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THE IMPACT OF ADDITIVE MANUFACTURING ON THE PRODUCT DESIGN CYCLE IN SLOVENIAN COMPANIES

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ABSTRACT

Additive manufacturing, often called 3D printing, is changing the way products are designed and made. This thesis looks at how companies in Slovenia are using this technology in their product development process. It also explores how agile methods, especially Scrum, can support this shift. The first part of the study explains the basics of additive manufacturing and the key principles of agile development. The second part focuses on interviews with professionals from Slovenian companies. These conversations reveal what works, what doesn't, and where the challenges lie. Some of the main issues include technical limitations, lack of skilled workers, and the need for new ways of working. At the same time, the research shows that agile methods help teams adapt faster, test ideas sooner, and work better together. In the end, the study offers practical insights for companies that want to make the most of additive manufacturing in a real-world setting.

KEY WORDS: Additive manufacturing, product design cycle, agile development, design for additive manufacturing.

SUSTAINABLE DEVELOPMENT GOALS

POVZETEK

Aditivna proizvodnja, pogosto imenovana 3D-tiskanje, spreminja način oblikovanja in izdelave izdelkov. To magistrsko delo raziskuje, kako slovenska podjetja uporabljajo tehnologijo v procesu razvoja izdelkov. Hkrati preučuje tudi, kako lahko agilna metodologija, zlasti Scrum, podpre te spremembe. Prvi del naloge pojasni osnovna načela aditivne proizvodnje in ključne elemente agilnega razvoja. Drugi del temelji na intervjujih s strokovnjaki iz slovenskih podjetij. Ti pogovori razkrivajo, kaj deluje in kaj ne, ter s kakšnimi izzivi se podjetja srečujejo. Med glavnimi izzivi so tehnične omejitve, pomanjkanje usposobljenih kadrov ter potreba po novih načinih dela. Po drugi strani raziskava pokaže, da agilne metode pomagajo ekipam hitreje prilagajati načrte, hitreje testirati ideje in bolje sodelovati. Delo na koncu ponudi praktične vpoglede za podjetja, ki želijo izkoristiti možnosti aditivne proizvodnje v vsakdanji praksi.

KLJUČNE BESEDE: Aditivna proizvodnja, cikel načrtovanja izdelka, agilni razvoj, oblikovanje za aditivno proizvodnjo.

CILJI TRAJNOSTNEGA RAZVOJA

8 DOSTOJNO DELO IN GOSPODARSKA RAST

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12 ODGOVORNA PORABA IN PROIZVODNJA

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LIST OF ABBREVIATIONS

AM – Additive Manufacturing

CAD – Computer-Aided Design

CNC – Computer Numerical Control

DED – Direct Energy Deposition

DfAM – Design for Additive Manufacturing

FDM – Fused Deposition Modelling

MVP – Minimum Viable Product

PBF – Powder Bed Fusion

1 INTRODUCTION

Additive manufacturing (from then on AM), more commonly known as 3D printing, has emerged as a powerful tool that is reshaping how products are designed and manufactured. Its ability to produce complex geometries with precision and a high degree of customisation is challenging traditional methods and opening up new possibilities across industries.

This thesis explores how AM is being integrated into modern product development, particularly within the Slovenian manufacturing sector. While the technology offers clear technical advantages, its wider impact extends into how organisations plan, design, and collaborate. By looking beyond machines and materials, this research investigates the organisational and process changes that support or at times, hinder its adoption.

The following chapters will examine the technologies behind AM, the design strategies it demands, and the management approaches that can make its implementation more successful. Together, these perspectives provide a broader view of what it takes to unlock the full potential of AM in real-world settings.

AM has come a long way from its early experimental roots to become a reliable and increasingly mainstream manufacturing approach. As described by Guo and Leu (2013) and Javaid and Haleem (2019), AM now includes a variety of methods such as material extrusion, binder jetting, vat photopolymerization, powder bed fusion, and directed energy deposition. Each of these processes has its own strengths and application areas, supported by a growing selection of compatible materials—from thermoplastics and resins to advanced metal powders.

This technological variety is part of what makes AM so versatile. It is now used across sectors like aerospace, automotive, healthcare, and consumer products, where complex parts, custom solutions, or low-volume production are valued. Importantly, AM also brings with it a shift in how companies think about supply chains and production models. As noted by Campbell et al. (2012), AM allows for more localised production, smaller inventories, and shorter development cycles. These are factors that are particularly relevant in today's dynamic and uncertain market conditions.

While the technology continues to mature, it is already clear that AM is not just about printing parts differently. It offers a fundamentally new way of thinking about design, manufacturing, and business strategy.

The design process plays a central role in the effective application of AM. Compared to conventional manufacturing methods, AM offers increased geometric flexibility, allowing for the production of complex, lightweight, and customised components. However, this flexibility also introduces new design considerations that differ significantly from traditional constraints.

Design for AM (DfAM) has emerged as a response to these unique requirements. It involves developing geometries and design strategies that are optimised for layer-by-layer fabrication, taking into account factors such as build orientation, support structures, and material behaviour (Gao et al., 2015). Techniques often include reducing part count, integrating functions, and using lattice or cellular structures for structural efficiency.

Recent advancements in digital design tools and simulation software have enabled more iterative development workflows. This allows for rapid prototyping and evaluation, which can support shorter development cycles. These iterative capabilities are increasingly relevant when AM is integrated into broader agile development approaches, where responsiveness and adaptability are prioritised.

The integration of AM into production systems has prompted a reconsideration of established organisational and process models. Among these, lean and agile methodologies offer relevant frameworks for navigating the distinct characteristics of AM. While lean principles emphasise waste reduction, efficiency, and continuous improvement, agile approaches prioritise adaptability, iterative development, and responsiveness to user needs.

In the context of AM, both frameworks can offer complementary benefits. As highlighted by Christopher and Towill (2001), combining lean and agile principles enables firms to enhance responsiveness while maintaining operational discipline. This hybrid approach, often referred to as “leagile”, may be particularly suitable for AM environments, where production cycles are fast, customisation is frequent, and uncertainty is relatively high.

When applied thoughtfully, lean-agile strategies can help AM-driven organisations streamline development processes, reduce lead times, and support continuous innovation. Importantly, these methodologies also promote a more collaborative and cross-functional working culture, which aligns with the demands of modern, digitally enabled manufacturing.

The goal of this thesis is to explore how Slovenian companies are using additive manufacturing (AM) in their product development processes—and how agile methods like Scrum can support that shift. It looks at both the technical side of AM and the organizational changes needed to adopt it effectively. Through interviews with industry professionals, the study highlights what’s working, what’s not, and how teams can better adapt to the opportunities and challenges that AM brings. The study aims to explore these topics through the following research questions.

Research questions:

RQ1: How are Slovenian companies integrating AM technologies into their product design cycles?

RQ2: What organisational and technological factors facilitate or hinder the adoption of AM in these companies?

RQ3: In what ways can Agile methodologies, specifically Scrum, be adapted to enhance AM-driven product development processes?

To help answer these questions I have divided the thesis into two main parts. The first half focuses on the technical background of AM and the principles of agile development. The second half presents original research, including interviews with Slovenian companies, and analyses how AM is actually being used in practice. Together, these parts build a full picture of where AM fits into modern product development and how it might evolve in the future.

2 ADDITIVE MANUFACTURING TECHNOLOGY OVERVIEW

AM has changed how products are designed and made. Unlike traditional methods that remove material to shape an object, AM builds parts layer by layer directly from digital files. This shift offers new possibilities in design, customisation, and production that were once difficult or costly to achieve.

A variety of AM technologies now exist, each suited to different materials, resolutions, and production needs. Understanding these methods is key to applying AM effectively.

- Material extrusion, most commonly seen in Fused Deposition Modelling (FDM), uses a heated nozzle to deposit melted material layer by layer. It's widely used for prototyping and small-scale production due to its low cost and accessibility (Gibson et al., 2015).
- Material jetting works like a 3D inkjet printer, placing small droplets of liquid photopolymer that harden under UV light. It produces high detail and smooth finishes, making it ideal for applications in dentistry, jewellery, and micro-scale engineering (Hull, 1986).
- Binder jetting spreads a layer of powder and applies a liquid binder to form solid shapes. It supports a wide range of materials and is often used in aerospace, automotive, and medical industries for its speed and flexibility (Narayan, 2016).
- In sheet lamination, thin layers of material—such as paper, plastic, or metal—are bonded together using adhesives, heat, or ultrasonic welding. While less known, it offers advantages in cost and material choice, especially for geometrically complex parts (Chua et al., 2010).

Together with techniques like powder bed fusion and vat photopolymerization, these technologies form a diverse toolkit. Each serves different industry needs, from customised medical devices to intricate aerospace parts.

In summary, AM provides a wide range of tools that challenge traditional manufacturing limits. The right method depends on what's being made—but across sectors, AM is proving to be a flexible and forward-looking approach to production.

2.1 Methods and equipment

This chapter provides a comprehensive exploration of the equipment and methods used in AM, offering insights into the diverse technologies that shape this field. From material extrusion to powder bed fusion and beyond, each AM technique brings unique advantages and capabilities, catering to a broad range of applications and industries.

The landscape of AM equipment is dynamic and continually evolving, driven by advances in materials science, hardware engineering, and software development. By examining the nuances of various AM technologies, this chapter seeks to equip readers with the knowledge required to navigate the complexities of AM, enabling them to make informed decisions and fully leverage the potential of these cutting-edge technologies.

In addition, the chapter addresses important factors such as production speed, part complexity, accuracy, and machine programming. These considerations are essential for understanding the practical challenges that influence the adoption and implementation of AM technologies in real-world scenarios. By shedding light on the intricacies of AM equipment and methods, this chapter aims to foster a deeper appreciation of AM's transformative potential and its expanding role in modern manufacturing.

2.1.1 Material extrusion

Machines in this category are often referred to as Fused Deposition Modelling (FDM) printers. FDM is one of the most widely adopted AM technologies due to its affordability and minimal equipment requirements (Bikas et al., 2015). In FDM, thermoplastic material is melted and extruded through a heated nozzle onto a build plate. As the build plate is lowered layer by layer, the nozzle deposits material in a controlled manner, creating a solid structure.

This technology allows for multiple nozzles, enabling the simultaneous printing of different materials. Commonly used thermoplastics in FDM include polylactide (PLA) and acrylonitrile butadiene styrene (ABS). In addition, composite materials are often employed, where thermoplastics are blended with reinforcements such as carbon fibre, para-aramid fibres, or even wood-based composites (Gibson et al., 2015). Some FDM machines are designed to work with materials containing metal powders and adhesive binders, which can subsequently be processed into solid metal components (Wohlers Associates, 2023).

Beyond thermoplastics, material extrusion techniques have also been adapted for large-scale applications, such as the extrusion of concrete for constructing buildings (Le et al., 2012). Owing to its accessibility and minimal need for additional equipment, material extrusion is particularly well-suited for office environments. It is commonly employed for design validation, visual aids, functional prototypes, and educational models (Petrovic et al., 2011).

Regardless of the specific implementation, FDM processes share several key features:

- Loading of material
- Liquification of the material
- Application of pressure to drive material through the nozzle
- Extrusion and plotting along a predetermined path
- Bonding of deposited layers to create a cohesive structure
- Inclusion of support structures for complex geometries

These features underscore FDM's versatility and accessibility, making it a foundational technique within the broader landscape of AM.

2.1.2 Material jetting

Material jetting is a liquid-based AM system that builds components layer by layer. In this process, a layer of liquid material is deposited onto the build platform and then cured with ultraviolet (UV) light. The build plate is subsequently lowered to accommodate the next layer of deposition. Because the liquid material must be supported during the printing process, material jetting typically involves a secondary support material, often water-soluble for easy post-processing (Bikas et al., 2015).

The liquid resin is delivered through a printhead, similar in mechanism to conventional 2D inkjet printers. This technology allows for the mixing of different liquids within the printhead, enabling the creation of components with varied characteristics and tailored material properties (Gibson et al., 2015). The primary materials used in material jetting are photopolymers and wax-like substances, which can also serve as patterns in investment casting (Javaid & Haleem, 2019).

Material jetting machines are highly sensitive and require careful maintenance and cleaning to ensure optimal performance. Although they can be operated in office environments, they demand a certain level of technical proficiency from the operator. The resulting components offer high dimensional accuracy and excellent surface finish, making them suitable for design validation, functional prototypes, and in some cases, end-use products.

While polymers and acrylic photopolymers remain the most common materials used in material jetting today, ongoing research and development are expanding the technology's scope to include ceramics and metals for future applications.

2.1.3 Binder jetting

In binder jetting, components are fabricated by selectively depositing a binder fluid into a powder bed. Only the binder needs to be dispensed through the printheads, which minimizes the risk of clogging (Gibson et al., 2015). Each layer consists of a spherical agglomerate formed by the binder and powder particles. Once a layer is complete, the build platform is lowered and a fresh layer of powder is spread across it. This process is repeated until the part is fully built.

The surrounding powder acts as a support structure during printing, though this does mean that any internal cavities in the part will be filled with unbound powder. After printing, the excess powder is removed as part of post-processing, and the unused powder can often be recycled for future builds. Metal parts produced by binder jetting require additional steps, including sintering and infiltration with a secondary metal, such as bronze commonly bronze, using a furnace (Wohlers, 2017).

Components produced through binder jetting typically have a rough surface finish and may need post-processing to meet desired mechanical properties (Petrovic et al., 2011). Commercially available materials include polymer composites with infiltration, stainless steel, bronze, ceramics, glass, Inconel, silica sand, and other inorganic materials. This technology also enables the printing of full-colour parts, making it particularly valuable for prototyping and design validation (Javaid & Haleem, 2019).

Common materials used in binder jetting include:

- Metals: Stainless steel
- Polymers: Acrylonitrile butadiene styrene (ABS), nylon variants, polycarbonate (PC)
- Ceramics: Glass

2.1.4 Sheet lamination

Sheet lamination involves the layer-by-layer assembly of thin materials, which are typically cut using either a laser or a mechanical cutting knife. The remaining portions of each layer are diced in a crosshatch pattern and serve as built-in supports during the fabrication process (Bikas, Stavropoulos, & Chryssolouris, 2015). Depending on the specific machine and application, the bonding between layers can be achieved through adhesive bonding, thermal bonding, clamping, or ultrasonic welding.

The most commonly used sheet lamination technique employs paper sheets, typically ranging in thickness from 0.07 to 0.2 mm (Gibson et al., 2015). However, a variety of sheet materials that can be cut and bonded are suitable for this process, including plastics, aluminium, low-carbon steel, and ceramics. Ultrasonic welding, in particular, is often used with metals such as aluminium, titanium, stainless steel, brass, Inconel, and copper (Ngo et al., 2018).

