management Review and Deloitte University Press*.

Figure 13: Global transformation investment in six key industries



Source:Geissbauer R., Bruns M., Wunderlin J. (2022). PwC Digital Factory Transformation Survery 2022. PwC

With regards to the adoption of specific technologies, businesses must first develop strategy and implement core technologies in their operations and organizational structure. With data analytics as key technologies for better decision making and further digitalization of their business. The following graphics (Figure 15.) represents the implementation stage of each technology in businesses with industry implementation status for each industry.

Figure 14.: Implementation stages for each technology and their share in specific industry.

Source: Geissbauer R., Bruns M., Wunderlin J. (2022). PwC Digital Factory Transformation Survery 2022. PwC

As expected in this survey, analytics and AI technologies are most implemented or in rollout phase, where highest full-implementation status is prevalent in high-tech and electronics industries (51%). Industrial manufacturing has 42% full-implementation of Analytics and AI, 40% implementation of wearables and smart devices (IoT), 38% full-implementation of RFIDs and 30% full-implementation of AM. Also, AM is implemented in 29% of survives businesses, where 38% are still in rollout phase of AM implementation. As manufacturing businesses adopt and applying data-driven technologies first, with data analytics, IoT devices and RFIDs as primary technologies, AM is next in line for rollout and full-implementation in industrial manufacturing industry.

4. Implementation of Additive Manufacturing

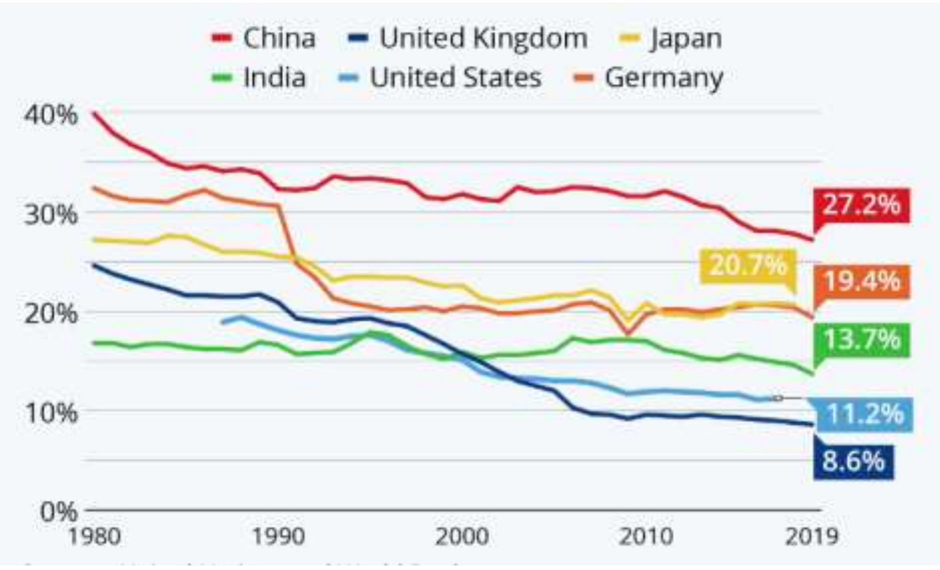
4.1. Current Practices in Manufacturing

4.1.1. State of Manufacturing Industry

First to put in perspective the state of the manufacturing industry worldwide. As digital transformation becomes more prevalent, shifts are happening between product-based (manufacturing) economies to service-based economies. Services are intangible, heterogeneous, inseparable (production and consumption are simultaneous), less formalized and decentralized[49].

The following graphic (Figure 16.) proves this point, manufacturing industries worldwide have been in steady decline.

Figure 15.: Decline of manufacturing's share of GDP in major economies



Source: https://www.statista.com/chart/20148/manufacturing-value-added-as-percent-of-gdp-in-major-economies/

Manufacturing is in decline throughout the global economies, from 1980s to 2019 the manufacturing sector lost between 8.6% up to 27.2% depending on the country. It is a showcase of ongoing digital transformation and movement towards a service-based economy.

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[49] Shek, D. T., Chung, P. P., & Leung, H. (2015). Manufacturing economy vs. service economy: Implications for service leadership. *International Journal on Disability and Human Development*

4.1.2. Lean manufacturing and ISA-95

Depending on the size of the manufacturing business, supply chain management and manufacturing process optimization is a key aspect which determines the future success of the business. Moreover, information flow from the supply chain to the distribution of the end-product is vital in optimizing both aspects. To establish effective information flow, businesses adopt enterprise resource planning (ERP) systems together with the manufacturing execution system (MES). These two overlap in some aspects, especially in the smaller businesses where manufacturing processes, performance analysis or quality control are not yet established. Both are software solutions that centralize information flow and help businesses with managing their operations. Manufacturing businesses are number one users or ERP systems[50].

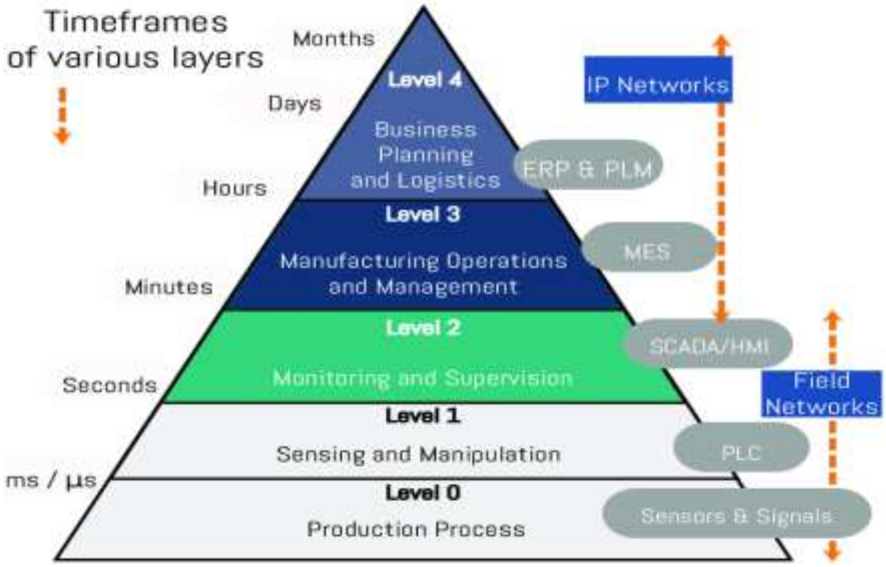
Today, small or big manufacturing businesses apply some type of manufacturing intelligence or methodology. One of the most applied methodologies and most popular is lean manufacturing methodology. One of the biggest success stories of lean manufacturing is Toyota, which started using lean manufacturing in their production systems in the middle of 20 st. Lean manufacturing puts value for the customer first while minimizing waste and non-valuable activities from the manufacturing process. It can be said that lean manufacturing is in accordance with principles of Industry 4.0. By minimizing waste and non-value adding activities it focuses solely on customer and value that customer gets from the products[51].

We can demonstrate the organization structure of information systems in manufacturing business with the ISA 95 framework. ISA-95 is the international standard for the integration of enterprise and control systems. ISA-95 consists of models and terminology. Its official name is “ANSI/ISA-95 Enterprise-Control System Integration" (known internationally as IEC/ISO 62264). Following graphics (Figure. 18.) represents the ISA-95 framework for manufacturing companies.

[50]Biel J. (2022.) 60 Critical ERP Statistics: 2022 Market Trends, Data and Analysis, retrieved from https://www.netsuite.com/portal/resource/articles/erp/erp-statistics.shtml

[51] Abolhassani, A., Layfield, K., & Gopalakrishnan, B. (2016). Lean and US manufacturing industry: popularity of practices and implementation barriers. *international Journal of productivity and performance Management*.

Figure 16: ISA 95 automation pyramid



Source: Katti, B. (2020). *Ontology-based approach to decentralized production control in the context of cloud manufacturing execution systems* (Doctoral dissertation, Technische Universität Kaiserslautern).

Manufacturing businesses started to adopt lean manufacturing methodology and ISA-95 framework as key modeling standards for implementing Industry 4.0 principles. One of the biggest challenges is integration between each level of the ISA 95 automation pyramid. Most businesses have defragmented systems without integration and data streamlining from bottom to top and vice versa[52].

Level 0 and level 1 are located on the manufacturing floor, with sensors (IoT) and programmable logic controller (PLC) as main touchpoints for data generation and measurement of condition in the factory. Level 2 is the gathering point of analyzed data gathered from sensors and PLCs. HMI/SCADA is a category of software-based control system architecture that uses networked data to provide operators with a graphical user interface that allows them to monitor the performance of many pieces of equipment and issue process commands and settings. First three levels are used mostly in developed industrial manufacturing companies, that can have number of manufacturing lines and employees who monitor, measure and operate machinery[53].

[52] Unver, H. O. (2013). An ISA-95-based manufacturing intelligence system in support of lean initiatives. *The International Journal of Advanced Manufacturing Technology*

[53] Reeser, J., Jankowski, T., & Kemper, G. M. (2014). Maintaining HMI and SCADA systems through

Level 3 and 4 are management and decision-making tools for business planning, they are centralized system with overview of the factory networks. A manufacturing execution system, often known as MES, is a comprehensive and dynamic software system that is used to monitor, track, record, and regulate the process of making goods, beginning with the raw materials and ending with the final goods. An MES is a management information system that acts as a functional layer between ERP and HMI/SCADA systems. It provides decision-makers with the data they need to improve operational efficiency on the plant floor and maximize output[54].

Biggest challenge for manufacturing businesses is integration between ERP and MES system. When ERP and MES systems are connected, data from activities such as customer service, order processing, finance, and procurement are combined with data from manufacturing such as production scheduling, machine throughput, work-in progress (WIP), inventory changes, delivered orders, and quality management. This leads to easier traceability and transparency to real-time changes that old and disintegrated system cannot[55].

4.1.3. Manufacturing Process and Techniques

4.1.3.1. Manufacturing process

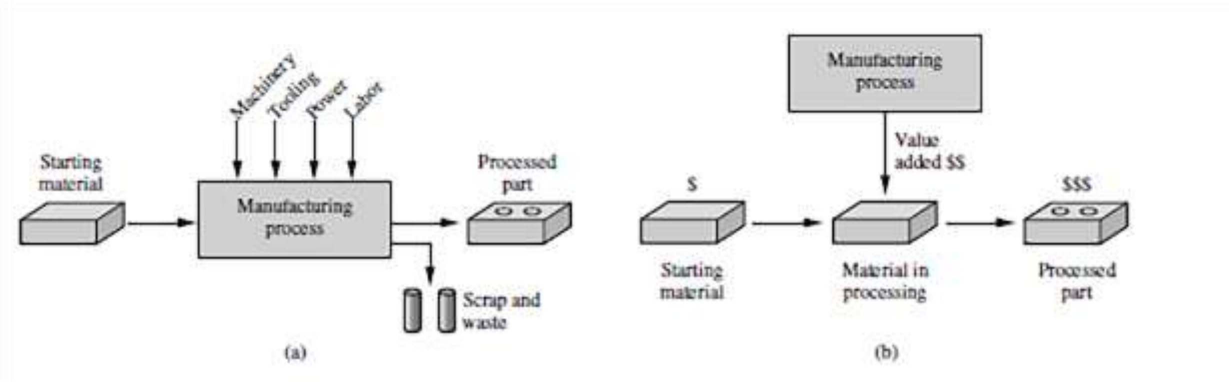
Today, businesses use different types of manufacturing processes and technologies to achieve desirable end-products. A company will develop its own manufacturing process in order to make things that are tailored to the needs of its clientele. A company will pick its method of production after considering a variety of aspects, including customer demand, sales projections, the assembly process, the materials required, and the resources that are at its disposal. For instance, businesses may decide to create a product in larger quantities when a certain component is in stock or on sale, or you could make the product in smaller amounts to meet client requests while avoiding the extra expenses associated with storage. The following graphics represent the technical and economical aspect of the manufacturing process.

computer virtualization. *IEEE Transactions on Industry Applications*

54 SAP Insight (2022.) What is an MES (manufacturing execution system)? , retrieved from https://www.sap.com/insights/what-is-mes-manufacturing-execution-system.html

55 Berić, D., Stefanović, D., Lalić, B., & Ćosić, I. (2018). The implementation of ERP and MES Systems as a support to industrial management systems. *International Journal of Industrial Engineering and Management*

Figure 17.: Tow ways to define manufacturing process a) as technical process, b) as economic process



Source: Groover, M. P. (2020). *Fundamentals of modern manufacturing: materials, processes, and systems*. John Wiley & Sons.

Depending on the business models and end-products, different manufacturing technologies may be applied in the manufacturing process. There are two types of manufacturing processes: 1) processing operations and 2) assembly operations. Processing operation transforms a work material from one level of completion to a more advanced condition that is closer to the ultimate target output. It adds value to the start material by modifying its shape, qualities, or appearance. Processing activities are often conducted on discrete work pieces, however certain processing processes are also relevant to integrated objects. While assembly operations combine two or more components to form a new entity known as an assembly, subassembly, or any other name referring to the joining process[56].

In regard to the AM, there are two types of manufacturing, where material is either manufactured through forming or subtracting. Both of these are part of processing operations which modify the shape and qualities of material to form end-product

4.1.3.2. Formative Manufacturing

Formative manufacturing techniques use processes like injection molding, die casting, pressing and stamping to form a material in a certain way. Forming processes make use of stresses like compression, tension, shear, or some combination to cause the plastic deformation of a material into a desired shape. This manufacturing process is typically for plastics and metals. No material is added or subtracted in this process. Furthermore, with

[56] Groover, M. P. (2020). *Fundamentals of modern manufacturing: materials, processes, and systems*. John Wiley & Sons.

mass-production, there is economic incentive in using formative processes. Starting costs of tooling are high, but with enough pieces produced, breakeven point can be surpassed.

There are a couple of advantages of formatting manufacturing, more precisely, injection molding since that is the most used formative technique in manufacturing. 1) speed and cost effectiveness, 2) lightweight, 3) superior dimensional quality, 4) design compatibility, 5) sustainability. Injection molding is widely used manufacturing technique because it is easily automated, compliant with CAD models and other digital tools and provide high material quality while enabling agility regarding coloring and weight of a product[57].

4.1.3.3. Subtractive Manufacturing

Subtractive manufacturing is conventional techniques, where items are made by methodically cutting away layers of material from the surface of a solid block or sheet. Cutting, drilling, boring, or grinding are some of the methods that may be used to remove the material from the starting material. Although it is possible to carry out these procedures manually, computer numeric control (CNC) is often used because it is faster and more accurate. CNC milling is now the most common kind of subtractive manufacturing technique used today. Turning, drilling, and milling are the three primary machining operations that are used to remove material in subtractive manufacturing processes.

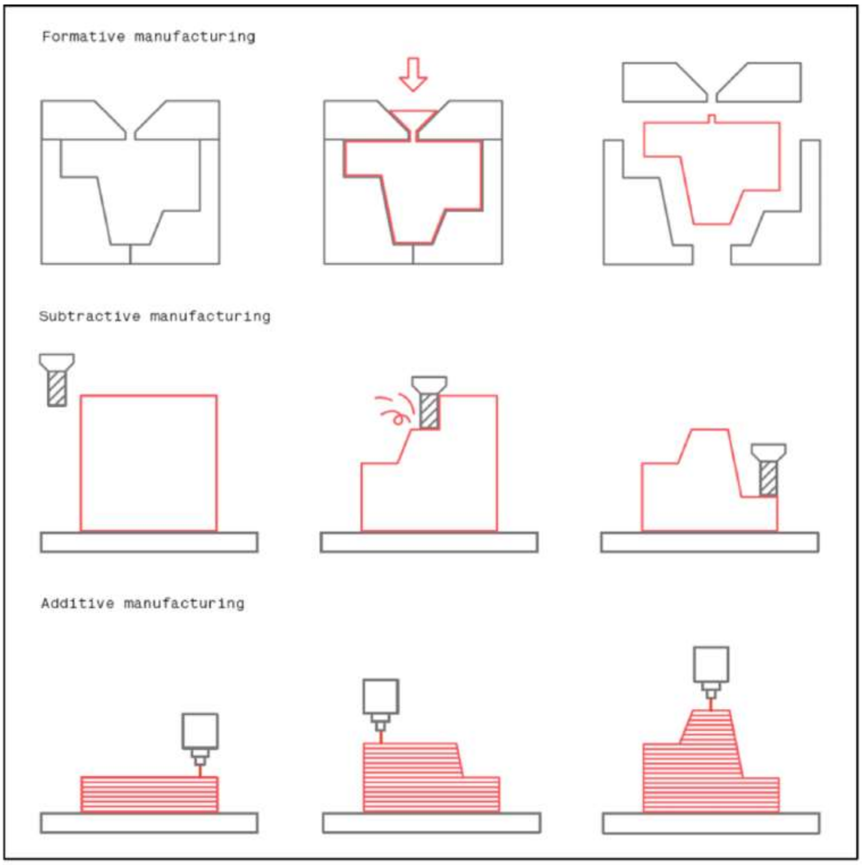
Characteristics of subtractive manufacturing are: 1) require simple geometries, 2) parts with high property quality, 3) Can achieve greater dimensional accuracy. Tolerances as tight as 0.025 mm are possible, 4) wide range of materials: plastics, metal, wood, stone, ceramics, 5) more complex CAD to production process, 6) cost effective in mass production. Biggest disadvantage of subtractive manufacturing is waste production[58].

The following graphics (Figure 23.) compares all three techniques – subtractive, formative and additive manufacturing techniques.

57 Rosato, D. V., & Rosato, M. G. (2012). *Injection molding handbook*. Springer Science & Business Media.

58 Newman, S. T., Zhu, Z., Dhokia, V., & Shokrani, A. (2015). Process planning for additive and subtractive manufacturing technologies. *CIRP annals*

Figure 18. Comparison between formative, subtractive and additive manufacturing techniques.

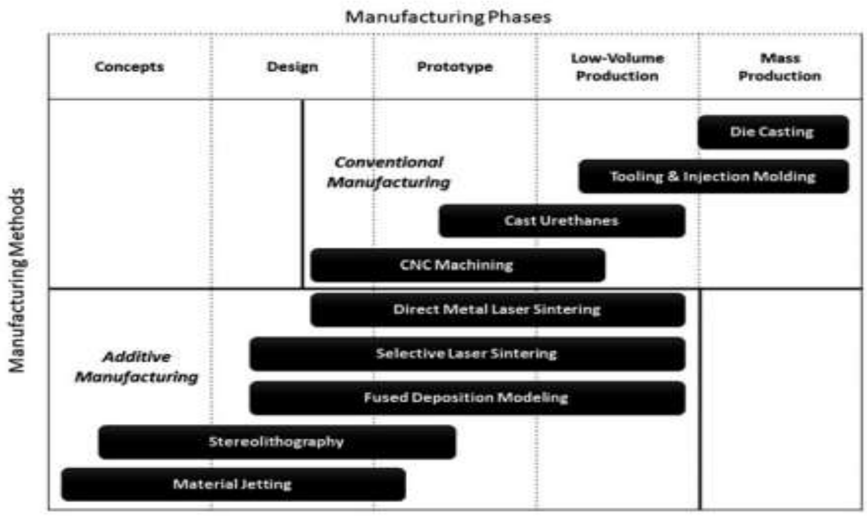


Source: Redwood, B., Schöffer, F., & Garret, B. (2017). The 3D printing handbook: technologies, design and applications. 3D Hubs

4.2. Selection of Additive Manufacturing Technology

Each manufacturing technology, both conventional and additive, has its unique application range. AM procedures are especially well-suited for prototyping models or low-volume production end-parts, while traditional manufacturing (CNC machining or injection molding) are the best methods for mass production. However, each AM technology has its own spectrum; for example, jetting systems (specifically multi-jet modeling and binder jetting) are perceived as best suited for concept modeling rather than prototyping or low volume production, whereas direct metal laser sintering is best suited for both prototyping and the production of end-useable products. The prototypes and tools categories also have an impact on technology choices. The following graphics represents the application spectors of convencional and additive manufacturing with regards to the type of production[59].