2.1.5 Powder bed fusion (PBF)

Machines that fall within this category are commonly referred to as Selective Laser Sintering (SLS) or Electron Beam Melting (EBM) systems. These technologies utilise a fine powder that is evenly spread across a build plate. Typically, a laser or electron beam melts the powder, bonding it to the previous layer (Gibson et al., 2015). After each layer is completed, the build plate is lowered and a new layer of powder is applied. As every layer completely fills the build chamber, all open spaces within the component—including those that might not be desirable—are also filled with powder. This requires careful consideration in the design process to ensure that there are effective means for removing this powder.

Powder bed fusion can be broadly divided into two groups, depending on the material system: polymer-based systems and metal-based systems. In polymer-based systems, the unbound powder acts as the support material itself (Bogers et al., 2016). In contrast, metal-based systems require additional support structures to counteract the stresses inherent in the material during the build process. These supports are integrated into the part design and must be removed after production, often using a saw or wire electrical discharge machining (EDM) (Bikas et al., 2015). When processing metals, the build environment must be filled with a protective gas or vacuum to prevent oxidation (Ngo et al., 2018).

Upon completion of the build, the component is surrounded by excess powder, which must be manually removed. Fortunately, the unused powder can often be recycled for future prints. In principle, any material that can be melted and subsequently solidified is suitable for this technology. Thermoplastics are particularly well-suited due to their ability to melt and resolidify repeatedly. In metal-based systems, common materials include stainless steels, titanium and its alloys, nickel-based alloys, certain aluminium alloys, and cobalt-chrome (Petrovic et al., 2011).

Powder bed fusion's versatility makes it a strong choice for manufacturing complex, high-strength metal components. Polymer-based systems, meanwhile, are frequently used for prototyping and end-use parts, especially in low- to medium-volume production (Bogers et al., 2016).

In theory, a wide range of materials can be adapted for PBF. The most commonly used examples include:

- Polymers and Composites: Thermoplastics are typically favoured because of their low melting points, low thermal conductivities, and reduced tendency for “balling” (where clusters of particles fuse together, leading to micro-cracks). Each thermoplastic material offers specific advantages and trade-offs in terms of speed, melting temperature, and process reliability (Bikas et al., 2015).
- Metals and Composites: A variety of steels (especially stainless and tool steels), titanium alloys, nickel-based alloys, aluminium alloys, and cobalt-chrome are commercially available and well-established in PBF applications (Bogers et al., 2016). Additionally, some companies have begun to offer precious metals such as silver and gold for AM.
- Ceramics and Ceramic Composites: Ceramic materials, including metal oxides, carbides, and nitrides, have also found application in PBF. The majority of equipment currently uses aluminium and aluminium oxide due to their commercial availability and performance characteristics.

2.1.6 Vat photopolymerization

Vat photopolymerization involves using a liquid resin that is poured into a tank, above which a build plate is positioned. A UV light source or laser selectively hardens the first layer of the model on the build plate. The plate is then lowered incrementally to enable the formation of subsequent layers. Once the model is complete, it is removed from the build plate and rinsed to remove any residual, unhardened material and supports. The component is then fully cured in an oven, producing an isotropic part with uniform strength in all directions and minimal residual stresses (Gibson et al., 2015).

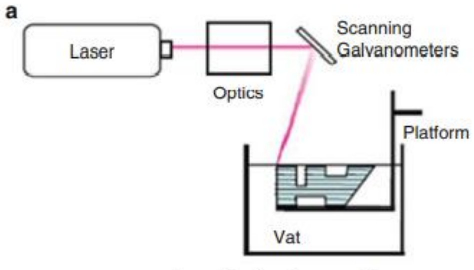
This technology yields components with fine tolerances and excellent surface quality (Bikas et al., 2015). However, it also presents certain limitations: the finished parts can become sensitive to UV light and may become brittle over time (Petrovic et al., 2011). The machines themselves are quite sensitive and must be levelled accurately to ensure even distribution of the liquid resin (Gustafsson, 2016).

The materials used in vat photopolymerization are typically UV-sensitive photopolymers, which act as a type of plastic (Javaid & Haleem, 2019). These materials are toxic in their uncured state and require careful handling (Gustafsson, 2016). Consequently, this technology demands strict safety protocols due to the open resin tank and manual material handling involved. Nonetheless, vat photopolymerization can produce parts with high surface quality at relatively fast speeds, making it especially useful for design validation (Bogers et al., 2016).

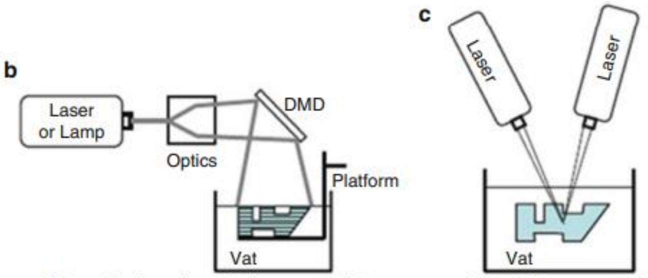
There are three primary methods within vat photopolymerization as presented in figure 1 (Gibson et al., 2015):

- Vector scan (point-wise) approaches, typical of commercial stereolithography (SL) systems.
- Mask projection (layer-wise) approaches, which cure entire layers simultaneously.
- Two-photon polymerisation, a high-resolution, point-by-point approach.

Figure 1: Visual representation of vat photopolymerization methods.



schematic of vector scan SL



Schematic of mask projection approach to SL.

Two-photon approach

Source: Bogers et al. (2016).

2.1.7 Directed energy deposition

Directed Energy Deposition (DED) is often referred to as metal deposition technology due to its primary focus on metal materials (Gibson et al., 2015). This process simultaneously heats a focused area and deposits molten material by directing energy into a narrow region. Typically, a laser or electron beam is used to melt metal powders or wires (Bikas et al., 2015). Additionally, hybrid machines that integrate DED with CNC milling are available and are particularly valuable for component repair and overhaul (Bogers et al., 2016).

The materials used in DED are generally in powder or wire form, and virtually any material or powder blend that can be melted is potentially usable (Guo & Leu, 2013). DED is capable of producing complex, fully dense metal components, making it well-suited for both new part fabrication and the repair of high-value, technologically advanced components (Petrovic et al., 2011). Table 1 provides an overview and compares the different AM methods.

Table 1: AM Method comparison table

AM Method	**Application Areas**	**Advantages**	**Disadvantages**
Material Extrusion	Prototyping, Concept Modelling, Tooling	Low Cost, Wide Material Selection	Limited Resolution, Anisotropic Properties
Material Jetting	Dental Applications, Prototyping, Jewellery	High Resolution, Multi-material Printing	Limited Build Volume, High Equipment Cost
Binder Jetting	Sand Casting, Metal Parts, Prototyping	High Speed, Low Material Waste	Limited Mechanical Properties, Post-Processing
Sheet Lamination	Aerospace Components, Packaging	Low Cost, Variety of Material Compatibility	Limited Strength, Limited Geometric Complexity
Powder Bed Fusion	Aerospace Components, Medical Implants	High Precision, Wide Material Selection	Limited Build Volume, High Equipment Cost
Vat Photopolymerization	Dental Models, Prototyping, Jewellery	High Resolution, Smooth Surface Finish	Limited Material Selection, Post-Processing
Directed Energy Deposition	Aerospace Components, Repair Applications	High Build Speed, Can Use Wide Range of Metals	Limited Resolution, High Equipment Cost

Source: Own work.

2.2 Properties and advantages

The major distinctions between AM and traditional subtractive processes such as CNC machining lie in several key properties and advantages of AM (Bogers et al., 2016), (Gibson et al., 2012):

1. Design Freedom – AM allows for the creation of complex geometries that are difficult or impossible to achieve with conventional methods. This includes intricate internal structures, undercuts, and lattice frameworks.
2. Material Efficiency – AM builds components layer by layer, significantly reducing waste material compared to traditional subtractive techniques.
3. Customisation – The digital nature of AM enables rapid design iteration and the ability to produce customised or patient-specific parts with minimal lead time.
4. Reduced Lead Times – The elimination of tooling and the direct-from-digital nature of AM can significantly shorten the product development cycle.
5. Lightweighting Potential – Topology optimisation and the ability to create lightweight lattice structures mean AM can produce parts with excellent strength-to-weight ratios.
6. Decentralised Production – AM's flexibility enables on-demand production at or near the point of use, reducing reliance on centralised manufacturing hubs and complex supply chains.
7. Integration with Other Manufacturing Processes – AM can be used to complement traditional methods, such as creating jigs, fixtures, or low-volume tooling that accelerates conventional production.

2.2.1 Material

AM technology was initially developed around polymeric materials, waxes, and paper laminates. Over time, its scope has expanded to include composites, metals, and ceramics. In comparison, CNC machining is commonly used for softer materials, such as medium-density fibreboard (MDF), machinable foams, machinable waxes, and certain polymers. However, in these cases, CNC machining typically prepares these materials for subsequent use in multistage processes, such as casting.

For final product manufacturing, CNC machining excels when working with hard, relatively brittle materials, such as steels and metal alloys. It produces high-accuracy parts with consistent, well-defined properties. In contrast, AM parts may exhibit voids or anisotropic characteristics depending on factors such as part orientation, process parameters, and design input. CNC parts, by comparison, tend to be more homogeneous and predictable in their quality (Gibson et al., 2015).

2.2.2 Production speed

Standard CNC methods can remove material more quickly than AM can build it up. However, a direct comparison between these two approaches is not particularly meaningful, as they operate under fundamentally different principles. Therefore, production speed should be assessed based on the total time required to complete an entire part or product.

CNC-manufactured parts typically result from multistage processes, often involving the creation of multiple components that are subsequently assembled into a final product. In contrast, AM's primary advantage lies in its ability to redesign and print entire parts in a single stage. This can significantly reduce complexity and accelerate the overall production process. Once the digital design is finalised, AM parts may take only a few hours to print, whereas CNC can take days or even weeks to produce and assemble (Bikas et al., 2015).

2.2.3 Part complexity

The greatest advantage that AM has over traditional CNC methods is its ability to disregard part complexity. As noted earlier, CNC-produced components are generally created from multiple separate parts that are subsequently assembled. This makes it challenging—if not impossible—to produce intricate structures as a single piece.

AM, by contrast, is not limited by the physical constraints of a spindle. Its layer-by-layer approach allows for the creation of almost any imaginable geometry, reducing material waste, cutting production time, and enhancing the performance of the final product by minimising the number of required components. This new method of design opens up a wealth of possibilities for how individual parts are conceived and manufactured, eliminating many of the limitations traditionally faced by engineers and designers.

In the following chapter, we will explore this emerging design process in greater depth and examine how computer-aided design (CAD) has the potential to fundamentally transform product manufacturing (Wohlers, 2023).

2.2.4 Accuracy and detail of the product

Both AM and traditional CNC methods are capable of producing parts with high levels of detail and accuracy. Although each method achieves these goals differently, both can reliably create components with the fine detail required for their respective applications. One advantage of AM lies in the ease with which machines can be reconfigured to meet the specific requirements of a build, without the need to redesign the part or modify the machine itself (Ngo et al., 2018).

The main factors determining the detail and accuracy of AM-produced parts are:

- Layer Thickness - This represents the height of each layer deposited during printing, affecting the vertical resolution of the build. Layer thickness is highly adjustable and plays a crucial role in determining both the level of detail and the overall build time. Typically, AM machines operate with layer heights of a few tens of microns.
- Movement Resolution of the Nozzle or Printhead - The resolution of the X and Y axes depends on the positioning mechanisms—often involving gearboxes and motors. While CNC milling may achieve slightly thinner walls due to its subtractive nature, AM offers the flexibility to reconfigure resolution quickly for different purposes. Prototypes and samples are often produced at lower resolution for faster iteration, whereas final products are printed at maximum resolution.
- Diameter of the Nozzle or Printing Laser - The final factor affecting accuracy and detail is the diameter of the nozzle or laser. In extrusion-based AM processes, nozzle size can be swapped or adjusted to achieve finer detail. Similarly, in laser-based AM, the laser's diameter can be configured to suit the desired resolution of the printed part (Wohlers, 2015).

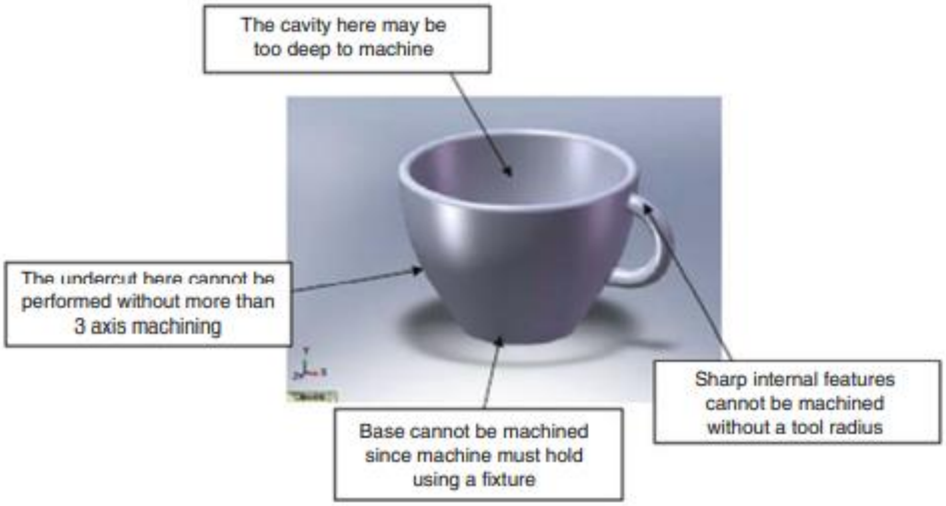
2.2.5 Part geometry

The geometry of individual parts underscores one of the most significant advantages that AM holds over conventional CNC methods. In AM, parts are effectively deconstructed from their three-dimensional form into a series of two-dimensional layers, which are sequentially applied to create the final build. This approach eliminates the traditional challenge of linking surfaces in three-dimensional space, as continuity is determined by the proximity of one cross-section to the next.

This is fundamentally different from CNC milling, which operates within three-dimensional space using simple geometric shapes such as cones, cubes, and cylinders. While CNC machining can efficiently join points along a defined path, it struggles when those points are extremely close together. Sharp corners, undercuts, enclosed structures, and similar features present significant challenges for CNC milling, often necessitating that complex parts be broken down into several components that are subsequently assembled.