Figure 19. Manufacturing technologies and application in each manufacturing phase



Source: Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer*.

Furthermore, the manufacturing business must assess and determine some requirements of parts of the product which will be made using AM technology. Since, AM is conceptually different from conventional manufacturing techniques, businesses must have designers and engineers with knowledge of AM and its strengths and weaknesses. As any new technology AM process require different approach to design and engineering.

Before implementing AM technology into their manufacturing businesses, decision-makers must take into account key requirements, there are eleven attributes for successful implementation and selection of AM technology[60].

- Fitting to office environment (considering the size, cleanliness, and environmental emissions)
- High build speed (ratio of cm3 per hour)

[59] Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business horizons*
[60] Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer*.

- Less need for setup (for example in construction of special tooling)
- Less need for post-processing
- Availability of either functional or high-strength raw materials for the system
- Good dimensional accuracy
- Good surface finish
- Economical processing for larger product sizes and production volumes
- Lower cost of raw materials
- Lower cost of operating the system
- Lower cost of setup (e.g. special tooling).

Moreover, optimal selection of AM technology is possible when taking into account five following categories: 1) Technology (the parameters relating to the capability of the specific technology in regards to dimensional accuracy and surface roughness), 2) Geometry (the geometrical complexity provided by the AM system), 3) Performance (the parameters relating to the mechanical properties and temperature resistance of the fabricated parts), 4) Economy (including the total operational costs of using a specific AM system), and 5) Productivity are all important considerations (including those parameters dealing with manufacturing time).

Another important aspect before selecting AM technology is compatibility with desirable material. Following table shows the AM technologies with the material capabilities for production.

Figure 20.: AM technology and material compatibility

Process	Acronyms	Feedstock	Thermoplastics	Photopolymers	Metals	Ceramics	Composites	Biomaterials	Multimaterial	Other
Extrusion	FFF, FDM, BMD	Filament, rod, pellets	●	● [1]	● (blue)	○	●	●	●	Food, Concrete
Photopolymerization	SLA, DLP, CLIP	Liquid		●	● (blue) [2]	● (blue) [3]	●	●		
Selective Laser Sintering	SLS, HSS, MJF	Powder	●			●	●			
Selective Laser Melting	SLM, DMLS, EBM	Powder			●					
Binder Jetting	BJ, 3DP	Powder			● (blue)	● (blue)		●		Sugar, Sand, Plaster, Pharmaceuticals
Material Jetting	MJ, Polyjet, Multijet	Liquid	●	●	● (blue) [4]	● (blue)		●	●	

● Capable of processing notet material

● (blue) Post processing is needed for desirable properties ex. sintering

○ Technology still in development, not yet commercalized

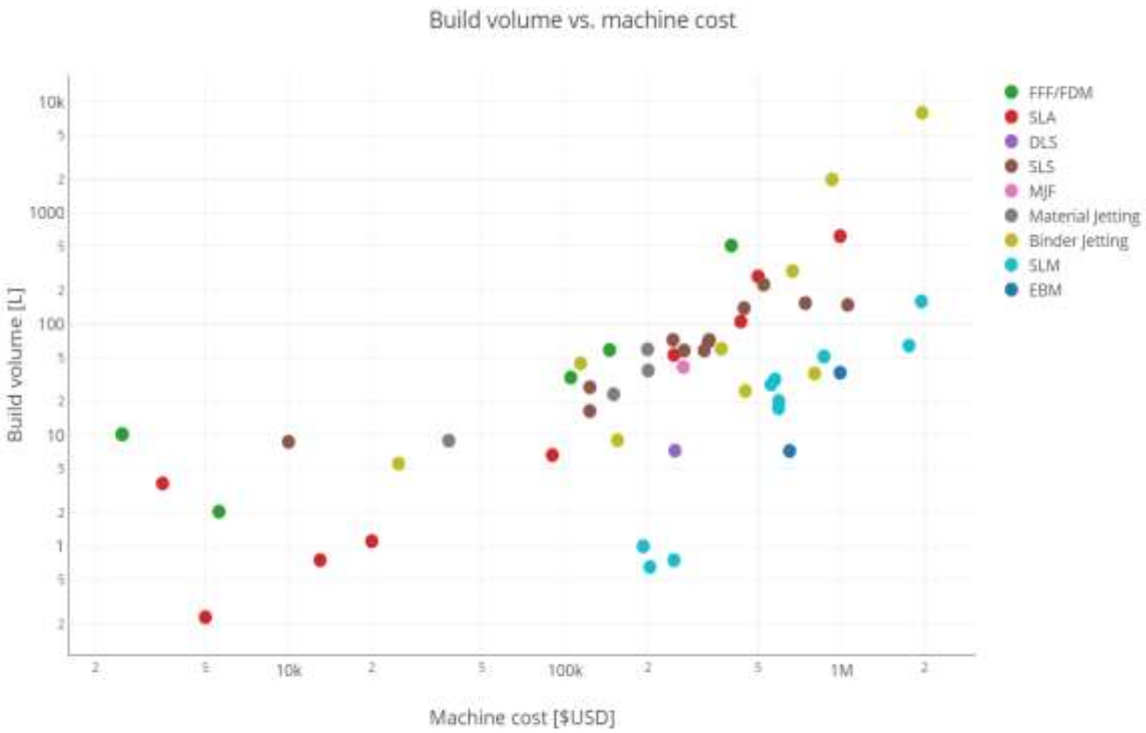
Source: http://apt.mit.edu/am-process-comparisons

Feedstock is material that is input in AM system before the process, these can come in different types but most common are: filaments, liquid and powder. From the following graphics, we can see that FDM technology is most versatile, which can be contributed to the widespread of this technology.

Furthermore, we can compare the AM processes regarding performance in specific areas. AM technology that uses polymers (FDM, SLA, SLS, Material Jetting) and AM technology that uses metal (SLM, EBD, BJ, BMD) is compared in the following charts[61].

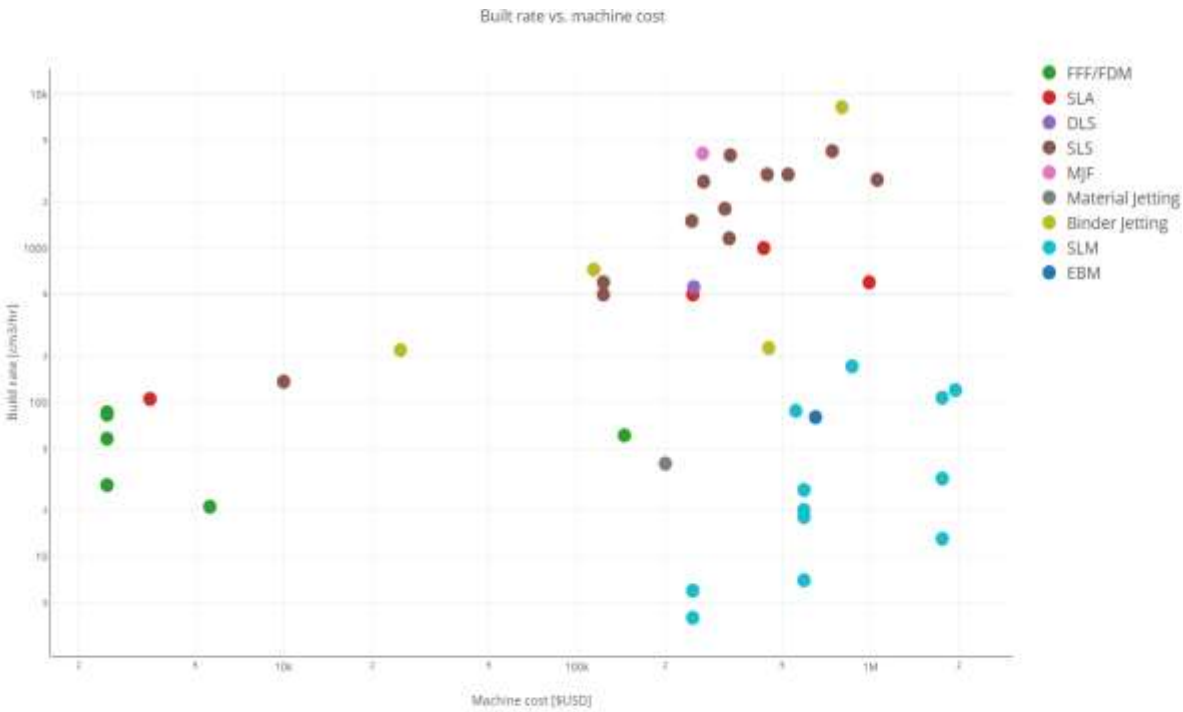
[61] MIT (2022.): Comparing AM Processes, retrieved from: http://apt.mit.edu/am-process-comparisons

Figure 21: Build volume and machine cost



Source: http://apt.mit.edu/am-process-comparisons

Figure 22: Build rate vs machine cost



Source: http://apt.mit.edu/am-process-comparisons

Charts represent the correlations between the build rate/build volume and the cost of the machine for additive manufacturing techniques using polymer and metal. Because of this, it is crystal evident why certain processes are more appealing for industrial uses, which are able to withstand the significant financial investment in exchange for a significantly higher rate of construction. In addition, the rate at which machines are assembled within each process category is typically proportional to their cost (and vice versa). Desktop machines are often far more cost-effective for prototyping, despite the fact that they might be significantly slower than industrial systems.

The cost of the machine increases proportionately with the amount of product that it produces, indicating that larger machines are inherently more expensive. This is due to the fact that larger machines require more robust constructions and larger, more accurate motion systems.

Also, most cost-effective AM technologies are FDM and SLA, they may not be the fastest, but with regards to the cost and build volume it can effectively product parts or products while offering great material selection. FDM and SLA can be entry level technologies of manufacturing businesses, with prototyping or spare part manufacturing as first applications. As designer and engineers are gaining knowledge and business is discovery new opportunities with AM, further expansion to other AM technology may be required[62].

4.3. Implementation Of Additive Manufacturing

Before the implementation process, businesses must acquire knowledge about the AM process, specific technology, and capabilities of AM regarding business application. Businesses must understand how the AM process affects the business environment and what are success and failure identifiers. These may include changes in operational management, business organization and planning and some business strategy. These steps are required for an effective implementation of advanced manufacturing technology:[63]

1) Identifying and understanding the competitive global business environment

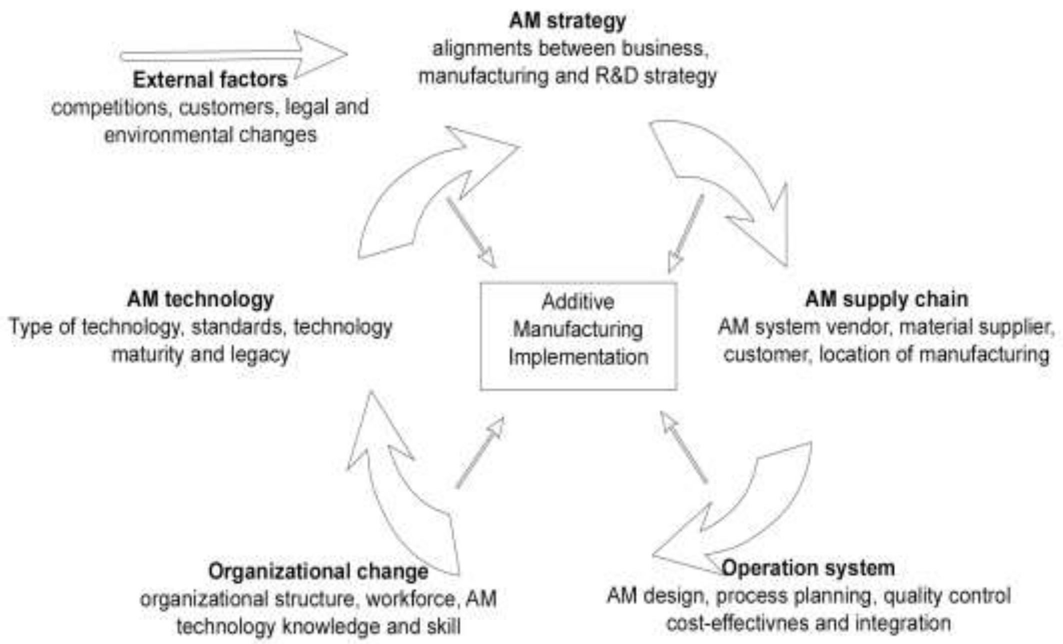
[62] Thomas, D. S., & Gilbert, S. W. (2014). Costs and cost effectiveness of additive manufacturing. *NIST special publication*,.

[63] Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer*.

2) Strategic responses to this competitive demand, including AMT adoption and implementation planning
3) Establishing organizational goals and measuring performance during the implementation process
4) Adopting structures to meet organizational goals
5) Supporting the new technology structure by infrastructural adjustments
6) Evaluating the profitability of investment in the technology
7) Technology choice, and support for the adoption of the chosen system
8) Advanced manufacturing technology performance evaluation

Furthermore, the following framework is used for implementation of AM.

Figure 23. : Implementation framework for AM



Source: Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer.*

1) **Organizational change**

The most important part of successfully implementing AM is adapting organizational structure to the new, disruptive technology. As other digital technologies, AM will have the potential of changing some parts of the business model. In accordance with this, businesses must prepare and plan for AM in organizational structure. When implementing AM, small and medium companies will have an easier time due to their small organizational structure, while at the same time, new technology will enable them to expand to new markets, increase competitiveness and find new customers. However, implementation speed is higher in larger companies, due to the clearer business and AM strategy and bigger pool of workforce talent. For example, companies can use current engineers and CNC operators to adopt and learn AM principles, this process shouldn't take time nor money, due to the similarities between technologies. Thus, it is important to for businesses (small or big) to create business partnerships with AM companies, especially if they offer educational programs together with AM systems, materials and so on.

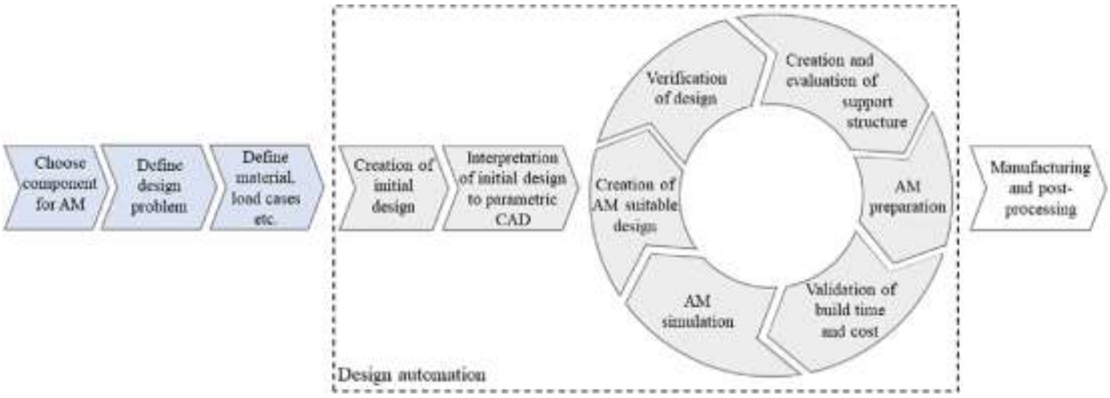
AM organization team, at least one, design engineer who is familiar with the AM technology, production engineer, specialist for quality testing and knowledgeable customer representative who can communicate and lead customers through AM process[64].

2) **Operational changes**

Biggest operational change that businesses will address with AN implementation is product design. Since AM offers completely different capabilities and technology from conventional manufacturing, businesses will have to reimagine the design process for parts or products. AM offers a completely different design approach to parts or products, by adding value with the form of new material properties and part complexities. Design process for AM is much more agile, versatile and has greater automation than conventional design methods. It requires a lot of iterations (redesigns) and simulations to get sufficient parts or products. The following graphics represent the design process for AM.

[64] Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer*.

Figure 26. Design process for AM



Source: Wiberg, A., Persson, J., & Ölvander, J. (2019). Design for additive manufacturing–a review of available design methods and software. *Rapid Prototyping Journal*.

First part of the design process, is where knowledge and experience of the design engineer will play crucial role in the outcome. There are some designer rules which only apply for AM. For example, orientation of the part plays a big role, minimizing support material is a goal, avoiding corners and sharp edges or avoiding large mass of material. After the creation of CAD model, starts topology optimization and simulation to determine the validity of design. Topology optimization is a method used on CAD models where geometry of a part is optimized, i.e. it minimizes parts weight while maintaining structural integrity[65].

Circular part of the design process is the part where AM production engineers reevaluates and adjusts the design with the AM designer, as well as manage and optimize the parameters for the final production. Two most important parameters before production are part orientation and layering. Before a production AM system must function, the process of preparing the AM system depends on the AM technology. Most used methods for quality control are: manual instrument inspection, visual and tactile inspection, mechanical tests or coordinate measuring machines.

Another opportunity for AM is possible integration with IoT systems, where while designing and producing parts or products with AM technology, RFIDs or other sensors

[65] Diegel, O., Nordin, A., & Motte, D. (2019). *A practical guide to design for additive manufacturing*. Springer Singapore.

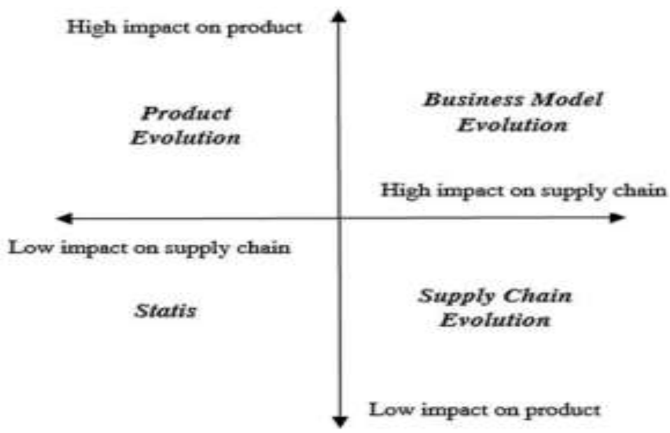
can be integrated within layers. Moreover, AM systems can be part of IoT system network for better quality control[66].

3) **AM supply chain and strategy**

AM's supply chain consists of customers, manufacturers, and suppliers of both raw materials and finished goods. Machine providers are frequently also material suppliers, and this is the scenario that most vendors are in at the moment, which is why they are attempting to acquire an exclusive market in order to secure their future markets. Given the current state of knowledge and the level of development of the technology, AM providers have the potential to play an essential part in the deployment process. They could provide a variety of advisory services, such as advice on selecting AM systems and the materials that are most appropriate for a particular application[67].

Finally, we can describe the four strategies for AM adopters which can navigate their implementation from supply chain side and production side. Following figure represent these strategies:

Figure 24. : implementation strategies for AM



Source: Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer*.

The first strategy, known as "stasis," is the approach with the lowest level of risk. It involves businesses enhancing the value they give to customers by integrating AM into their

[66] Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer*.
[67] Bromberger, J., & Kelly, R. (2017). Additive manufacturing: A long-term game changer for manufacturers. *The Great Re-Make: Manufacturing for Modern Times; Backwell, E., Gambell, T., Marya, V., Schmitz*

already established operations. They can use the technology for prototyping and the product development process, and they can also use it as a supplementary production technique for the supply chain that is already in place, which offers them a number of benefits.