Figure 2 shows an example commonly used to illustrate these limitations is a shape that appears relatively simple to the human eye but highlights the constraints of CNC machining (Wohlers, 2015).

Figure 2: Limitations of standard manufacturing methods



Source: Wohlers, (2015).

AM overcomes these challenges through its layered approach, enabling the design and production of shapes previously considered impossible or impractical. In the next chapter, we will delve deeper into how AM's supported geometry capabilities are reshaping product design and purpose.

2.2.6 Machine programming

Programming CNC machines is a notoriously complex process that demands precise sequencing of factors such as machine speed, tool selection, and the position and angle of the machine. In comparison, while AM machines also require careful configuration to suit the specific task, the overall complexity of these choices is typically much lower.

The most significant difference emerges in the consequences of incorrect programming. In AM, the worst outcome of an improper setup is generally a failed print, which simply requires reprinting with corrected settings. Conversely, in CNC machining, incorrect programming can lead to damage to the machine itself or even present risks to the safety of the operator, making precise and careful programming a critical consideration (Wohlers, 2015).

3 ADDITIVE MANUFACTURING DESIGN CYCLE

This chapter describes the differences and unique characteristics of the creative freedom afforded by designing products for AM.

The design and production stages of new product development are critical, as decisions made at this stage directly influence the cost and quality of the final product. The literature highlights basic principles and design guidelines, which support designers in this process. These guidelines traditionally focus on areas such as manufacturing, assembly, risk minimisation, sustainability, standardisation, prevention of corrosion, recycling, durability, materials, maintenance, and cost efficiency. However, these guidelines largely consider conventional manufacturing methods, including joining, casting, machining, forming, material processing, and finishing (Javaid et al., 2019).

To fully realise the benefits of AM, designers must embrace a fundamentally different mindset, centred around creating powerful and value-added industrial solutions. Design theories, methods, tools, processes, and techniques should be adapted to accommodate the inherent interdependence of geometry, materials, and quality in AM systems. Customised tools and processes should be developed to support the design of complex structures such as cellular architectures, heterogeneous artefacts, materials with tailored properties, and biological scaffolds. Moreover, each build should be treated as a unique design object with its own set of requirements and characteristics (e.g., part layout and support structures) that must be carefully designed and continuously improved (Rubin, 2012).

3.1 Designing for additive manufacturing (DFaM)

When designing a product, regardless of the chosen manufacturing method, it is crucial for the designer to understand the inherent constraints of the process and to minimise any potential violations of these limitations. While some of these challenges are mitigated through AM technologies, others persist and must be carefully addressed (Gibson et al., 2015).

It is therefore important to structure projects in a way that leverages the advantages of AM while simultaneously addressing its limitations. Well-designed AM products typically excel in the following areas:

3.1.1 Object complexity

In the context of AM, object complexity refers to the intricate geometries and sophisticated structures that can be produced. Unlike traditional manufacturing methods, which are often restricted by the subtractive nature of processes such as milling or casting, AM enables the fabrication of highly complex and organic forms with minimal physical constraints. Designing for object complexity involves utilising the inherent strengths of AM to create geometries that optimise performance, reduce material consumption, and improve overall functionality. By doing so, designers can unlock new levels of efficiency and creativity in product development (Ford & Despeisse, 2016).

3.1.2 Design Freedom and Geometric Complexity

AM introduces unprecedented freedom in terms of design, allowing engineers and designers to transcend the constraints imposed by traditional subtractive processes. With AM, complex structures such as lattice geometries, internal channels, and organically shaped surfaces can be manufactured in a single build, thus eliminating the need for multiple parts or complex assemblies (Vanek et al., 2018).

This design freedom enables engineers to optimise components for specific functions, such as reducing weight without compromising structural integrity, improving fluid flow through internal channels, or enhancing thermal performance. The ability to produce parts that are tailored to performance rather than to the limitations of the manufacturing process is a defining strength of AM (Kruth et al., 2007).

Such geometric complexity is often achieved using advanced design tools such as generative design and topology optimisation, which allow for the automatic creation of efficient structures based on defined constraints and functional requirements. These tools are now being integrated into mainstream computer-aided design (CAD) software, making them increasingly accessible to designers across industries (Bendsøe & Sigmund, 2013).

3.1.3 Topology Optimization and Generative Design

To fully exploit the design potential of AM, advanced engineering methods such as topology optimisation and generative design have become essential tools in the designer's workflow.

Topology optimisation is a computational design strategy that redistributes material within a defined design space to achieve optimal performance, typically by maximising stiffness-to-weight ratio under given loading and boundary conditions. The method is particularly well-suited to AM, as it often results in organic, non-intuitive geometries that would be difficult or impossible to manufacture using traditional subtractive methods (Sigmund, 2001; Bendsøe & Sigmund, 2013).

Topology optimization has become an integral part of the design process throughout the years and is showing great potential in the performance and efficiency of current market-ready products. Cellular parts have found their place in the biomedical, automotive and aerospace industries with growing interest from other industries (Gibson et al., 2015).

Generative design, while related, uses algorithms to automatically explore a vast number of design iterations based on specified constraints and objectives. Unlike topology optimisation, which modifies a pre-defined geometry, generative design starts from design goals and constraints to generate numerous feasible solutions—often incorporating topology optimisation techniques internally (Kunz et al., 2021). These solutions can then be evaluated for criteria such as weight, material use, cost, or performance.

Together, these methods are transformative for AM. They enable the production of parts that are lighter, stronger, and better suited to their functional roles, while simultaneously reducing waste and consolidating part count. As these techniques are increasingly integrated into mainstream CAD tools, such as Autodesk Fusion 360 and Siemens NX. This is making them more accessible to engineers and product designers across a range of industries (Bendsøe & Sigmund, 2013).

The key advantage that AM has is its versatility to be able to manufacture any object shape with little constraint. This opens the door for designers to innovate and explore options that were previously not available. Cellular structures may be created using computer aided design software (CAD). These CAD programs are able to calculate variations of the most efficient designs using a set of initial parameters set by the user. Often times the outcome are organic structures that were previously not considered and would be impossible to created using standard machining. Figure 3 illustrates the evolution of a product design using generative design.

Figure 3: Product evolution using generative design

Source: Bendsøe & Sigmund (2013).

3.1.4 Functional complexity

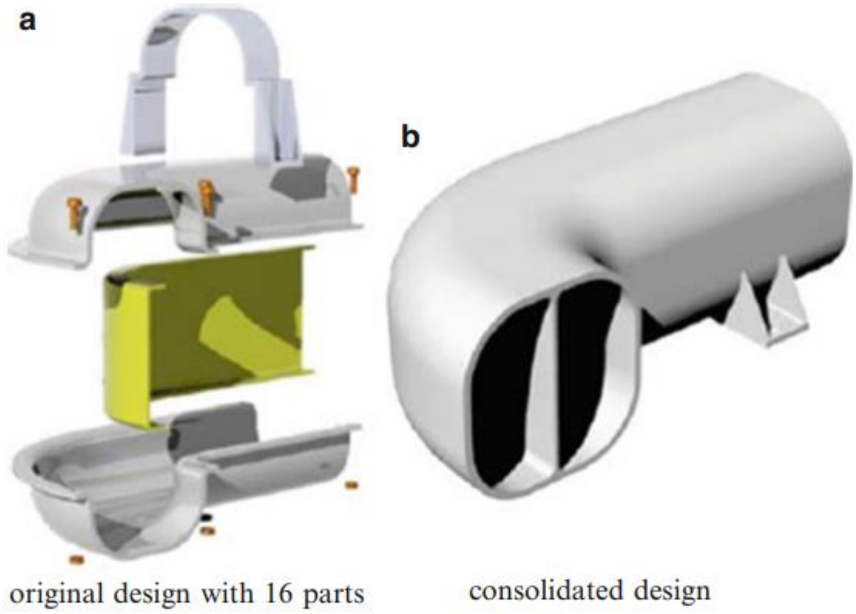
Functional complexity describes the capacity of AM to integrate multiple performance features within a single component. Traditionally, engineering design has relied on assembling numerous individually manufactured parts, each fulfilling a specific function. AM disrupts this by enabling designers to embed functions such as structural support, thermal management, fluid flow, and even sensing, without the need for complex assembly.

This level of integration not only simplifies the manufacturing process but also allows for more compact, efficient, and lighter designs. It has already been successfully demonstrated in industries such as aerospace and healthcare, where high-value components benefit from part consolidation and performance-driven design. For instance, internal cooling channels can be printed directly into turbine blades, or porous lattice structures can be created. (Guo & Leu, 2013; Thompson et al., 2016).

Functional complexity also includes the potential for multifunctional materials and multi-material printing, which allow for the realisation of components with location-specific properties. Examples include combining stiff and flexible regions within a single part, or integrating conductive pathways into structural housings. Although still emerging, these capabilities are steadily becoming more viable as AM technology matures (Tofail et al., 2018).

Moreover, designers should exploit the design freedom of AM to consolidate multiple parts into single assemblies, reducing the overall part count and assembly complexity. By combining components and integrating features directly into the design, designers can minimize assembly time, lower production costs, and improve product reliability (Kruth et al., 2007). This is achieved by controlling the creation of each individual layer of a part. This approach lowers the restriction of standard machining and increases the design freedom for the final product. Ultimately this will lower the complexity, weight and cost of the final product while improving efficiency, strength and flexibility of the parts. The figure shows an example of a helicopter duct that has been consolidated from 16 parts into a single one. Doing this across the entire vehicle amounted up to a 40 percent lighter and 60 percent cheaper overall design as illustrated in figure 4.

Figure 4: Design consolidation using AM



Source: Kruth et al. (2007).

By leveraging functional complexity, AM enables a shift from component-based design to holistic product design. This not only enhances technical performance but also streamlines the supply chain and reduces life-cycle costs, particularly in industries where high customisation, low-volume production, or mission-critical functionality is essential (Liu J, 2016).

3.1.5 Material and support complexity

In just the past ten years, the world of AM has grown in remarkable ways, especially when it comes to materials. What once relied mostly on basic plastics like ABS and PLA for simple prototypes has now evolved to include a much wider selection: high-performance polymers, metal alloys, ceramics, composites, and even concrete. This expanded range opens the door to a wide range of new applications, but it also brings new complexities. Every material behaves differently, and the best choice often depends on both the specific AM process being used and what the final part is meant to do (Gibson et al., 2015).

When designing for AM, choosing the right material is critical. Designers need to think about the performance demands of the part they're creating. Things like strength, heat resistance, chemical stability, or whether the material is safe for use in the human body. For instance, aerospace components often require lightweight but durable metals like titanium or aluminium, while medical devices may rely on biocompatible materials such as medical-grade polymers or titanium alloys (Thijs et al., 2010).

Another key factor in AM is support structures. These are often necessary to build complex features like overhangs or bridges, especially in processes like fused filament fabrication or vat photopolymerization. Supports are usually made from the same material or a secondary one and need to be removed once printing is done. Powder-based systems like selective laser sintering offer a bit more freedom since the unused powder can naturally support the part during printing. But even here, designers have to think ahead—especially when it comes to removing powder from internal cavities or channels (Jiang, et al., 2018).

Beyond the properties of the finished material, how a material behaves during printing also matters. Some polymers, for instance, absorb moisture from the air and need to be dried before printing, or they'll cause defects. Metal powders bring their own set of requirements, such as controlling particle size and managing heat transfer during each layer. With high-performance materials, even small changes in the process can have big impacts on the quality of the final print.

To minimize material and support complexity, designers can employ advanced design optimization techniques such as generative design or topology optimization. These methods use algorithms to iteratively generate and refine designs based on specified performance criteria, resulting in highly efficient structures with minimal material usage and support requirements (Tofail et al., 2018).

Previous research has classified the types of material that can be used in AM as follows:

- Metals and alloys
- Polymers and composites
- Ceramics
- Concrete
- Combination of the above

This makes the technology very versatile and applicable to almost any situation. The different materials offer several benefits, including multifunctional optimization, reduced material waste, mass customization, the possibility of repairing damaged or worn metal parts, fast prototyping, control of lattice porosity, the printing of complex structures and scaffolding for the human body, and the usage of no framework (Ngo et al., 2018). Different materials have different application areas. Polymers may be used in situations of rapid prototyping, whereas a combination of metals ceramics and polymers is more suited for the automotive, aerospace or medical industry. A rise in concrete printers, that enable the construction of solid structures, is contributing to the spread of the technology to other sectors of the economy.

Due to the layer-by-layer method of printing each part may require support structures to keep it stable during the printing process. In those cases, the support structure is almost part of the product design, as it has similar goals of being as minimal and efficient as possible. Things to consider are the effects of building time, the removability of the support and post-processing requirements after supports have been removed. A general rule is that any overhang above 45° requires a supporting structure. The CAD software used to create the product support features that calculate areas above any threshold that is set and automatically generate the most optimal support structure with minimal waste (Liu J, 2016).

In the end, successful AM design depends not just on understanding how to build a shape, but on balancing the complex interplay between geometry, material, machine behaviour, and post-processing. The more deeply a designer can understand these factors, the more effectively they can leverage AM's full potential, while keeping production costs and risks in check.

3.2 Challenges and constraints

While AM presents remarkable opportunities for innovation, particularly through its design freedom and potential for part consolidation. It also introduces a distinct set of challenges that must be acknowledged during the design phase. Successfully leveraging AM requires not just creativity, but a deep understanding of the material, technical, and process-specific limitations that can affect the manufacturability and performance of a product.

3.2.1 Material Selection

Choosing the right material is one of the most critical decisions in AM design. Although technologies now support a broad range of materials. From polymers and metals to ceramics and composites, not all materials are compatible with every AM process. Some require specialised post-processing or handling, and each comes with trade-offs in mechanical, thermal, or chemical performance. Designers must weigh these factors carefully to align material capabilities with functional requirements (Kumar et al., 2017).

3.2.2 Geometric Constraints

AM allows for highly complex geometries that traditional manufacturing cannot achieve. Yet, these benefits come with their own limitations. Minimum feature sizes, build orientation, and surface quality must be considered when preparing designs. Parts that are too intricate or unsupported may require simplification or modification to ensure they are manufacturable. Redesigning parts to reduce overhangs, manage internal stresses, and minimise post-processing effort is a common and necessary step (Bandyopadhyay & Bose, 2019).

3.2.3 Support Structures

Many AM processes require support structures to maintain stability during printing. These supports add to material usage, build time, and post-processing effort. Moreover, if not properly managed, they can leave marks or distort the final geometry. Strategic orientation of parts within the build volume can help minimise the need for supports. Newer software tools assist with this optimisation, but the responsibility ultimately rests with the designer to make informed choices (Wong & Hernandez, 2012).

3.2.4 Surface Quality and Post-Processing

Achieving an acceptable surface finish remains a known limitation in several AM methods. Layer lines, rough textures, or thermal inconsistencies can affect both appearance and function. In critical applications, these imperfections may compromise part integrity or require extensive finishing, such as polishing, coating, or machining. In some cases, additional treatments like heat curing or surface smoothing are necessary to meet application-specific standards—especially in aerospace or biomedical contexts (Tofail et al., 2018).

4 ADAPTED SCRUM FRAMEWORK FOR ADDITIVE MANUFACTURING

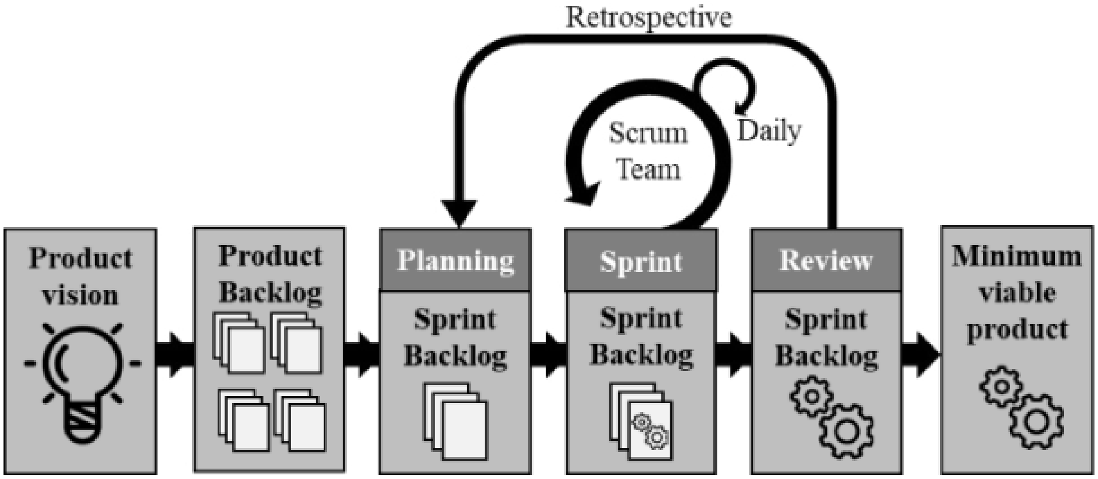
In the fast-paced world of AM, where innovation drives competitiveness, the ability to adapt quickly to changing requirements and market dynamics is paramount. Agile methodology, initially developed for software development, has found widespread applicability across various industries, including manufacturing. Agile offers a flexible and iterative approach to project management, emphasizing collaboration, adaptability, and continuous improvement (Kumar, 2017). This chapter explores the application of Agile methodology within AM companies, focusing on its framework structure and key components such as product vision, product backlog, sprint planning, sprint cycle, sprint review and retrospective, and Scrum roles.

In general, the framework is structured around the stages presented below although each team will eventually create their own version, slightly different, to the core model. The scrum model is based on a set of values, principles, and practices that provide the foundation for the way of work. Its advantage lies in complementing these foundations with team and problem specific components making it very adaptable across different use cases (Rigby et al., 2016).

4.1 Scrum framework structure

Scrum is a widely adopted agile framework. It's designed to help teams work together, manage complexity and deliver outcomes through development cycles. Originating in software engineering, it has since proven effective across a wide range of industries due to its structured yet adaptable approach. At its core, Scrum is built around development cycles called sprints, clearly defined roles, and regular feedback mechanisms that promote transparency. The main goals are quick deliveries with continuous improvement. This section outlines the fundamental components of the Scrum framework and explains how these elements interact to support the project execution. A visual overview of this framework is provided in Figure 5, illustrating the cyclical nature of Scrum and the flow of work from planning to delivery.

Figure 5: Scrum framework structure



Source: Rubin et al. (2012)

4.1.1 Product vision

At the core of any Agile project lies a clear and compelling product vision that serves as a guiding beacon for the development team. In the context of AM, the product vision encapsulates the overarching goal and purpose of the AM project, whether it involves prototyping, production, or innovation (Rubin, K.S. 2012). The product vision defines the intended outcome, target market, and value proposition of the AM product or service. For example, the vision for a new 3D-printed medical device may focus on enhancing patient care through personalized treatment solutions (Wohlers, 2015).

4.1.2 Product backlog

The product backlog in Agile serves as a dynamic repository of all requirements, features, and enhancements envisioned for the AM project. In AM, the product backlog encompasses a diverse range of items, including design specifications, material requirements, quality standards, and regulatory compliance criteria. Each item in the backlog is prioritized based on its value to the customer and its feasibility for implementation. For instance, the backlog for a 3D-printed automotive component may include specifications for material strength, geometric accuracy, and surface finish (Kumar, 2017).

Each user story behaves similarly as the whole product vision. Its intent is to focus on a specific part of the project and define, into even smaller detail, each task that needs to be done to finalise the story. Each of these tasks are compiled into a product backlog per user story which serves to define, estimate, track and prioritise each item that needs to be completed by the scrum team. The tasks should be broken down to the level that they are able to be achieved within on sprint cycle. If the task is larger than that then it is a candidate for further grooming or even a separate user story all by itself (Rubin, K.S. 2012).

The structure of the backlog is always flexible and changing. Items get changed in their priority thus always looking for the best candidates for development. With this in mind the backlog is always considered emergent as it must take into account outside factors like market development or stakeholder wishes and be adapted to best fit into the wider picture of the company.

4.1.3 Sprint planning

Sprint planning marks the beginning of each iteration or sprint in Agile methodology. During sprint planning sessions, the AM team collaborates to select backlog items for implementation and define the tasks required to complete them. In the context of AM, sprint planning involves assessing the feasibility of printing specific components, optimizing printing parameters, and allocating resources effectively. The goal is to establish a clear plan of action for achieving the sprint objectives within the designated time frame. For example, sprint planning for a 3D-printed aerospace part may involve selecting the optimal printing technology, setting layer thicknesses, and configuring support structures (Schwaber & Sutherland, 2017).

The backlog contains a multitude of items and not all can be included in a short sprint cycle. The scrum team conducts a sprint planning to determine the items that will get worked on. This may be done in a single or multiple iterations and at the end, the sprint plan along with the product backlog will form the sprint backlog for the next sprint.

Although it’s very important to have a high-level project plan created – in scrum this is called a roadmap - it is much more crucial to have a well-defined sprint plan for the upcoming cycle. Sprint planning’s are usually done a week of a few weeks before the sprint starts, meaning that some upfront knowledge is needed and decisions cannot be put-off until the last minute. The planning itself is intended for all the scrum members where they cooperate to balance the plan according to the resources and time available. This makes the planning phase a very important one as decisions, good or bad, will cascade into the development phase impacting performance of the whole scrum team.

In the context of AM, the sprint cycle is a crucial aspect of Agile methodology. Each sprint cycle contributes to a sprint release, with distinct objectives depending on whether the project is in a release or non-release sprint. Prioritization plays a significant role, especially in release sprints, where items may require rigorous testing or have dependencies. In non-release sprints, there's more flexibility in the order of delivered items, but the overall release plan must still be considered to accommodate items not suitable for the current release. Cleland-Huang suggests that shorter release cycles offer more flexibility and lower project risk (Cleland-Huang, 2009).

4.1.4 Sprint cycle

The sprint cycle, typically lasting two to four weeks, represents the iterative cadence of development activities in Agile methodology. During each sprint, the AM team works collaboratively to design, prototype, and iterate on the AM product or components. The sprint cycle in AM encompasses various activities, including 3D modelling, slicing, printing, post-processing, and testing. By breaking the development process into manageable iterations, the sprint cycle enables continuous feedback, rapid iteration, and incremental improvement. For instance, a sprint cycle for developing a new 3D-printed consumer product may involve multiple iterations of design refinement and functional testing (Wohlers, 2015).

The daily scrum meeting is intended to give the team a chance to coordinate and update the others on their work. It is another way that scrum promotes flexibility and quick decision making. It consists of a 15–30-minute meeting with the whole scrum team on a daily basis. The intent is to inspect, synchronise and adapt the daily plan along with any activity that the team needs to self-organise for the day. The main objectives should be updating the team on the bigger picture and highlighting any blockers to the backlog. This minimizes the time for waiting on any items in need of resolution.

Communication between the team members is crucial and there are several tools that they can use to their advantage. A task board is a common example that is used. Items from the backlog that are in the to-do status are moved into progress and once completed are marked as done. The granularity of the steps is project dependant and teams normally add steps such as in review, on hold or pending change to their workflow to increase visibility into the work (Rigby et al., 2016).

4.1.5 Sprint review and retrospective

The two major activities that are required nearing a sprint end are a sprint review and a sprint retrospective. The sprint review provides an opportunity to the whole team to see the sprint results and give feedback on the work done in the past cycle. It is considered a more informal activity with the intent of showcasing work that was done. Keep note that only completed items are up for discussion and even if an item received attention, it must first be validated and confirmed by the team and ultimately by the product owner. The criteria of an item being done should be very strict and include several steps of testing and validation by all involved parties before being signed-off. Any items that do not fit the criteria at the end of the sprint are moved to the next one or replanned accordingly. The demonstration of work, when possible, should be done by the team responsible for each item. The intent is to bring transparency to the rest of the team and focus on the practical results that have been achieved – feature showcase, demo presentation or progress walkthrough. The outcome of the demonstration is a general discussion on the item along with any suggestions for adaptations if needed. At the end of the review a general summarization is created along with action points to be carried on to the next sprint and provide talking points for the sprint retrospective (VersionOne, 2020).

The sprint retrospective's purpose is for the scrum team to examine the overall process being used within each sprint to achieve the sprint goal. It gives time to scrutinise and come up with improvements to improve their way of working. The retrospective is part of a continuous improvement mentality that should exist within the team. It gives a voice to each team member and increases the agency that each worker has.

The retrospective usually consists of an information gathering activity where statements, comments and general thoughts are gathered. The information is then grouped into categories based on their similarities, out of which several action items are created. These might be short term or long-term goals that the team wishes to achieve either on a personal or team level. The goals fit three buckets: actions to continue and improve, actions to stop performing and actions to try. The decision on how to handle these actions is usually done by the product owner as some might require support from outside the team to achieve. These action items fit together to form an insight backlog which should be handled similarly like the product backlog with items being included in each sprint on a regular basis (Rigby et al., 2016).

4.2 Scrum roles

This section explores the key roles and responsibilities typically found within Scrum teams. It outlines how these roles contribute to the team's structure, highlights their benefits, and explains the overall purpose of the team. Scrum teams are generally composed of three main roles: the product owner, the scrum master, and the development team.

4.2.1 Product owner

A product owner is present on every project and has a central leadership position within the team. His responsibility is to balance the two major sides of each project which are the stakeholders and the scrum team (Rubin, 2012). One the hand are the expectations and priorities of the business stakeholders and on the other is a practical scrum team responsible for achieving those goals.

A product owners main activities revolve around:

- Managing economics
- Participating in planning
- Collaborating with the stakeholders and development team

Managing economics is related to the initial scope of the project which normally focuses on the final release date, scope of development, budget and minimal viable product. The project owner must make continuous trade-offs between these factors to successfully deliver the project within a given time-frame.

The activity is continuous and the high-level plan must be revaluated anytime there is a significant change to the original plan. This can be due to uncertainties in the development process, reprioritisations of key activities, resource constraints or any other unexpected event. In the event of the project not showing positive results, it is the decision of the product owner to either continue with the effort or stop the expenditures to focus on other projects.

Sprint level economics concern the return on investment of each individual sprint. Although the project's success is measured by the end result, each sprint must be able to deliver on a set of goals to show progress and instil confidence in the final result. Having a good understanding of where the reoccurring costs come from and how to measure the return of each sprint are key characteristics that a good product owner should possess. Close collaboration with both the stakeholders and scrum team is needed to correctly convey the progress and current focus of the project so that expectations may match the capabilities of the implementation team.

Product backlog economics is the third economic indicator that the product owner should keep track off. As he is responsible for handling the overall product backlog, he should also adjust his cost/benefit ratio of each item as soon as any new information is received. For instance, an item that was deemed simple might require more time to complete, increasing its overall cost with no change to its benefits. This might change the net balance of some items making the candidates for a change in priority or further grooming.

The product owner is one of the key members that should be heavily engaged in all levels of planning. From the high-level portfolio perspective up to the daily level, the project owner should always be in touch with the overall plan and strategy to achieve set goals. He is the final decision maker on how the final plans will look like. He must work with both the stakeholders and the development team to produce a viable plan for each level of business - portfolio-, product-, release- and sprint-planning activities. (Rubin, 2012).

A key activity is backlog grooming. The product owner must incorporate stakeholder requests into the existing product backlog and coordinate with the development team to correctly adjust the backlog item. Each backlog item should have an acceptance criterion which the product owner creates based on feedback from the stakeholder and development team. He is also the person who confirms if the acceptance criteria have been met for a set project.

The project owner always acts as a bridge between the stakeholder and development team. He must be able to coordinate incoming requests with the resources he has available. The engagement with both sides will change during a single sprint. Normally at the start of a project there is higher engagement with the customer/stakeholder as requirements and criteria need to be defined. This transitions into a more development heavy stage where the engagement from the stakeholders drops to a minimum thus allowing the scrum team to focus on development. Nearing the end of the project, the stakeholders are engaged once again to review the product and evaluate it based on their acceptance criteria. Any feedback or insights gathered should be formed into action items and included into the insights backlog for future improvement. This engagement level may be projected from the sprint level up to the portfolio level as the general pattern of engagement remains similar. As the sprint cycles are quite short in duration this leaves no room for extended periods where stakeholder engagement does not exist. Similarly, the development team is constantly informed of incoming requests and regularly provide their insight to the product owner. This minimizes the chances of anyone being disconnected from the conversation and mitigates the risk of any team blaming another, further asserting the constant growth mentality (Piller, et al., 2015).

4.2.2 Scrum master

The scrum master is an individual within each scrum team that is focused on helping everyone else on the team embrace and understand the core principles, values and practices that scrum has to offer. He has a leadership role acting both as advisor and to a degree the product owner. His activities pertain to assisting the product owner, communicating, impediment removal, change agent and leading team scrum activities.