The second strategy is known as supply chain evolution, and it makes use of the potential of AM to relocate the location of production closer to the people who utilize the product. In addition, the production is done on demand, which has a substantial impact on the supply chain. This enables the organization to mitigate risks, deal with unsold goods, and increase inventory turnover.

The third strategy, which is referred to as product evolution, will primarily have an impact in the realm of product development. In this context, businesses who employ AM technologies reap benefits in the form of increased innovation and the production of extremely complex goods that include superior functionality and performance. Manufacturing products that are customized to meet the specific requirements of each individual consumer with regard to their dimensions, shape, and color would provide further benefits.

The final strategy is called "business model evolution," and it refers to how certain organizations change their product development as well as their supply chain to find new business models. As a result of additive manufacturing's capacity for mass customization, the technology enables collaborative product creation and production with open communities or individual clients. This, in turn, boosts both customer satisfaction and innovativeness. The term "supply chain disintermediation" refers to a supply chain that is flatter and involves fewer logistic and business partners. One example of supply chain disintermediation is manufacturing done directly by consumers or prosumers.[68]

4.4. Sustainability and Environmental Impact

There is a growing demand across all sectors of industry and technology to lessen their influence on the environment and cut their CO2 emissions. In the same way that a growing number of businesses operating in virtually every industry have pledged to achieve carbon neutrality or net-zero CO2 emissions in the coming decade(s), AM must also do its part to contribute to the realization of a more sustainable future. Recycling, the use of renewable

[68] Niaki, M. K., & Nonino, F. (2018). The management of additive manufacturing. *Birmingham: Springer*.

raw materials, and the reduction of waste are a few of the other major challenges related to sustainability, along with all of the other aspects of the environmental, social, and governance components. Sustainability is not just about cutting CO2 emissions[69].

While most AM manufacturing technologies use more energy during the material and production phases, the major benefit of AM is during the use phase, which results in lower overall energy consumption. Conventional manufacturing techniques may have a lower environmental footprint than AM at the beginning of the process. But AM can exceed conventional manufacturing with its capabilities in on-demand manufacturing and decentralization of manufacturing. Thus, greatly reducing emissions from transportation and completely changing the supply chain management. Furthermore, one of the biggest advantages of AM, compared to conventional manufacturing, is in the production of complex parts with unlimited design capabilities and material property. This is where AM truly outperforms conventional manufacturing. By improving and optimizing current biggest environmental emitters like the transportation industry or energy industry, AM can have an indirect effect on the environment and improve the product life cycle of current infrastructure.

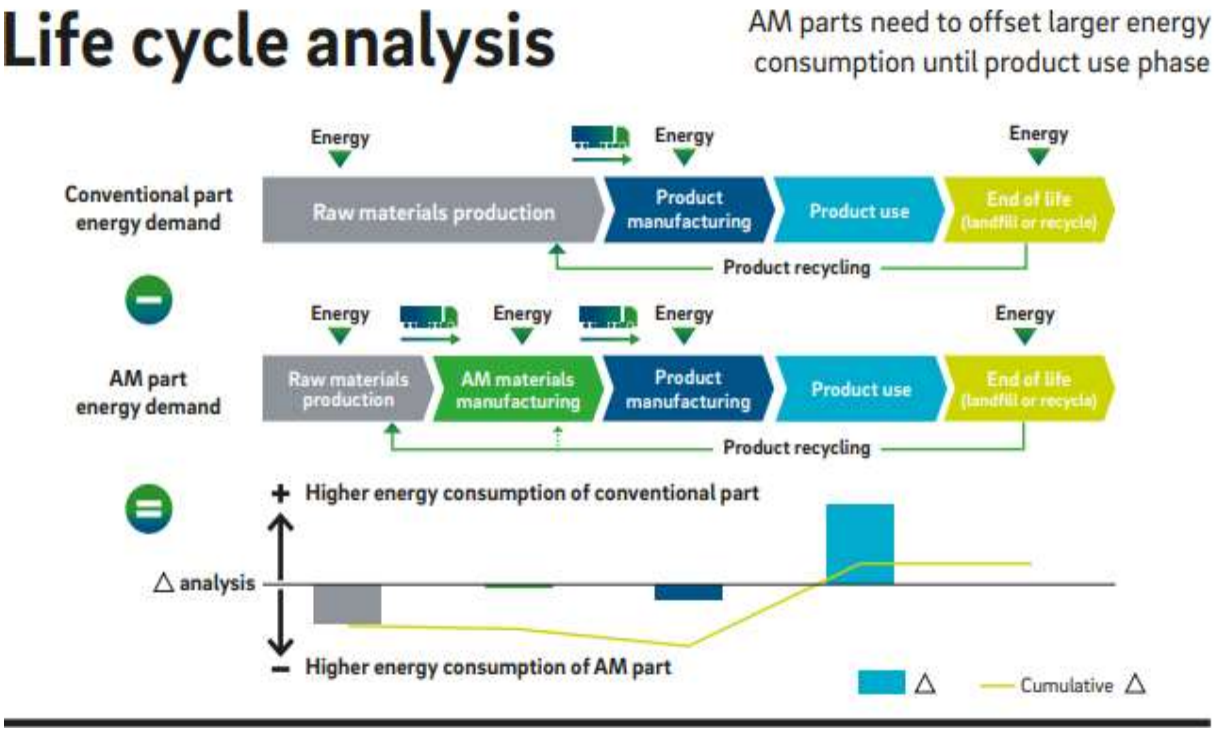
By applying geometric complexities to the parts or products, AM can achieve less material usage and waste per part. Production of parts is not limited to the technology, with AM production optimized, while light-weight capability greatly reduces material consumption. Less resources for production mean less emission which lead to greater environmental impact and overall sustainability of manufacturing process[70].

The following graphics represent the life cycle analysis of AM and conventional manufacturing

[69] Sihg R., Kumar R. (2022.): Additive Manufacturing for Plastic Recycling: Efforts in Boosting a Circular Economy. CRC Press

[70] Niaki, M. K., Torabi, S. A., & Nonino, F. (2019). Why manufacturers adopt additive manufacturing technologies: The role of sustainability. *Journal of cleaner production,*

Figure 25: Life cycle analysis of AM and conventional manufacturing



Source: Langefeld B. (2022.): Sustainability in Additive Manufacturing. Roland Berger

Since AM has a component of material manufacturing, which increases energy consumption, at the beginning of product AM product life cycle, energy consumption is higher. But with the advancement in technology and AM material manufacturing adopting greener forms of production and transportation, this part can also be reduced.

There are four steps how to improve AM life cycle analysis: 1) Make the environmental effect of AM materials, machines, and processes more transparent; 2) Create an life cycle analysis database, focusing on the usage and recycling stages; 3) Before printing, estimate the environmental impact and 4) Take action to lessen AM's environmental impact[71].

[71] Langefeld B. (2022.): Sustainability in Additive Manufacturing. Roland Berger

5. Case Study: Application of Additive Manufacturing in Industries

Application of AM today is widespread in the matured industries, where big companies started to adopt AM, first as a tool for prototyping then it became an integrated part in their manufacturing parts or end-product production. First adopters of AM were aerospace and automotive industries, they discovered value in AM capabilities of complexity design and material property manipulation. Moreover, AM became one of the leading technologies in cutting costs of tooling and production. Following industries were selected because they have biggest adoption of AM and can serve as a great example for possible application in other industries.

5.1. Aerospace

Lisi Aerospace is one of the biggest aerospace manufacturers in the industry, their parts are featured in the majority of the world's aircrafts and at every stage of their life cycle. They are active since the 1950s, while being recognized as the biggest manufacturer of metal components for aircraft engines and airframes. They serve more than 300 customers across 30 countries, while having 5504 employees in 19 different locations in 9 different countries.

They partnered with Creat3D, a AM solution provider, to helped them with AM application, engineering and advice. Creat3D used AM technology from Markforged which provided Lisi Aerospace with AM systems, cloud based technology and AI-powered systems. The challenge for Lisi Aerospace was how to optimize faster manufacturing of the highest quality fasteners of the Aerospace industry, while maintaining stringent standards and produce at a lower cost across multiple variants. Main material of produced fasteners is titanium, while a small percentage of parts are made in steel. There are many product categories for fasteners, this creates challenges in their manufacturing process.

- **Challenge 1:** The diameter of the fastener is used to determine how the production lines are configured to cut down on the number of required line changes. However, there is a great variety of fasteners, and in addition, clients frequently place last-minute orders for customized and fast-track batches. This calls for agility and quick problem solving.

- **Challenge 2:** Because of the nature of the aerospace sector, the manufacturing units operate according to very tight tolerances and undergo highly demanding testing; therefore, all procedures must comply with these standards.
- **Challenge 3:** Timing of the delivery to the consumer is of vital importance. Lisi Aerospace must be able to deliver on production schedules in order to maintain its status as a Tier 1 Supplier to the Aerospace and Civil Aircraft markets. This will ensure that manufacturing at their clients' locations is not disrupted. It is crucial to ensure that the production lines continue to operate efficiently.

Figure 26: Example of a fastener from Lisi Aerospace

Source: https://www.lisi-aerospace.com/en/product/taper-hi-lite-fasteners/

Solution

Lisi Aerospace from 2020. started with the use of Ultimaker FDM 3D printers and added multiple 3D printer from Markforged due to consulting from Creat3D. Ultimaker FDM 3D printers were used for prototyping and product development, while Markforged was used for continuous fibre reinforcement technology (type of FDM technology) where polymer material is mixed most commonly with carbon fibre to produce high quality parts. AM equipment included: 5x Ultimaker 2+ FDM machines, 3x Markforged Onyx Pro and 1x Markforge Mark Two. Overall price for all 3D printers is around $53.000.