The emphasis on each activity changes throughout each sprint period, thus one of the important characteristics of a scrum master is his adaptability and quick thinking. The start and end of the sprint emphasise more on scrum activities as those are the periods where the sprint planning and review are conducted. These activities are in majority set-up and lead by the scrum master. During the core of the sprint over half of his time is dedicated to impediment removal, meaning any potential obstacle that would hinder the work of the development team. Acting quickly is often required as uncertainty is always a factor. His job is to assess the risk of any potential threat and coordinate with the rest of the scrum team to find an adequate solution. The remainder of his time are normally spent equally among the other activities described above (Piller, et al., 2015).

The scrum master must have a high level of insight into the project as his main communication is mostly with the product owner and lead developers on project specifics.

Some key traits of a good scrum master are: Being knowledgeable about the project itself and the scrum method being used. He often questions the decisions being made to explore new options promoting a constant growth mindset. He must be collaborative, patient and protective of his team. The final trait is transparency, both on a personal and business level. Team members should have high insight into any documentation that they might require and should expect honesty from the scrum master (Piller, et al., 2015).

4.2.3 Development team

The development team consists of individuals from different field such as: software/hardware engineers, testers, designers and so on. They form into groups which are called scrum teams. They are a self-organising team whose primary responsibility is performing the sprint execution and completing the items. Apart from that they should be able to inspect and adapt their work. With the help of the daily scrum activities any individual should have insight into others work and adjust their focus if needed. An important activity for the development team is participating in the backlog grooming sessions. They have unique insight into the product that they are building and any decision made should respect any concerns or suggestions from the development team. They should similarly be engaged in the sprint planning itself as they are crucial towards making the plan reasonable and the goal achievable. Better knowledge about the dependencies and estimations of items allows the scrum master and product owner to correctly structure the work in a way that lowers uncertainty and minimises risk (Cooper, et al., 2005).

The last two scrum activities where the development team has a role to play are the sprint review and retrospective. The intent, as mentioned, is to showcase work done in the previous sprint and acquire insight from the wider team. Thus, the team should incorporate quality ideas into their thinking and be able to quickly adapt and change the course of the project if needed. The recommended size of the team is somewhere between four and nine individuals with five to seven proving the best in most cases.

Mike Cohn lists a handful of reasons to keep teams small, which include the following (Cohn, 2009):

- There is less social loafing. People exert less effort because they believe that others will pick up the slack.
- Constructive interaction is more likely to occur on a small team.
- Less time is spent coordinating efforts.
- No one can fade into the background.
- Small teams are more satisfying to their members.
- Harmful overspecialization is less likely to occur.

5 INTEGRATING AGILE FRAMEWORKS WITH ADDITIVE MANUFACTURING

Based on the above we have identified that an adapted scrum methodology fits well with the strengths and benefits of AM. The following describes the usage of a scrum framework for AM oriented projects.

The initial step is setting up the work process to fit the scrum structure. This means that user-stories need to be created and team organized in a way that fits the scrum framework. It is possible to adapt a previously used methodology or use the opportunity to structure it from the ground up. Once the team is setup and knowledgeable about the scrum methodology, work should be dedicated into building the product backlog. This will serve as a record of all the tasks that need to be created to produce a minimal viable product. Planning of these tasks is done in the same way as described above and should be the responsibility of the whole scrum team, with the product owner confirming and refining the plan as progress is done. Priority and task type play a large role in deciding what to plan for the next sprint cycle. In addition to taking into account the team's availability the product owner must also balance the availability of the machines along with larger dependencies between the tasks (Cohn, 2009).

The most important phase is execution of the plan itself within each sprint cycle. For AM there are four main activities that are done within each sprint cycle. These are supported by the standard daily scrum meeting where experience and insights are shared among the team. The first part of the sprint should be dedicated towards developing and printing. Within this period designers prepare a computer model of as specific part and test their design using computer software to quickly identify any flaws before moving into production (Cohn, 2010). Next the design that is likely a culmination of previous sprints and iterations is printed – likely at a lower resolution, using prototyping material such as polymers to lower costs and build time. Once this reference model has been created the designers may move into the second half of the sprint which is intended for exploring opportunistic and restrictive design techniques. This mean reviewing the current product and looking to either minimize certain elements or try and add complexity or explore different design iterations for an individual part. At the culmination of each sprint the team should have a physical model as a reference along with ideas any examples of how the design may be improved. These suggestions are reviewed by the scrum team and any changes made to the part will likely impact planning of future sprints. This is normal as knowledge gained through designing and mainly testing and manufacturing should be shared and applied at the end of each sprint cycle (Cooper, et al., 2005).

The result of using scrum should be a shorter time to market. Functional prototypes can quickly be created and used to speed-up the detection of any design flaws. Additionally, these flaws can quickly be amended and a new iteration of the product built. The framework provides opportunities for the various parts of the product line to work more closely together. In general, there is a linear path between the design and the manufacturing process. In scrum feedback from each team-member is quick and any potential constraints that exist from design-to-product can be avoided sooner in the product development process. Similarly quality checks and minimal viable product criteria help to determine when a design is ready to move from the prototyping phase into manufacturing. Knowing when exactly this is crucial as the final product will likely be made using higher quality materials and methods and redesigning at that stage would incur additional costs (Piller, et al., 2015).

5.1 Bridging Theory and Practice in AM Integration

Despite extensive academic discussions around AM and Agile methodologies like Scrum, there remains a limited understanding of how these theories play out practically, especially within Slovenian manufacturing companies. While research often highlights the benefits of AM. Such as greater design freedom, customization, and faster prototyping. Businesses frequently encounter practical challenges that theories don't fully capture. Issues like technical obstacles, workforce skill gaps, and necessary organizational changes often complicate the adoption of these methods in everyday business operations. As a result, there's a significant gap between what is theoretically possible and what companies experience in reality.

The purpose of this study is to bridge this gap by exploring how Slovenian companies are actually integrating AM technologies and adapting Agile and Scrum practices in their daily operations. Through qualitative methods, including interviews with company representatives, the research seeks to reveal authentic experiences and practical insights. Understanding these real-world scenarios is critical—not just for enriching academic theory but also for providing actionable guidance to businesses aiming to adopt and optimize these innovative technologies and methods. Consequently, this study holds practical and academic importance, helping to close the gap between theory and practice.

5.2 Applying Agile and Scrum to additive manufacturing

5.2.1 Iterative Product Development:

In AM, where prototyping and iteration are inherent, Agile methodologies align seamlessly with the iterative nature of the technology. By breaking down the product development process into small, manageable sprints, AM companies can quickly iterate on designs, gather feedback, and refine prototypes in a continuous cycle of improvement (Goh, 2012). This iterative approach allows for rapid exploration of design variations, material properties, and manufacturing parameters, facilitating faster time-to-market for new products and innovations (Guski, 2019).

5.2.2 Cross-Functional Teams

Agile teams in AM companies comprise individuals with diverse skill sets, including engineers, designers, materials scientists, and domain experts. By fostering collaboration and cross-functional communication, Scrum teams can leverage collective expertise to address complex challenges and accelerate innovation (Conboy, 2009). This multidisciplinary approach enables AM companies to integrate design, engineering, and manufacturing considerations seamlessly, resulting in more robust and optimized solutions (Lindemann et al., 2017).

5.2.3 Flexible Adaptation

AM is evolving rapidly, with constant advances in materials, machines, and software. Agile methods empower teams to embrace this change rather than resist it. The Scrum framework supports early testing, responsive design alterations, and adaptive planning, helping AM companies stay aligned with shifting market demands and technological progress (Abrahamsson et al., 2017; Sutherland & Schwaber, 2017).

5.2.4 Customer-Centric Approach

Agile methodologies prioritize customer collaboration and feedback, placing the end-user at the centre of the development process. In AM, where customization and personalization are key drivers, Agile methodologies enable companies to engage with customers iteratively, gather insights, and tailor products to meet specific needs and preferences (Cohn, 2010). By co-creating solutions with customers, AM companies can enhance product relevance, customer satisfaction, and market competitiveness, driving long-term success and loyalty (Anderson et al., 2013).

5.2.5 Continuous Improvement

The iterative nature of Agile and Scrum fosters a culture of continuous improvement within AM companies. By regularly reflecting on processes, identifying bottlenecks, and implementing iterative changes, AM teams can optimize efficiency, enhance quality, and drive innovation throughout the product lifecycle (Leffingwell, 2010). This commitment to continuous improvement enables AM companies to stay agile, responsive, and adaptable in a rapidly changing environment, unlocking new opportunities for growth and differentiation (Ambler and Lines, 2012).

5.3 Benefits of Agile Methodology in AM

The following section describes the benefits of agile as a business process. While primarily used in software development, it offers several practical advantages to manufacturing companies practicing AM. Agile can help teams bring products to market faster, adapt flexibly to changes, enhance product quality based on customer feedback, and encourage innovation. Each of the benefits are described in the list below, highlighting how agile methodologies can support companies in being more efficient and competitive.

1. Accelerated Time-to-Market: Agile methodologies enable AM companies to accelerate product development cycles, reducing time-to-market for new products and innovations. By embracing iterative development and incremental delivery, companies can respond swiftly to market demands and gain a competitive edge (Goh, 2012).
2. Enhanced Flexibility and Adaptability: Agile methodologies empower AM teams to adapt quickly to changing requirements, market dynamics, and technological advancements. This flexibility enables companies to navigate uncertainty, mitigate risks, and seize emerging opportunities (Abrahamsson et al., 2017).

3. Improved Product Quality and Customer Satisfaction: By prioritizing customer collaboration and feedback, Agile methodologies help AM companies deliver high-quality products that align closely with customer expectations. This customer-centric approach enhances product usability, reliability, and overall satisfaction (Leffingwell, 2010).
4. Fostered Innovation and Creativity: Agile methodologies cultivate a culture of innovation and experimentation, encouraging teams to explore new ideas, technologies, and design possibilities. By embracing a mindset of creativity and exploration, AM companies can drive breakthrough innovations and unlock new avenues for growth (Anderson et al., 2013).

5.3.1 Challenges and constraints

Alongside the benefits, companies also encounter new challenges and constraints when adopting agile methodologies in AM. Companies are often faced with difficulties related to cultural acceptance, technical complexities specific to AM, regulatory compliance issues, and the demands of iterative resource planning. This section identifies and describes these challenges. Doing so helps provide a clearer understanding of the ways to overcome said challenges. Such understanding is essential for successfully integrating Agile practices with additive manufacturing technologies.

This section outlines the key challenges and constraints that companies may face when adopting Agile methodologies in additive manufacturing (AM). Although Agile can offer many benefits, integrating it into manufacturing isn't always straightforward. Companies often encounter difficulties related to cultural acceptance, technical complexities specific to AM, regulatory compliance issues, and the demands of iterative resource planning. Understanding these challenges can help companies prepare better and implement Agile approaches more effectively in the context of additive manufacturing

- Cultural Transformation: Adopting Agile methodologies may require a cultural shift within AM companies, necessitating buy-in from leadership, team members, and stakeholders. Overcoming resistance to change and fostering a culture of collaboration and experimentation are essential for successful Agile implementation (Fitzgerald & Stol, 2014).
- Technical Complexity: AM projects often involve technical complexities, such as material properties, printing parameters, and post-processing requirements. Integrating Agile methodologies with technical workflows and addressing domain-specific challenges are critical for effective project management (Levy & Dubey, 2017).
- Regulatory Compliance and Safety: Compliance with regulatory standards and industry certifications poses challenges for Agile implementation in safety-critical applications of AM. Balancing agility with regulatory requirements and ensuring product safety and

reliability are paramount considerations for companies operating in highly regulated industries (Mergel et al., 2019).

- Resource Allocation and Planning: Agile methodologies rely on iterative planning and resource allocation, requiring careful management of time, budget, and personnel. Balancing short-term objectives with long-term goals, prioritizing tasks, and optimizing resource utilization are key challenges for AM companies adopting Agile practices (Schwaber & Sutherland, 2017).

5.4 AM and the Product Design Cycle

Over the past decade, AM has shifted from a niche prototyping tool to an increasingly important enabler of industrial innovation. Numerous studies have highlighted AM's potential to transform traditional product development cycles by enabling rapid iteration, design flexibility, and cost-efficient low-volume production (Gibson et al., 2015; Petrovic et al., 2011; Gebler et al., 2014).

One of the most widely acknowledged benefits of AM is its ability to accelerate the product design cycle. By eliminating the need for tooling and enabling direct fabrication of parts from digital models, AM allows for much faster prototyping and testing of new designs (Rayna & Striukova, 2016). Researchers such as Attaran (2017) and Tuck et al. (2007) emphasize that AM shortens design iteration loops, enabling more experimental and customer-driven design processes.

In particular, AM enables greater design freedom through the ability to manufacture complex geometries, lightweight lattice structures, and multi-functional integrated parts (Leary, 2019; Ford & Despeisse, 2016). This has driven a shift toward Design for AM (DfAM) approaches, which seek to fully leverage AM's unique capabilities (Rosen, 2007). At the same time, DfAM requires new design thinking and skills, as designers must move beyond the constraints of traditional manufacturing processes (Thomas et al., 2013).

Several studies have explored how AM affects the balance between exploration and exploitation in product development (Gao et al., 2015; Holmström & Partanen, 2014). On one hand, AM enhances *exploration* by enabling radical innovation and rapid experimentation. On the other hand, it also supports *exploitation* by allowing efficient small-batch production and mass customization, particularly in high-value or niche markets.

However, the literature also highlights important limitations. Post-processing requirements, material qualification challenges, and the cost of industrial-grade AM equipment remain significant barriers to scaling AM for mass production (Baumers et al., 2011; Wohlers, 2023). These challenges reinforce the view that AM is most valuable as part **of** hybrid manufacturing models (Khorram Niaki & Nonino, 2017), where it complements rather than replaces traditional manufacturing.

5.5 Agile Methods in Product Development

In parallel with the evolution of AM, there has been a growing interest in applying **agile methodologies**. Originally developed for software engineering it may be applied to physical product development (Conforto et al., 2016; Rigby et al., 2016). Agile approaches such as Scrum emphasize iterative development, cross-functional collaboration, and responsiveness to customer feedback—principles that align closely with the capabilities of AM.

Several researchers have explored how agile methods can support rapid hardware development (Sommer et al., 2015; Cooper & Sommer, 2016). The iterative nature of AM processes makes them well-suited to integration with agile frameworks. By enabling frequent prototyping and testing, AM allows agile teams to maintain fast feedback cycles and continuously refine product designs (Schuh et al., 2019).

Moreover, AM can help bridge the inherent challenges of applying agile methods to physical products, where design changes are traditionally costly and slow. The removal of tooling constraints through AM facilitates the kind of rapid iteration that agile processes rely on (Cooper & Sommer, 2018). This has led to new hybrid models of Agile Hardware Development that combine agile project management with advanced manufacturing technologies (Schuh et al., 2019; Ringenberg et al., 2019).

At the same time, the literature warns that agile adoption in physical product development must be carefully managed. Physical constraints, supply chain dependencies, and regulatory requirements can limit the full application of agile principles (Cooper & Sommer, 2018). Successful integration requires adapting agile frameworks to the realities of manufacturing contexts and ensuring that engineering teams are equipped with appropriate tools and mindsets (Sommer et al., 2015).

5.6 The Intersection of AM and Agile in Industrial Practice

The intersection of AM and agile methods is an emerging area of interest in both research and practice. Studies suggest that AM acts as a key enabler of agility in manufacturing by reducing lead times, enabling flexible production, and supporting late-stage customization (Ngo, et al., 2018; Holmström & Partanen, 2014).

In particular, the combination of AM and agile project management offers a powerful approach to accelerating product innovation (Schuh et al., 2019). By integrating AM into Scrum-based development cycles, companies can create more adaptive and responsive product development processes (Ringenberg et al., 2019). This is particularly valuable in industries facing fast-changing customer demands or competitive pressure.

However, empirical research on how companies are actually combining AM and agile methods in practice remains limited. Most studies focus either on AM's technical impacts or on agile process adaptation, with relatively few examining their integration in real-world industrial contexts (Schuh et al., 2019). There is a clear need for more qualitative research capturing how firms manage this integration, what challenges they encounter, and what organizational capabilities are required.

5.7 Contribution of This Study

While there has been a lot of research on AM in recent years, much of it has focused on the technical side like materials, printing methods, and machine capabilities. Less attention has been given to how companies are actually using AM in their product development process, especially in smaller or mid-sized markets like Slovenia. There's also limited research on how project management approaches, like Agile or Scrum, fit into AM workflows in a practical setting.

This is where the gap lies. There is a need to better understand how companies are combining AM with flexible, iterative development methods. While Agile is well known in software, its use in physical product development is still being explored. There are some studies that look at this in larger global contexts, but not much specific to smaller European countries or manufacturing companies that are still building experience with AM. This thesis helps fill that gap by focusing on real-world examples from Slovenian firms. It brings together two areas, advanced manufacturing and modern project management, that are often discussed separately. By exploring both the technology and the process side, the research gives a broader view of what adopting AM really looks like in practice.

The contribution of this study is mainly practical. It shows how companies are thinking about AM, what challenges they face, and how some are starting to apply Agile methods like Scrum to speed up development and improve collaboration. These findings can help other firms understand what to expect and how to get started.

At the same time, the study adds to academic research by connecting AM adoption with organizational change and workflow design. It opens the door for more research on how teams, tools, and methods interact when companies move toward more flexible and digital ways of working.

6 METHODOLOGY

This chapter outlines the methodological framework employed in collecting, analysing, and structuring the interview results presented in this report. Given the complex and multifaceted role that AM plays across various industries, a qualitative interview approach was selected to capture in-depth insights from key industry players. The chapter explains the rationale for using interviews, the design of the interview process, the selection of companies, and how the findings were structured to reveal common themes and divergent perspectives across sectors.

6.1 Research Design

6.1.1 Overarching Research Aim

This dissertation investigates the adoption, application, and transformative potential of AM technologies within the Slovenian industrial landscape. The primary objective is to comprehensively explore the current utilization patterns, perceived benefits, persistent challenges, and prospective evolution of AM across diverse industrial sectors in Slovenia. Given the emergent status of AM in many regional contexts and the complex interplay of technical, organizational, and strategic factors influencing its integration, an exploratory research design was imperative.

6.1.2 Methodological Justification

To capture the nuanced realities of AM implementation, a qualitative methodology was employed. Semi-structured interviews, guided by a pre-defined protocol, constituted the principal data collection instrument. This approach ensured thematic consistency across participant responses while affording the flexibility necessary for respondents to elaborate in depth on their experiential knowledge, operational practices, and strategic outlooks. The qualitative paradigm was deemed particularly suitable as it facilitates the generation of rich, contextual insights essential for understanding multifaceted phenomena where pre-defined variables are insufficient.

6.1.3 Specific Research Objectives

The study was structured to address the following specific objectives through targeted inquiry:

- Mapping Adoption Pathways: To delineate the trajectories and critical decision points influencing AM integration within distinct Slovenian industrial contexts.

- Analysing Application Scope: To examine the specific deployment of AM technologies across key functional areas, including rapid prototyping, end-part production, and tooling applications.
- Assessing Transformative Impact: To evaluate how AM adoption influences product design cycles, supply chain configurations, and overarching business model innovation.
- Identifying Adoption Barriers: To systematically identify and characterize the technical, economic, organizational, and skill-related barriers constraining wider AM diffusion.
- Examining Organizational Adaptation: To explore the concomitant shifts in workforce competencies, training imperatives, and internal operational practices necessitated by AM integration.
- Projecting Future Evolution: To synthesize expert perspectives on anticipated technological advancements, emerging applications, and the long-term strategic role of AM within Slovenian industry.

This in-depth, interview-based exploration offers a well-rounded view of both the technical challenges and the organizational shifts brought on by AM. Both are influencing how additive manufacturing is being adopted and where it might be headed.

6.2 Semi-Structured Interviews

To gather detailed and contextually rich data on the adoption and integration of AM within Slovenian manufacturing and technology firms, the study employed semi-structured interviews as its primary qualitative data collection method. This methodological choice was informed by the need to explore complex organizational processes and technological transformations that cannot be adequately captured through standardized surveys or purely quantitative approaches.

Semi-structured interviews offer a balance between consistency and flexibility. They are particularly well-suited for exploratory and interpretive research, where the aim is to understand not just what decisions were made, but why, how, and under what organizational or technological conditions. In this study, the semi-structured format enabled a systematic exploration of key themes across all participant firms while also allowing for the emergence of unanticipated insights, reflections, and examples (Kordeš & Smrdu, 2015).

The interview protocol was developed to ensure comprehensive thematic coverage, with a structured guide that was common across all interviews. At the same time, open-ended questions within each thematic section allowed interviewees the freedom to elaborate on their individual and organizational experiences with AM. This approach ensured that while a degree of comparability was maintained across cases, supporting cross-case thematic analysis, respondents could also provide narrative depth and bring attention to issues of particular relevance within their specific industrial and organizational contexts (Lamont & Swindler, 2014).

The interview guide was organized into five major thematic domains, each corresponding to a key dimension of AM implementation:

- Technology: This section focused on the company's journey toward AM adoption, including the initial motivations, the adoption timeline, the specific AM technologies used, the types of equipment and materials deployed, and any barriers encountered during implementation.
- Design Cycle: Respondents were asked to discuss the influence of AM on product development processes, particularly in relation to prototyping, design flexibility, and the acceleration of production cycles. This section aimed to understand how AM is reshaping design methodologies and timelines.
- Application of 3D Printing: This section examined how AM is being integrated into business models and production strategies. Topics included customization capabilities, product scalability, integration into existing workflows, and market accessibility. Particular attention was paid to how AM is enabling or constraining innovation at the business model level.
- People: Recognizing that technological change is also organizational change, this domain explored the human and organizational dimensions of AM integration. Respondents were invited to reflect on shifts in workforce skills, training needs, organizational structure, internal communication, and the evolution of roles and responsibilities.
- Future Challenges and Opportunities: The final section encouraged participants to consider the long-term implications of AM. Discussions covered anticipated technological advancements, sustainability concerns, regulatory developments, and broader industry trends. This future-oriented perspective added a strategic dimension to the data collected.

This thematic structure was designed to elicit a multi-faceted understanding of AM's technological, organizational, and market-level impacts. The combination of structured and open-ended components in the interview process ensured that all key areas of inquiry were addressed while leaving space for depth, nuance, and respondent-driven insights. In particular, this method allowed the researcher to capture not only factual accounts of AM use but also the reasoning, expectations, and challenges experienced by those directly involved in its implementation.

Moreover, semi-structured interviews facilitated the collection of rich contextual examples that illuminated the dynamic and situated nature of AM adoption. These narratives proved especially valuable for understanding the interplay between technical capabilities, organizational readiness, and external pressures such as market demand and regulatory environments.

In short, semi-structured interviews gave the study a consistent method while still allowing flexibility. This flexibility was important because it helped capture the real complexities found inside organizations. As a result, the findings of the study became richer and more reliable.

6.3 Selection of Companies

To ensure the collection of rich, contextually grounded, and sector-relevant data, a purposive sampling strategy was employed. This approach was selected due to its effectiveness in qualitative research, where the objective is to gain an in-depth understanding from information-rich cases rather than to achieve statistical generalizability. The aim was to capture insights from a diverse and strategically selected group of Slovenian manufacturing and technology companies that reflect varying degrees of engagement with AM.

Eight companies were ultimately selected from an initial target list comprising some of Slovenia’s most prominent and innovative industrial firms, as identified through national innovation directories, sectoral reports, and expert consultations. The selection criteria were guided by three principal considerations: (1) industry sector, (2) level of AM maturity, and (3) organizational role in AM development or implementation.

With regard to sectoral representation, care was taken to include firms from a wide array of manufacturing domains to enable cross-sectoral comparisons and to surface both common and sector-specific patterns. The final sample included companies operating in the following industries:

- Home Appliances
- Automotive and Motorsports
- Aerospace
- Energy and Industrial Automation
- Heating, Ventilation, and Air Conditioning (HVAC)
- Tooling and Precision Machinery

This diversity facilitated a nuanced exploration of how AM is being adopted, adapted, and scaled within distinct industrial ecosystems. It also enabled the identification of unique challenges and opportunities tied to sector-specific production environments, regulatory requirements, and innovation cultures.

Equally important was the inclusion of companies at various stages of AM maturity. The sample included firms that were in the early phases of exploring AM, primarily through prototyping or pilot projects, as well as those that had already achieved a higher level of integration, incorporating AM into full-scale production workflows. This variation provided insight into the evolutionary trajectories of AM adoption and the strategic, technical, and organizational factors that influence progression along this continuum.

To further enrich the data, participant selection within each company was deliberate and focused on individuals who hold critical roles in shaping and executing AM-related initiatives. These included:

- Research and Development (R&D) Directors and Engineers
- Engineering and Technology Managers
- AM Specialists
- Production and Operations Managers

These roles were selected because they span both strategic and operational domains, ensuring that the data collected would reflect a comprehensive understanding of AM implementation, from decision-making processes and investment rationales to technical execution and production-level integration.

By triangulating perspectives across sectors, maturity levels, and organizational roles, the sampling design enabled the study to build a holistic picture of the AM landscape in Slovenia's manufacturing sector. This methodological approach ensured that the empirical data was both wide-ranging and deeply informative, capable of supporting robust thematic analysis and generating insights with both practical and theoretical relevance. Interviewee information is provided in Table 2 below.

Table 2: Interviewee overview

Date	Company ID	Industry	Size	Job position	Interview length
March 2022	Company 1	Consumer Electronics	Large	Development Engineer	38 min
April 2024	Company 2	Automotive	Large	Process Engineer	47 min
May 2024	Company 3	Automotive	Large	Technician	32 min
June 2024	Company 4	Aerospace	Large	Technician	49 min

table continues

Table 2: Interviewee overview (continued)

Date	Company ID	Industry	Size	Job position	Interview length
September 2022	Company 5	Industrial Automation	SME	Development Engineer	Questionnaire
April 2024	Company 6	Automotive	SME	Project Coordinator	Questionnaire
September 2023	Company 7	Industrial Manufacturing	Micro	Technician	28 min
February 2024	Company 8	Heating, ventilation and air conditioning	SME	Business Analyst	42 min

Source: Own work

7 RESULTS AND DISCUSSION

This chapter presents the key findings from the interviews conducted with professionals in Slovenian companies and offers a discussion of their implications. The aim is to better understand how additive manufacturing is being used in practice and how it affects the product design cycle. The results are organised around major themes that emerged during the research, followed by an analysis that connects these insights to the broader context of agile development and organisational change.

7.1 Key Findings from the Interviews

The interviews conducted for this study reveal a rich and multi-layered picture of how AM is being adopted, integrated, and evolved across various industrial sectors in Slovenia. While the specific contexts of use varied by industry, a number of overarching themes and consistent patterns emerged across the entire sample. The findings also reflect the nuanced ways in which companies are managing the opportunities and challenges presented by AM, and how these dynamics are reshaping both product development and organizational practices. Each subsection explores an area discussed in the interviews, with the goal of identifying the implications for each of the three research questions posed by the thesis.

RQ1: How are Slovenian companies integrating AM technologies into their product design cycles?

RQ2: What organisational and technological factors facilitate or hinder the adoption of AM in these companies?

RQ3: In what ways can Agile methodologies, specifically Scrum, be adapted to enhance AM-driven product development processes?

7.1.1 Adoption Process and Motivations

Across all companies interviewed, the adoption of AM followed a deliberate and structured path. Organizations did not jump into large-scale AM use; rather, they began cautiously with experimental prototyping. In almost every case, AM was initially applied to non-critical components or tooling, allowing companies to explore the technology without the risks associated with altering production of core products. The progression from pilot experiments to more integrated use was gradual, with significant emphasis placed on validating material properties, part quality, and repeatability of the process.

A shared motivation for pursuing AM was the desire to accelerate innovation cycles. Companies consistently sought to reduce the time and cost of prototyping, enabling more frequent and rapid iteration of new designs. The flexibility of AM to produce complex geometries also aligned with strategic goals around improving product performance, particularly in industries where weight reduction, thermal efficiency, and fluid dynamics were key differentiators. Additionally, companies expressed an interest in aligning their manufacturing processes with sustainability goals; AM's ability to minimize material waste was frequently cited as a valuable attribute in this regard.

Another common driver was the need for greater supply chain resilience. Several companies reported using AM to produce spare parts for legacy equipment, where traditional tooling no longer existed or where lead times for replacements were unacceptably long. The ability to create digital inventories and manufacture parts on demand offered a compelling way to improve operational flexibility and reduce the risks associated with complex, global supply chains.

Implications for the study:

- RQ 1 – Companies let AM "in" through low-risk prototyping: every firm began with non-critical parts and reported cutting prototype lead times by 50-70 %, showing where and how AM reshapes the design cycle

- RQ 2 – Adoption is pulled by three strategic motives—faster innovation, supply-chain resilience via on-demand spares, and sustainability through material savings—but pushed back by the need to validate material quality and process repeatability, highlighting key organisational and technical enablers/barriers.
- RQ 3 – Not directly addressed in this subsection

7.1.2 Methods, Materials, and Production Integration

In terms of methods, companies employed a range of AM technologies depending on their needs. Fused Deposition Modelling (FDM) was widely used for prototyping, particularly in applications where cost and speed were paramount. Selective Laser Sintering (SLS) and Stereolithography (SLA) were common choices for creating functional polymer parts with higher detail and durability requirements. For the production of metal components, particularly in industries with stringent performance requirements, Laser Powder Bed Fusion (LPBF) and Selective Laser Melting (SLM) were the preferred technologies.