Results

There were three requirements to meet in production, 1) high volume of variants, 2) safety and quality of the parts, 3) timely delivery. The implementation of AM i.e. Markforged 3D printers were to replace conventional tooling and components of the production lines, as well as create functional prototypes for design, development and testing. By using AM they achieved 1) higher productivity, with less damage, wastage and downtime, 2) ability to identify and fix issues earlier in the production process, 3) improved preventative maintenance for reduced stoppages. This was achievable by:

1) **Cross-functional teams**:

Manufacturing team is the central part of Lisi Aerospace operations, they require tooling, components and functional prototypes to produce end-parts. The process development department mainly tasks it to supply these 3D printed tools and prototypes to the manufacturing team. With the implementation of AM, the process from design to the tool became quicker and more agile, both departments shared designs, feedback while collaborating and cross-communicating which enabled faster problem solving and improved productivity across the whole business.

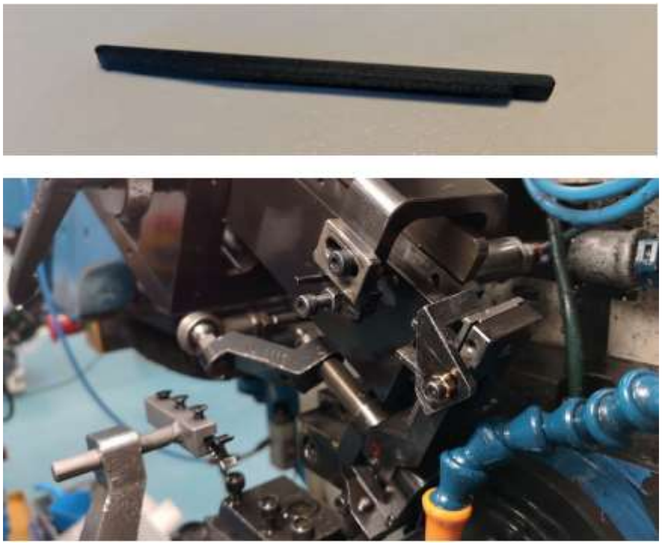
2) **3D printed tooling in supply system**

Big improvement was in the supply systems, where material like Nylon with micro carbon fibres enabled the production of resistant and high-strength parts for 3D printed tooling. The demand for 3D printed tooling was so high that vending machines became available in every department. These machines had a stock of 3D printed tools which could be easily accessed. Tools included: jaws, separator fingers, jigs and end of arm effectors. Supply system will notice the manufacturing team when the stock is low, and on-demand 3D printed tools will be produced. It enables continuous supply of essential tools to keep production running.

3) **Big saving on parts quality (lower costs)**

The switch to using 3D printed separators has a number of unforeseen advantages, one of which is a significant reduction in scrappage, or the amount of non-quality parts produced. The scrappage expenses were reduced to zero as a result of switching to 3D printing for one of the separators. Following picture is a separator finger which moes fasteners in the groove process.

Figure 27: 3D printed separator finger



Source:

https://www.creat3d.solutions/_files/ugd/043fbe_208f0c065d09454a9c731d18394db5bd.pdf

Convencional separator finger was made out of stainless steel and had a high risk of damaging the fasteners, which resulted in the higher scrappage costs. With the adoption of AM, separator finger was 3D printed at the cost of just £0.05 with the outcome of £0 scrapping costs and zero damage.

Another part which was made by AM was holding jaw, seen in the following picture.

Figure 28: 3D printed holding jaw

Source:

https://www.creat3d.solutions/_files/ugd/043fbe_208f0c065d09454a9c731d18394db5bd.pdf

These are supporting jaws which hold fasteners during the manufacturing process. Metal jaws caused damage to the fasteners. Convencional jaws were made out of stainless steel and approx. Cost to was £180 with the lead time of 2-3 weeks. With the 3D printed holding jaws cost dropped from said £180 to £4.15 which is cost saving of 97.7%. Even Though, lifetime of 3D printed holding jaw is shorter, the cost-benefit of using them outweigh the convencional stainless steel holding jaw.

Rate of Investment (ROI) in Less Than 6 Months

The AM application within Lisi Aerospace is constantly rising. One of the commonalities between all applications is the benefit in lower cost and lead time saving. By bringing AM in-house Lisi Aerospace realised big savings which is seen in the return on the investment on two printers in the under 6 months. Furthermore, Lisi Aerospace embraced the AM into their manufacturing process, and they can't imagine going back to manufacturing without AM. New technology is valued not only from the team on the factory floor, benefiting daily tasks and performance, but also at a strategic level by middle and senior management due to the cost and time saving, with more agility and higher productivity[72].

5.2. Automotive

Briggs Automotive Company (BAC) is a United Kingdom based company from Liverpool. During the development of BAC Mono and the recently launched Mono R supercar. Mono R is the highest peak of design, engineering, and innovation. It has claimed a number of world-firsts and records, which helps to establish it as a truly ground-breaking supercar. During the development of the Mono R, BAC used FDM technology from Stratasys to produce a precise, innovative and unique supercar.

Mono R weighs just 555 kg and incorporates the use of graphene-enhanced carbon-fibre in every single body part. The biggest challenge was satisfying the high performance objectives, its lightweight shape needed to guarantee a pure driving experience for drivers who place a premium on design, engineering expertise, and handling.

- **Challenge 1:** the BAC team had to produce the design working against a strict deadline. The unveiling of the car was coming soon and one component was pushing

[72] https://www.creat3d.solutions/_files/ugd/043fbe_208f0c065d09454a9c731d18394db5bd.pdf

the deadline. The car's air box needed to be developed in time and fit into the design frame.

- **Challenge 2:** The airbox has an extremely complex and unique geometry, while the final part must be entirely carbon-fibre. Airbox required expensive mould tooling and the carbon-fibre production process was expensive. Prototyping was the biggest problem here, due to the strict deadline and already cost-intensive production. If they wanted to achieve the deadline they had to sacrifice performance and functionality of the airbox for the production's lead time and expenses.

Figure 29. Mono R supercar

Source: https://www.autojakal.com/2022/03/2020-bac-mono-r.html

Solution

With the help of Stratasys and Tri Tech 3D, they used the F900™ production 3D printer, the biggest FDM system from Stratasys, to produce the car's airbox which costs between $100000 – $250000. The production was quicker than would have been possible with conventional mould techniques, and testing of airbox's design was quickly underway. With the hours they managed to produce a functional prototype and install it on the car for testing. This significantly reduced the design-to-manufacturing process. The lead time for convencional moulding technique was more than two weeks, which was simply unaffordable to BAC.

Results

Another requirement for the airbox, was the heat resistance more than 100 ºC, withstaning of high pressure of incoming air, as well as the extreme mechanical and thermal load created during the drive.

With the use of the Stratasys F900 3D printer and material FDM® Nylon 12CF™, a carbon-fibre reinforced thermoplastic with heat resistance over 140 ºC. This material was sufficient in the testing phase and was good enough as the planned material. The functional prototype managed to withstand the conditions on the track and was as good as the final product. Accuracy was really important for the part, since every millimeter makes a difference. With the Stratasys FDM technology, airbox was produced with the accuracy of 0.089 mm layer.

The freedom of design was the crucial part of successful airbox production using AM. Since AM technology provided guarantee that changes in CAD model will turn out as planned, which helped the team with quick production and prototyping. The following image is the installed airbox.

Figure 30: 3D printed Airbox

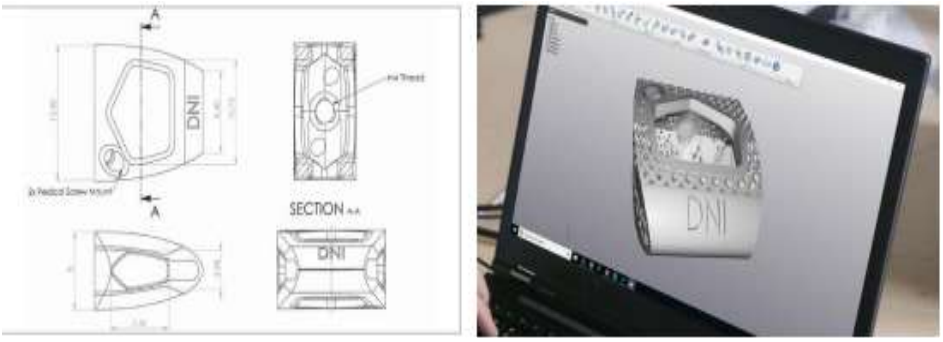
Source: https://www.stratasys.com/en/resources/case-studies/?filter=RR_Case_study+RI_Automotive

5.3. Medical and Healthcare

Renishaw, a global engineering company, collaborated with two other cutting-edge technology companies to demonstrate the capability of metal additive manufacturing (AM) technology to produce lightweight spinal implants that mimic the mechanical properties of bone. This was accomplished through the use of the AM technology. Irish Manufacturing Research (IMR) is an Irish based manufacturing company which provides tools for the next generation of digital manufacturing. It produces high quality medical devices with of metal-based AM technology. Another company which was part of this case study, was nTopology, an industry leading generative design company based in New York. It provided unique software platform for enabling creation of complex performance-driven designs that fully exploit the capabilities of AM. All three companies together, set to create spinal implants which are needed to restore the height between the intervertebral discs in patients who suffer from a variety of medical disorders such as osteoporosis, degenerative disc disease, herniated discs, spondylolisthesis, and spinal stenosis among others.

- **Challenge 1:** Conventional manufacturing techniques are unable to produce spinal implants with a lattice structure. This structure offers a high surface area to encourage migration of osteoblasts into the implant and the ability to optimise the mechanical properties of a porous volume to meet the required loading conditions. However, conventional manufacturing techniques are unable to produce spinal implants with a lattice structure.
- **Challenge 2:** IMR discovered that additive manufacturing with metal could be used to produce lattice structures that were optimized for osseointegration. However, it was necessary to find the design software and AM machines that were the most appropriate.

Figure 31: a) Multiple designs and features consider during the design process, b) Lattice creation in nTopology software



a) b)

Source: https://www.renishaw.com/en/medical-and-healthcare-case-studies--39174

Solution

Renishaw, IMR, and nTopology have collaborated to develop implants for the cervical spine (c spine) that make use of atomic layer deposition (AM) to create lattice structures. The acronym ACID stands for "Anterior, Cervical, and Interbody Device," which is the designation given to this particular type of implant in the context of the research.

First, IMR developed a design envelope (parameters) in order to determine the one-of-a-kind possibilities offered by AM in order to enhance the outcomes for patients. After then, nTopology was responsible for providing the software required to design the intricate geometry of the spinal implants, and Renishaw's RenAM 500M machine was the additive manufacturing device that was utilized to create the implants. RenAM 500M uses Selective Laser Melting (SLM) technology, primary material is metal, it has build size of 250x250x350 mm and costs between $600,000 and $700,000.

Furthermore, IMR conducted extensive research to identify all needed parameters for specific use-case. They calculated exact loading conditions the implant must be able to withstand in everyday life. All three companies then worked together to design the mechanical properties of the implant with the most challenging task of designing optimal lattice structure to achieve mechanical properties of human bone. IMR developed the design files for the implants using nTop Platform once it had been determined which design parameters would be used for the implants. nTopology and Renishaw worked closely together to guarantee that their respective products were compatible with one another. As a result, a design could be transferred from the nTop Platform to the RenAM 500M without any problems.

After that, IMR made prototypes out of grade 23 titanium using the RenAM 500M. (Ti 6Al-4V ELI). The organization carried out a battery of tests in order to provide evidence that the product satisfied the most important prerequisites outlined by the FDA's standard requirements. The chemical properties were put through a series of tests to ensure that they met the requirements of ASTM F136 and ASTM F3302, which are, respectively, the standard specification for wrought grade 23 titanium to be used in orthopedic implants and the standard specification for the additive manufacturing of titanium alloys by powder bed fusion. ISO 13314 is a test technique that is used to determine the compressive properties and failure mechanism of a porous metallic material. The mechanical properties of the porous structure were characterized in accordance with this test method. Last but not least, testing established conformity with ASTM 1104 and ASTM 1147, which are standard test procedures to demonstrate that porous structures do not delaminate from the solid faces of the device. These standards were reached successfully thanks to the testing.

Figure 32: Implant final design, with the lattice design colored in yellow

Source: https://www.renishaw.com/en/medical-and-healthcare-case-studies--39174

Results

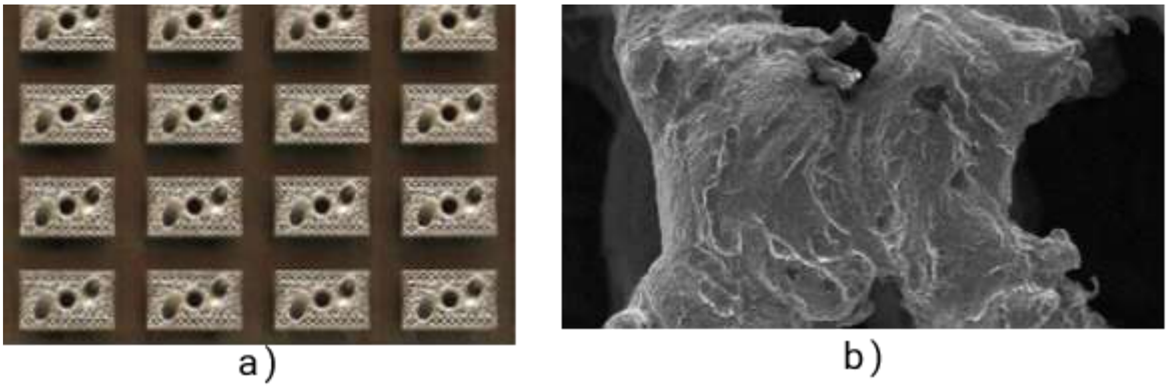
This proof of concept demonstrated that AM can be used to produce spinal implants with characteristics that are not possible to achieve with conventional manufacturing methods.

These characteristics include reduced risk of infection, reduced risk of postoperative pain, and reduced risk of infection. As a result of the fact that the RenAM 500M was utilized for the production of both the prototypes and the final implants, the technique did not need to be adapted for use on machines of a different kind. Because of the improved procedure, medical device manufacturers will experience significant reductions in both costs and amounts of time.

This case study shows that it is possible to reduce reliance on medical supports and, as a result, reduce the number of finishing operations by considering design for additive manufacturing (DfAM) at an early stage. In addition to demonstrating that AM is capable of producing spinal implants, this study also shows that it is possible to do so.

Finally, it can be concluded that this case study showcased the three key aspects of AM in the medical industry. Throughout the whole process, there were a continuous optimization of design software capabilities with the AM system, which both had to be in accordance with the mechanical and material consistencies of the implant[73].

Figure 33: a) final produced implant ready for operation, b) microscopic view of the material



Source: https://www.renishaw.com/en/medical-and-healthcare-case-studies--39174

[73] https://www.renishaw.com/en/medical-and-healthcare-case-studies--39174

5.4. Renewable Energy

Vestas was founded in Denmark in the years immediately following World War II as a modest, family-owned firm. The company was in the business of manufacturing and supplying hydraulics for light trucks for a good number of years. It was in the 1970s when it initially started researching and developing alternative energy sources, and it didn't finish its first commercial wind turbine until 1979.

Since 1989, the company has been concentrating solely on the development of wind turbines, and it now designs, manufactures, installs, and provides maintenance for wind turbines all over the world. Today, Vestas is the largest manufacturer of onshore and offshore wind turbines as well as blades for wind turbines in the world. The company's headquarters are located in Denmark, and it has more than 15 manufacturing sites located in different countries across the world. AM is one of the ways that Vestas is making progress toward achieving its sustainability objective of reaching net-zero decarbonization by the year 2030. Their Sustainability Strategy calls for the production of wind turbines with zero waste by the year 2040.

- **Challenge 1:** Wind turbines need to work reliably with little downtime as possible for maximum energy production. Because of this there is little room for error, that is why Vestas uses a lot of quality tests and inspections on gauges at factories and installation sites. Furthermore, the company had many suppliers who had to sent parts to Vestas sites for further testing. Sometimes parts weren't sufficient for use which came at a cost (low energy production or downtime) and wasn't in line with the strategy goal of zero waste.
- **Challenge 2:** Even when parts passed the specialized inspection process, most of them were made using traditional machining methods and raw materials, which took a long time and cost a lot. Take the top center (TC) marking tools as an example. Most of the time, it would take about five weeks to make these important tools, which are used by Vestas to mark the root end of turbine blades so that the pitch is correct. Even worse, because there are limits to what can be machined, the Vestas team would have to order more than one version of the TC marking tool so that it could fit a variety of blades. Or, think about the lightning tip receivers that are made to reduce

damage from lightning strikes. These receptors are made out of aluminum using a process called subtractive manufacturing, which takes at least 12 weeks to finish.

Solution

The Vestas team started looking into a variety of different ways that they may improve their production process overall. The company was able to successfully begin its direct digital manufacturing (DDM) program in 2021 by using the cloud-based, AI-powered Digital Forge AM technology that Markforged developed. The initiative eliminates the need for production processes to rely on outside suppliers and establishes a knowledge base that can be used for collaborative problem solving.

The TC marking tools and lightning tip receptors that were previously discussed provide some excellent illustrations of how the DDM system operates. The production of the TC marking tool, which previously required many weeks and thousands of dollars, may now be completed in only a few short days. The formerly metal sections of the tool now weigh 85% less than they did before since it is printed using a substance called fiber-reinforced Onyx, which is a tough nylon blend material that is also lightweight. Concerning the lightning tip receptors, regional blade manufacturing sites will be able to make them at the moment of need using 3D printed copper. When fully operational, Vestas anticipates that the production of each of these receptors will take approximately two days.

Figure 34: Composite prototype of lightning tip receptor

Source: https://markforged.com/resources/case-studies/vestas

Results

Vestas considers DDM to be absolutely essential for new product development across the board, as well as for the availability of tools and end-use parts. The business plans to begin implementing direct digital manufacturing (DDM) for inspection gauge tooling beyond its blades in 2022 in order to support on-demand gauge manufacture at all 23 of its manufacturing facilities. In addition, Vestas has formed a partnership with Wurth in order to create an additive ecosystem and to manage an inventory of spare parts that were manufactured using The Digital Forge platform. These initiatives are intended to support maintenance, repair, and operations (MRO) for local field support and other suppliers.

As soon as the initial roll-out has been finished, Vestas will shift its focus to the implementation of a more comprehensive, end-to-end procedure at each of its locations. Individuals at any Vestas site with the appropriate permissions will find it much simpler to scan a part code or search for a part in the company's enterprise asset management (EAM) and enterprise resource planning (ERP) systems, and then have the data automatically sent to the appropriate local 3D printer. This change was made by the company. With the help of Blacksmith and Eiger FleetTM, a centralized control of users, printers, and parts inspection will be implemented, which will result in the production of high-quality, high-performance tools and end-use parts that are capable of completing the tasks for which they were designed. When Vestas brings more of its production in-house through the use of additive manufacturing, its goods will reach the market more quickly, and the company will save more time and money as a result of these efficiencies[74].

5.5. Analysis and Critical Discussion

These four case studies showed us how AM can be used through different industries and cause disruption while creating new value and possibilities which are not possible with conventional manufacturing.

[74] https://markforged.com/resources/case-studies/vestas

First let's start with the organizational aspect of AM implementation. Before AM implementation, there are two or three actors involved. AM business who provides the AM system and knowledge, Industry specific business (customer) who demands the AM service or product in desire to solve a problem.