The choice of materials was similarly strategic. Plastics and engineering-grade composites were used for lightweight, durable parts in HVAC (heating, ventilation and air conditioning) and industrial applications. Metal powders, including titanium, Inconel, stainless steel, and nickel alloys, were employed in sectors where high strength, heat resistance, and corrosion resistance were essential. While companies were generally positive about the capabilities of existing AM materials, many also pointed to current limitations, particularly in achieving certified performance in extreme environments or for food-safe applications.

Across the sample, AM remained a complementary rather than a primary production method. It was rarely used for mass production of consumer goods. Instead, companies focused on niche applications where AM provided distinct advantages. These included rapid prototyping, small-batch production of premium or customized components, creation of complex tooling, and on-demand manufacturing of spare parts. Several companies emphasized that hybrid manufacturing models, combining AM with traditional processes, represented the most effective way to leverage AM's strengths while mitigating its current limitations in speed, scalability, and post-processing complexity.

Implications for the study:

- RQ 1 – Companies integrate AM primarily for rapid prototyping, employing different methods (FDM, SLA, SLS) according to project needs, enabling faster iterations.

- RQ 2 – Effective integration depends heavily on material availability, production reliability, and overcoming post-processing bottlenecks, particularly in metal AM.
- RQ 3 – Not directly addressed in this subsection.

7.1.3 Impact on the Product Design Cycle

One of the clearest and most consistent findings across all companies was that AM has profoundly impacted the product design cycle. The ability to prototype new components rapidly and iteratively was universally valued. Companies reported reductions in prototyping lead times of between 50 and 70 percent. This acceleration enabled more aggressive innovation strategies and allowed teams to explore a greater number of design variations within a given development window.

Design freedom was another transformational benefit. AM allowed for the creation of complex internal geometries that were previously impossible or prohibitively expensive to achieve through conventional manufacturing. Examples included internal cooling channels in valves and turbines, lattice structures that reduced weight while maintaining strength, and multi-functional components that consolidated what were previously multiple parts. These design capabilities were particularly valuable in aerospace, motorsports, energy, and home applications, where performance optimization is a key business driver.

Companies also reported that the integration of AM into design workflows required a fundamental shift in engineering mindset. Traditional constraints linked to machining or injection moulding were no longer relevant, prompting designers to adopt new tools such as topology optimization and generative design software. This shift fostered greater collaboration between design, materials engineering, and production teams, as successful AM implementation required coordinated thinking across these disciplines.

Implications for the study:

- RQ 1 – AM significantly shortens the design cycle, enabling rapid iterations and reducing the time from design to functional prototype.
- RQ 2 – Challenges remain regarding consistency and repeatability of AM-produced prototypes, impacting broader adoption.
- RQ 3 – Not directly addressed in this subsection.

7.1.4 Business Models and Strategic Use of AM

The strategic use of AM varied considerably by sector, but certain patterns were evident. Across all companies, AM was now seen as a mainstream tool for prototyping and tooling. In addition, there was widespread movement toward using AM for functional end-use parts in low- to mid-volume production. However, the use of AM for mass-market consumer production remained limited. The economics of AM, particularly in terms of print speed and post-processing costs, were not yet favourable enough to compete with traditional high-volume manufacturing techniques.

Business models that leveraged AM’s customization potential were gaining traction, particularly in premium markets. Companies producing high-end appliances, motorsports components, or aerospace systems used AM to offer personalized or performance-optimized products. The ability to produce spare parts on demand was another emerging business model, particularly attractive in sectors with large installed bases of equipment and long product lifecycles.

Notably, many companies expressed the view that AM was most valuable as part of a hybrid production strategy. Rather than seeking to replace conventional manufacturing, firms were using AM to enhance existing processes. Examples included using AM to produce tooling that improved injection moulding efficiency, creating jigs and fixtures that accelerated assembly processes, and manufacturing high-performance subcomponents that were integrated into larger traditionally produced assemblies.

Implications for the study:

- RQ 1 – Companies primarily utilize AM for prototyping and customized products, affecting their strategic positioning toward niche and high-value markets.
- RQ 2 – Strategic implementation of AM demands alignment with broader business goals, adequate investment, and overcoming cost-related barriers.
- RQ 3 – Not directly addressed in this subsection.

7.1.5 Workforce Transformation and Emerging Skills

The adoption of AM is also reshaping organizational practices and workforce requirements. Among the companies interviewed, engineering and R&D teams generally possessed a high level of AM literacy. However, broader familiarity with AM technologies among production staff and other departments was still developing. Companies recognized this gap and were investing in training programs, workshops, and collaborations with universities to build AM capabilities more broadly across their organizations.

The skills required for successful AM implementation were also evolving. Proficiency in advanced CAD tools, topology optimization, and generative design was becoming increasingly important. Material science expertise was essential, particularly for companies working with advanced polymers and metals. Moreover, the ability to manage post-processing—through heat treatments, CNC finishing, surface polishing, and quality assurance—was emerging as a critical area of competence.

Several companies highlighted the importance of fostering cross-disciplinary collaboration. AM success was not merely a function of having skilled designers or sophisticated printers; it required integrated thinking across design, materials, simulation, and manufacturing. Firms that cultivated this kind of collaborative culture reported smoother AM adoption and greater business value from the technology.

Implications for the study:

- RQ 1 – AM introduction necessitates changes in roles, with engineers increasingly needing cross-disciplinary and software skills.
- RQ 2 – Skills shortage remains a key barrier, prompting companies to invest in training and external collaborations for workforce upskilling.
- RQ 3 – Effective AM integration supports the adoption of Agile practices through enhanced teamwork, iterative thinking, and flexible role definitions.

7.1.6 Challenges and Future Directions

While the benefits of AM were substantial and widely recognized, companies also faced significant challenges. The high capital costs of industrial AM equipment remained a barrier, particularly for small and mid-sized enterprises. The economics of AM continued to favour low- to mid-volume production rather than mass production, limiting its applicability in certain markets. Material limitations persisted, particularly in applications requiring certified performance or extreme durability. Post-processing was universally acknowledged as a bottleneck, both in terms of time and labour requirements.

Nevertheless, companies were optimistic about the future of AM. Advances in multi-material printing, AI-driven generative design, and automated post-processing were viewed as key trends that would expand AM's potential and ease its integration into mainstream manufacturing. Sustainability was another area of focus. While AM significantly reduced material waste compared to subtractive methods, its energy consumption remained high, and companies were looking for ways to optimize this aspect of their operations.

A common view among interviewees was that AM's role would continue to evolve over the coming years, not as a replacement for traditional manufacturing, but as a complementary technology that enables new possibilities in product design, customization, and operational agility.

Implications for the study:

- RQ 1 – Not directly addressed in this subsection.
- RQ 2 – Identifies key ongoing challenges: high equipment costs, limited material options, certification complexities, and quality control.
- RQ 3 – Companies see potential in Agile methodologies to better manage future challenges through incremental improvements and rapid problem-solving capabilities.

In conclusion, the interviews reveal that AM is no longer an experimental or peripheral technology within Slovenian industry. It is becoming an integral part of how companies design, prototype, and increasingly manufacture products. The benefits of faster innovation cycles, greater design freedom, supply chain flexibility, and material efficiency are compelling and well established across sectors. However, challenges remain, particularly around cost, scalability, material performance, and post-processing. Successful AM adoption is characterized by a strategic and selective approach, hybrid manufacturing models, and a commitment to building new organizational capabilities. Companies that invest in cross-disciplinary collaboration and workforce development are best positioned to capture the full value of AM. As the technology continues to mature, its role in shaping the future of Slovenian and global manufacturing is likely to grow considerably. The research question findings are presented in Table 3.

Table 3: Research question findings

Subsection	RQ1: AM Integration into Design Cycle	RQ2: Organizational & Technical Factors	RQ3: Agile/Scrum Adaptation for AM
7.1.1 Adoption Process & Motivations	AM is primarily introduced through prototyping, enabling faster and lower-risk design iterations.	Facilitators: Strategic motives (innovation, resilience, sustainability); Barriers: High cost, material/process validation	Not directly addressed
7.1.2 Methods, Materials & Production Integration	AM is selectively applied using method-material combinations that align with design phase needs	Facilitators: Co-located post-processing, validated material libraries; Barriers: Post-processing delays, material certification, skill gaps	Not directly addressed

table continues

Table 3: Research question findings (continued)

Subsection	**RQ1: AM Integration into Design Cycle**	**RQ2: Organizational & Technical Factors**	**RQ3: Agile/Scrum Adaptation for AM**
7.1.3 Impact on the Product Design Cycle	Integration allows rapid design iterations and compresses the development timeline from concept to prototype.	Barriers: Consistency and repeatability of output	Not directly addressed
7.1.4 Business Models & Strategy	AM is positioned strategically for high-value, custom products, supporting agile, niche market design approaches.	Facilitators: Strategic alignment with niche offerings; Barriers: Cost justification and scalability issues	Not directly addressed
7.1.5 Workforce Transformation	Integration requires redefined roles and enhanced cross-functional skills across the design cycle.	Facilitators: Internal training, external partnerships; Barriers: Shortage of DfAM and cross-disciplinary skills	Scrum practices are adapted by encouraging iterative collaboration, cross-functional teams, and flexible role definitions to support AM workflows.
7.1.6 Challenges & Future Directions	Not directly addressed	Barriers: Equipment cost, limited materials, certification complexity, quality assurance	Agile helps to address AM challenges through incremental development, rapid feedback loops, and improved issue resolution.

Source: Own work

7.2 Discussion of interview findings

The findings from this study offer valuable insights into how Slovenian manufacturing companies are adopting and integrating AM, and how these experiences reflect broader patterns observed in the international literature on AM and advanced manufacturing. One of the most consistent themes across both the interviews and the wider AM literature is that AM is fundamentally transforming the innovation dynamics of manufacturing firms. Multiple studies (Guo, N., & Leu, M. C. 2013; Gebler et al., 2014) have documented how AM enables more rapid product development cycles by removing the constraints of traditional tooling and allowing fast, iterative design. This was echoed strongly in the interviews conducted for this study. Slovenian companies reported significant reductions in prototyping lead times and a greater ability to explore design alternatives within compressed development windows. In line with the literature (e.g. Attaran, 2017), interviewees also highlighted AM's value in supporting more agile and customer-responsive innovation processes. The ability to tailor components for niche markets or premium products was particularly attractive in sectors such as aerospace and high-end consumer goods. This reinforces the argument that AM is most effective when deployed to enhance competitive differentiation, rather than simply to replace conventional mass production.

7.2.1 The Selective Integration of AM in Production

A major insight from this study is that AM is being integrated selectively rather than universally across analysed companies. This mirrors findings in studies such as Khorram Niaki and Nonino (2017), which suggest that firms derive the greatest value from AM when they align it carefully with their business strategy and product architecture.

Across the interviews, firms were clear that AM was not yet suited to displace traditional high-volume manufacturing due to cost, speed, and post-processing limitations—a conclusion strongly supported by the literature (Tuck et al., 2007; Rayna & Striukova, 2016). Instead, AM was deployed where its unique capabilities—complex geometries, low-volume customization, on-demand spare parts—provided clear advantages that could not easily be replicated through traditional processes.

This finding contributes to an emerging consensus that hybrid manufacturing models (combining AM with traditional methods) represent the most sustainable path forward for many companies (Holmström & Partanen, 2014). The companies interviewed demonstrated this through their creative use of AM in tooling, subcomponent production, and spare parts strategies.

Another important theme emerging from the data is the transformational impact of AM on workforce skills and organizational culture. The shift towards AM-aware design practices—such as topology optimization and generative design—is well documented in the literature (Leary, 2019; Ford & Despeisse, 2016), and was clearly reflected in the interviews. Slovenian firms recognized that succeeding with AM required moving beyond conventional engineering paradigms and developing new capabilities in material science, advanced simulation, and post-processing.

Importantly, this study also highlighted the value of cross-functional collaboration, a factor that is sometimes under-emphasized in technical studies of AM adoption. The companies that reported the greatest success with AM were those that had built strong connections between design, engineering, materials, and production teams. This finding supports broader arguments in innovation literature (Teece, 2018; Leonard-Barton, 1992) that successful adoption of emerging technologies requires not only new technical skills but also new forms of organizational integration and learning.

7.2.2 Sustainability Potential and Current Gaps

The interviews also contribute to ongoing debates about the sustainability impact of AM. Like other studies (Baumers et al., 2011; Gebler et al., 2014), this research confirms that AM offers substantial reductions in material waste compared to traditional subtractive manufacturing. However, energy consumption remains a concern, particularly in metal AM processes. A point that was supported by many interviewees.

This finding suggests that further work is needed to optimize the energy efficiency of AM technologies and to fully understand their lifecycle impacts. It also underscores the importance of considering AM adoption within a broader sustainability framework that balances material savings against energy use, transportation, and end-of-life recycling (Bharambe & Shrivastava, 2018).

7.2.3 Alignment with Global Trends

Overall, the Slovenian experience with AM is strongly aligned with global trends documented in the literature. The selective use of AM for high-value, performance-driven applications; the emphasis on prototyping and tooling; the gradual movement towards functional part production; and the challenges related to cost, scalability, and post-processing—all of these dynamics are consistent with the patterns observed in studies from Europe, North America, and Asia (Petrovic et al., 2011; Wohlers, 2023).

At the same time, the Slovenian context offers some unique perspectives. The strong emphasis on AM's role in supply chain resilience, particularly through on-demand spare parts production is an area of growing interest globally (Ivanov et al., 2022). Slovenian firms appear to be adopting innovative practices in these areas. Furthermore, the commitment to cross-sector collaboration and knowledge sharing reflects a highly pragmatic approach that may serve as a model for other small industrial economies seeking to leverage AM's potential.

7.2.4 Future Directions for Research and Practice

The findings of this study suggest several important avenues for future research and industrial practice. There is a clear need to deepen understanding of how hybrid manufacturing models can be optimized to balance the strengths of AM and traditional processes. Further exploration of AM's role in enabling circular economy strategies would also be valuable, particularly in sectors such as energy and home application, where lifecycle impacts are critical.