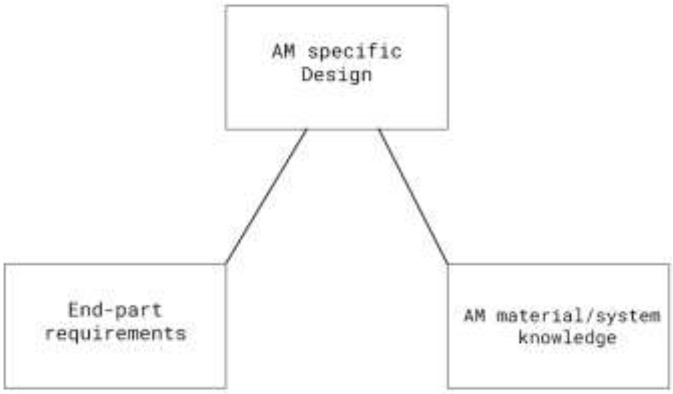
Customers must have a clear vision of the project with specific requirements for design and AM use-case. If a customer cant provide design for AM i.e. doesn't have know-how, then design must be outsourced to another business or be provided by the AM business.

As we saw from the medical case study, having a third party design specific team sometimes is necessary due to the complexity of the 3D printed part. Usually, most AM businesses have an AM design team department who take care of the AM design process. Also, the AM design process is agile, where changes in design are detected early on (sometimes still in software) and corrections and iterations are an integral part of the design and production process.

Therefore, knowledge of the AM process is a key in managing the successful implementation of the AM. Design and production must be viewed as two separate aspects, where knowledge of the AM designer and AM material expert knowledge must be accompanied with the specific requirements so the end-part can provide a desirable outcome. This is especially important for small-and-medium sized companies who are looking to implement AM into their production or as a service. On the other side, bigger companies must be ready to outsource AM design teams, since designing with AM technology is different from conventional manufacturing, especially if the end-parts require high quality and standard.

From the standpoint of AM providers, businesses can provide customers with the AM service, which is specific for deadline set projects where AM acts as production accelerator, or end-to-end solution where implementation of AM is done through multiplate tools while affecting many departments. Main goal here is to provide customer with the necessity of future AM usage, where without the AM technology they could not envision their business operations. As well as provide key metrics and measurements for the operational AM systems. Since AM is supporting digital technology in ongoing digital transformation, data-usage from these systems is one advantage which businesses can use to add value and bring data-centric mindset to the AM and the customer. Following graphics is depiction of three main function in AM implementation.

Figure 35: Three key function in AM implementation



Source: Made by author

Secondly, within all case studies, there were similar or same conclusions. With AM businesses lowered they costs and shortened lead time on parts. Since these are two biggest metrics in manufacturing, we can say that AM is economically valuable disruptive technology and with reason one of the fundamentals of Industry 4.0.

- **Lead time**

  Since conventional manufacturing consists of many supply chains and distributors, the lead time for each specific part can sometimes take weeks. This creates real problems in planning and delivering products. Manufacturing businesses usually function in two ways: make-to-stock or make-to-order, where inventory management and lead time plays a key role in maintaining business operations running.

  AM completely disrupts the lead time of parts for manufacturing, be it tools, spare parts or end-parts, AM can deliver on-demand manufacturing which shortens the lead time by 90%, from a couple of weeks, parts are printed in a few days.

  With AM, supply chains became digital, which can have effect across all departments. With digitalization businesses can also automate parts of the process and measure to gain better insight into the supply chain.

  Furthermore, if lead time is shorter the environmental impact of transportation and business operations will be lower, which aligns with the goals of zero-waste or carbon neutral companies.

- **Costs per part**

Since lead time is shorter, immediate cost is lower. But despite the short lead time, parts are less costly due to the material properties which can be manipulated according to the topology of the design part.

Since testing can be done in the software, design can be optimized before production, which means that 3D printed parts are ready for usage. This completely cuts scrappage costs and defect costs, which was high due to the disk fragmented supply and quality test process. There is no need for individual quality tests, rather if a model is tested, a high-quality AM system will produce the same part without exception.

Even Though, life cycle of AM parts is shorter, they are cost effective because above mentioned characteristics. On the other hand, AM parts can significantly improve the life cycle of other parts, where they are implemented, due to the specific material properties and complexities.

For a specific use-cases, AM can be used to lower the costs per part up to 90% which overtime can justify high costs of AM systems. AM also brings manufacturing in-house which make it easier to manage and measure. With the AM platforms that have integrated management, quality and performance control, businesses can gain additional insight and further optimize their production and supply chain.

- **Design Complexity**

There are other variables which contributed to the adoption of AM in these industries. Complexity is one of the biggest advantages of AM when comparing it to conventional manufacturing. Due to the complexities, applications in medical industries are possible. Complexities also enable optimization of parts with the function of cutting costs.

Another variable is the material used, since AM has a wide variety of materials, in industrial applications most used materials and polymers with fiber carbons and metals. When talking about metals most used machines are SML/DMLS, while FDM is used for polymers with added carbon fibers. Furthermore, standards for materials are becoming higher. For medical use material must be of the highest standard, it's the same with other industrial applications. Material manipulation is also one big advantage of AM, where designers and engineers can intentionally lower material density to lower the costs while keeping structural integrity.

Finally, it can be said that various industries are starting to apply AM into their manufacturing processes. Industrial application of AM has proven to be in the best interest of business, from the economical, operational and technological standpoint. With shorter lead time, due to the in-house manufacturing of spare parts and end-parts, to the lower costs and design freedom. AM is causing disruption and digital transformation manufacturing to the new Industry 4.0 based manufacturing, where data integration from AM systems make decision making more efficient and transparent.

6. Conclusion

AM also known as 3D printing manufactures objects in layer-by-layer fashion. It is completely different from conventional manufacturing techniques like subtractive and formative manufacturing. It uses a 3D model to visualize and feed the AM system with the parameters for building material on the X-Y-Z axis – creating 3D objects.

First significant development of AM happened in 1980s, first AM technology that was developed was SLA, after that SLS, FDM and others were invented. Companies like 3D Systems and Stratasys have been key players in AM technological and commercial development. First who embraced the AM technology were automotive and aerospace industries, after the industrial use-cases, „maker movement" brought AM technology to the wider market, with individuals owning desktop printers which became cheaper and available for personal use.

AM technologies can be divided in three main categories: powder-based, liquid-based and filament-based. These three are the feeding material for the AM system. Most common materials used are: photopolymers, thermoplastics and metals. Most popular AM technology in the desktop 3D printer category is FDM, while SLS/SLM/DMLS is one of the dominating AM technologies in industrial use-cases.

AM is one of the supporting technologies that is part of on-going digital transformation of businesses and our economy. By adopting digital technologies, businesses can optimize operations and bring value to the customer, putting him in the center of their business model. By gradually adopting digital technologies, businesses are changing their business models, since digital transformation is a strategic change that is affecting businesses and society at large. Industry 4.0 is a more specific term for digital transformation and includes a data-driven approach to business, while integrating all new up-coming digital technologies. Technologies like IoT, cloud computing and big data analysis are fundamentals for successful transition to Industry 4.0.

Since digital transformation is affecting every industry, manufacturing industries have declined. Because the transition from mass- production, product base economy to the service-based economy with the customer in the center. Moreover, with the concepts of lean manufacturing, businesses are cutting non-value adding activities while making manufacturing more sustainable and wasteless. Because of this trend AM is disrupting industries all over the world.

For successful implementation of AM, businesses must develop AM strategy and gain knowledge of AM and its possible applications. AM is disrupting whole supply chains and brings on-demand manufacturing while reducing lead time and cutting costs. With capabilities of complex design and manipulation of material properties, AM is become value adding technology, but with knowledge gap between businesses and AM service or system providers. By bringing AM technology to the businesses and discovering challenges in manufacturing, AM service or system providers can offer business know-how and further improve digital transition to digital manufacturing with adding AM as key support technology in their manufacturing.

From the case studies, we have seen the different applications of AM. All cases had similar conclusion. AM manages to lower the lead time on parts while significantly reducing costs and bringing value to all departments. With new capabilities in design, businesses are reimagining their product development processes while finding new ways to further optimize the process.

With the successful integration of AM and other digital technology and creation of AM strategy and managing system, businesses can gain competitive advantage by reducing spare part or end-part lead time, reducing costs and bringing manufacturing in-house and on-demand. Finally, except advantages in businesses, AM can have significant impact on environment and sustainability of manufacturing process. By reducing waste and expanding life cycle of already operational products, AM is helping businesses with longer life cycles, less waste and more agile manufacturing.

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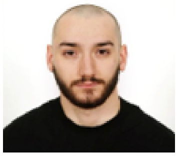
LIST OF FIGURES

Curriculum vitae



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Undergraduate Study, Bachelor Degree in Business – TOURISM MANAGEMENT — *2016 - 2020*
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Skills & Abilities

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Technical: MS office, basics of HTML/CSS/JavaScript, basics of SQL, R programming language, Canva, BPMN
Languages: Croatian (native), English (C2), French (A2), German (A2)
Driving License B

Experience

Tourist Entertainer — *Camps Kovačine & Poljana, Cres/Čikat*
BLOO d.o.o (IAC) — *Summer 2019-2020.*
- communication with the guests and event planning
- creating and leading different activities within set schedule
- promotion and advertising (in-person and online)
- managing whole entertainment team in camp Poljana

Work&Travel Program - United States — *Nancy's Restaurant & MV salads, Martha's Vinyard*
Nancy's Restaurant & MV Salads — *Summer 2021.*
- maintaining supplies, preparing drinks and food
- receiving orders, managing bills and communicating with the customers
- procuring and managing invoices in MV Salads

Community Manager — *AMPnet, Zagreb*
AMPnet — *11 2021. - 1. 2022.*
- managing and administrating telegram group of 3000 users
- answering and giving support to the group members
- researching and writing about tokenization, blockchain and web 3.0

Sales Assistant — *3DPrintaj, Zagreb*
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Dean's semestral award 2016/2017 Rijeka

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University of Rijeka, Faculty of Tourism and Hospitality Management *2019.*

- Education on personal career and future development

Online Course - Elements of AI *Online*

REAKTOR I University of Helsinki *2021.*

- Basics and development of AI

Hobbies

reading, gaming, playing drums, fitness, history buff, traveling