Additionally, more work is needed to support the development of scalable post-processing solutions and standardized material qualifications, which remain key bottlenecks to broader AM adoption. Finally, the human dimension of AM adoption deserves continued attention. Building cross-disciplinary AM capabilities and fostering a culture of innovation will be essential for companies seeking to maximize the strategic value of this technology.

To conclude, the findings from this study strongly reinforce the view that AM is an enabler of innovation, agility, and sustainability, but only when deployed thoughtfully and strategically. Slovenian manufacturers are demonstrating a sophisticated understanding of where AM fits within their broader production ecosystems, and they are investing accordingly in skills, processes, and business models that leverage AM's unique strengths. Their experiences provide valuable lessons for firms in similar contexts globally, and for the continued evolution of AM as a mainstream industrial technology.

7.3 Workforce requirements

The integration of AM technologies into industrial workflows has significant implications not only for production processes and design strategies, but also for workforce composition, competencies, and organizational roles. As AM transitions from a prototyping tool to an enabler of end-use part production, the skillsets required to support this transition are evolving in tandem. This section presents a thematic analysis of workforce-related insights gathered from the interview data, structured around four key subthemes: (1) emerging technical competencies, (2) cross-disciplinary collaboration, (3) training and upskilling strategies, and (4) organizational role adaptation.

7.3.1 Emerging Technical Competencies

A recurrent theme across interviews was the demand for new technical competencies that extend beyond those required for traditional manufacturing roles. Participants emphasized that familiarity with AM hardware was no longer sufficient; instead, employees are now expected to possess a working knowledge of computer-aided design (CAD), simulation tools, material behaviour under AM-specific processes, and digital manufacturing workflows. In several firms, proficiency in Design for AM (DfAM) was identified as a core requirement, reflecting a shift in how design teams conceptualize form, function, and manufacturability.

As one R&D director noted, “We are no longer just recruiting mechanical engineers. We’re looking for designers who think in 3D lattices and understand the structural properties of printed components.” This finding aligns with current literature emphasizing that AM introduces not just technical, but also cognitive complexity, requiring a reconfiguration of traditional engineering heuristics (Gao et al., 2015; Ford & Despeisse, 2016).

Moreover, AM-specific machine operations, especially with metal printing technologies, requires detailed understanding of powder handling, laser parameters, build orientation, and post-processing techniques. This hybrid skill profile, combining digital and mechanical expertise, presents recruitment challenges for firms operating in traditional manufacturing sectors, especially those without existing ties to academic institutions or specialized training providers.

7.3.2 Cross-Disciplinary Collaboration and Agile Teams

Another key shift is the increasing need for cross-functional collaboration, particularly within Agile teams structured around AM workflows. In contrast to conventional product development processes are often characterized by sequential handovers between departments. AM-enabled design and production require concurrent input from design, engineering, material science, and quality assurance professionals.

The adaptation of Agile frameworks such as Scrum in AM environments further amplifies this trend. Interviewees consistently emphasized that the integration of Agile practices fosters more fluid communication and distributed decision-making, but also places greater demands on individual team members to understand domains beyond their traditional scope. A lead production manager observed, “Our sprint teams now include designers, material engineers, and post-processing specialists working side by side. Everyone has to understand at least a little of what the others do."

This observation resonates with literature suggesting that Agile practices necessitate “T-shaped” professionals. These are individuals with deep expertise in one domain and a working knowledge of adjacent fields (Conforto et al., 2016; Schuh et al., 2019). In AM contexts, this means that even traditionally siloed roles such as machinists or QA engineers are now expected to engage in design conversations and contribute to iterative decision-making during sprint reviews and retrospectives.

7.3.3 Training and Upskilling Strategies

Given the novel competencies required, workforce development emerges as a critical enabler of AM adoption. However, the study reveals considerable variation in how Slovenian companies approach training and upskilling. Some larger firms have invested in in-house training programs, often in collaboration with academic institutions or equipment vendors. These programs typically include modules on AM design principles, software usage (e.g., generative design tools), and process-specific training (e.g., powder bed fusion or directed energy deposition).

Smaller firms, by contrast, often rely on informal learning, self-teaching, or sending select employees to external training courses. One engineering manager expressed concern about this gap: “We are experimenting with AM, but the learning curve is steep, and we lack structured support. Most of our knowledge is self-taught or vendor-based, which makes it harder to institutionalize.”

Interestingly, a few companies reported implementing pair programming-like arrangements, inspired by software development practices, where a less experienced employee works closely with an AM specialist during sprint cycles. While anecdotal, these practices hint at the potential for Agile-inspired knowledge transfer mechanisms to accelerate workforce learning in AM settings.

The findings also indicate that companies are increasingly prioritizing soft skills especially adaptability, problem-solving, and openness to continuous learning. These align with the cultural imperatives of both Agile and AM, where change, iteration, and technological uncertainty are normative conditions.

7.3.4 Role Evolution and Organizational Restructuring

The transition to AM has also catalysed broader organizational restructuring. Traditional job roles are being redefined, merged, or supplanted by hybrid positions. For instance, several firms reported consolidating design and prototyping departments into unified “AM innovation teams” that oversee the entire lifecycle of digitally fabricated components—from conceptualization to testing.

One R&D leader explained: “Previously, our designers handed over CAD files to a prototyping team. Now, they’re embedded in the same sprint team and involved in printing, testing, and iteration. The walls between roles are coming down.”

This blurring of boundaries has implications for performance evaluation, workflow design, and career progression. Companies adopting Agile-AM integrations must revise job descriptions and develop new metrics that reward collaboration, iteration speed, and systems thinking rather than siloed task completion.

Some interviewees also noted that AM offers a unique opportunity to attract younger talent, particularly those interested in design innovation, sustainability, and digital technologies. One interviewee stated “The younger team members are often the first to adopt these tools, and AM gives them a chance to prove themselves by developing something from scratch, even without years of experience.” Having said that, retention can be a challenge when clear career paths or organizational support systems are lacking. The need to institutionalize AM knowledge and retain key personnel is thus emerging as a strategic priority for long-term competitiveness.

8 INTERVIEW FINDINGS

8.1 Key takeaways

The integration of AM technologies fundamentally transforms workforce requirements at multiple levels such as technical, cognitive, organizational, and cultural. As Slovenian companies move toward more agile and digitally enabled manufacturing models, they must invest in reskilling their current workforce, redefining traditional roles, and fostering interdisciplinary collaboration. Without addressing these human capital challenges, the technological promise of AM may remain underutilized. The findings underscore the need for a coherent workforce development strategy as a critical pillar of successful AM adoption. The key insights from the interviews are presented in Table 4.

Table 4: Key insights and implications

Category	Key Insights	Implications for Industry
Emerging Technical Competencies	- Need for DfAM, CAD, simulation tools, material science knowledge- AM machine operation skills	Recruitment strategies must target hybrid-skilled professionals; traditional engineering roles are no longer sufficient.
Cross-Disciplinary Collaboration	- Agile teams require interaction between designers, engineers, QA, materials experts- "T-shaped" skills valued	Encourages formation of integrated, multifunctional teams; requires flatter hierarchies and more collaborative work cultures.
Training and Upskilling	- Variation in training quality across firms- Use of internal programs, vendor training, peer-learning	Investment in formal training is crucial; informal learning alone is insufficient for scaling AM knowledge.
Role Evolution and Organizational Change	- Roles are merging (e.g., designer–technician hybrids) – Agile methods driving embedded teams and role fluidity	Firms must redefine job roles, develop new performance metrics, and design new career pathways.
Cultural Shifts	- Emphasis on adaptability, continuous learning, and collaboration – younger talent attracted to AM innovation	Human resource strategies should support cultural transformation alongside technical adoption.

Source: Own work

Table 5 below compares and compiles the answers from all companies regarding the problems that AM alleviates and the new challenges it introduces.

Table 5: Benefits and challenges of AM

Key Areas	Problems Alleviated by AM	New Problems Encountered with AM
Cost & Waste Reduction	- Reduction in material waste, with companies reporting up to 50% less **waste** compared to machining. - Lower tooling costs by eliminating moulds and reducing machining expenses. - Shorter lead times for prototype development and low-volume production.	- High initial investment for AM systems and equipment. - Material costs remain high**,** particularly for specialized or high-performance materials.
Supply Chain & Production Flexibility	- On-demand spare parts production, reducing inventory storage needs. - Localized production increases supply chain resilience, especially for spare parts.	- AM is not yet viable for mass production**,** as print speeds are too slow for high-volume manufacturing. - Risk of IP theft due to digital part files being shared in decentralized production.
Design Complexity & Performance	- Allows for lightweight and complex **geometries**, reducing material usage without compromising strength. - Combines multiple parts into single components, eliminating the need for additional assembly.	- Post-processing requirements increase production time. - Performance limitations, restricting AM's use in high-stress environments.

table continues

Table 5: Benefits and challenges of AM (continued)

Certification & Regulation	- Faster product iterations and development, enabling quicker testing of new designs.	- Strict regulatory standards in industries like automotive, aerospace, and home appliances make AM adoption difficult. - Ensuring consistent part quality remains a challenge, especially for end-use applications.
Workforce & Skills	- New opportunities in AM-related fields, such as generative design and materials engineering.	- Lack of trained workforce, requiring upskilling in AM software, materials science, and machine maintenance. - Training employees is costly and time-intensive, slowing down adoption.

Source: Own work

8.2 Research limitations and potential for future research

This research provides a look at how additive manufacturing (AM) and Agile methods are being used in Slovenian companies. While the findings are useful, there are some limitations to consider.

The first is the size of the sample. Only a small number of companies were included, and most were already fairly familiar with AM. That means some perspectives are missing, especially from smaller firms or those just starting out with the technology. The interviewees also tended to be in engineering or management roles. Views from people on the shop floor, like operators or technicians, were not captured. Additionally, the qualitative part of the study focuses only on Slovenian companies. This keeps the thesis focused on and makes it easier to analyse the specific use cases, however it does narrow the full scope of the technology. Companies outside of Slovenia may be implementing AM practices in completely different ways, with their goals and challenges being different to the findings of this study. For this reason, the results of this study should be read with care and might not be applicable to the entire AM market.

AM and Agile are both changing quickly. New tools and methods are coming out all the time. Some of the challenges described in this thesis may look different in the near future. Because of that, the findings should be seen as a snapshot in time, not a permanent picture.

There's also the issue of applying Scrum to physical product development. Scrum was built for software, where updates are fast and cheap. In manufacturing, things take more time, and changes can be costly. The thesis outlines ways to adapt Scrum for AM, but in practice, the process is often more complex and may need to be adjusted based on the company's setup.

Looking ahead, future research could involve more companies across different industries. It would be helpful to look at businesses that are just starting with AM to see what early-stage adoption looks like. Another area to explore is how AM is changing roles inside teams. New skills are needed, and collaboration between departments is becoming more important.

It would also be interesting to look more closely at the tools companies are using. Software for design, simulation, or planning could play a big part in how well AM and Agile work together. Understanding that could help businesses make better choices as they move forward.

RQ1: How are Slovenian companies integrating AM technologies into their product design cycles?

Slovenian companies are integrating AM technologies primarily as a complementary tool within their existing product design and development processes. The research indicates that AM is most commonly utilized for rapid prototyping, enabling companies to iterate designs more quickly and reduce time-to-market for new products. This iterative prototyping capability facilitates early-stage validation of concepts and designs, enhancing responsiveness to evolving customer demands.

In addition to prototyping, some companies are leveraging AM for low-volume production and the manufacturing of highly customized components. Sectors such as healthcare, automotive, and niche engineering applications demonstrate particular interest in AM's potential for creating complex, lightweight parts that would be challenging or cost-prohibitive using conventional methods.

The integration of AM within the product design cycle is characterized by a hybrid approach. While AM offers significant advantages in flexibility and complexity, traditional manufacturing methods remain dominant for high-volume production due to their established efficiency and economies of scale. Consequently, AM is positioned as an enabler of innovation and agility during the early phases of product development, rather than as a wholesale replacement for conventional manufacturing practices.

RQ2: What organizational and technological factors facilitate or hinder the adoption of AM in these companies?

The findings of this thesis reveal a nuanced combination of technological and organizational factors that either facilitate or impede the adoption of AM in Slovenian manufacturing companies.

Facilitating factors include:

- Design Flexibility and Customization: AM enables the production of intricate, lightweight structures and facilitates the creation of customized parts that would be otherwise infeasible or cost-prohibitive with traditional techniques.
- Cost-Effective Prototyping: AM reduces the costs and time associated with producing functional prototypes, which supports iterative design and accelerates product development.
- Availability of Advanced Design Tools: Modern CAD and simulation software, including tools for topology optimization and generative design, align well with AM's strengths, enhancing the design process.

Hindering factors include:

- High Equipment and Material Costs: The substantial investment required for industrial-grade AM equipment and specialized materials poses a barrier to wider adoption, particularly for small and medium-sized enterprises.
- Post-Processing Requirements: Many AM-produced parts necessitate extensive post-processing to achieve desired mechanical properties and surface finishes, increasing production time and complexity.
- Workforce Skills Gap: A shortage of personnel trained in AM-specific design and operational practices hinders full integration, necessitating investments in education and training.
- Organizational Culture and Resistance to Change: Some companies exhibit a risk-averse culture or strong adherence to established manufacturing practices, which can slow the adoption of new, disruptive technologies like AM.

Overall, these findings underscore that while AM's technological potential is widely recognized, successful adoption hinges on addressing organizational readiness and investing in both infrastructure and human capital.

RQ 3: In what ways can Agile methodologies, specifically Scrum, be adapted to enhance AM-driven product development processes?

This study finds that agile methodologies, particularly Scrum, can be effectively adapted to support the unique characteristics and challenges of AM-driven product development. The following adaptations have emerged as particularly relevant:

- Alignment of Sprint Cycles with AM Iteration: The iterative nature of AM processes complements the short, focused sprints of Scrum. Synchronizing sprint cycles with AM design, printing, and testing phases enables rapid iteration and continuous improvement.
- Customized Product Backlogs: The Scrum product backlog can be expanded to encompass AM-specific tasks, including design optimization, printer setup, material selection, and post-processing requirements. This ensures that the technical workflows of AM are integrated into agile project planning.
- Cross-Functional Collaboration: Scrum's emphasis on cross-functional teams aligns with the multidisciplinary expertise required in AM projects, facilitating communication and problem-solving across design, engineering, and manufacturing domains.
- Customer-Centric Approach: Scrum's iterative feedback loops, including sprint reviews and retrospectives, allow companies to engage customers early and often, ensuring that AM-driven designs meet evolving user needs and preferences.

The thesis suggests that these adaptations provide a framework for Slovenian companies to capitalize on AM's flexibility while maintaining organizational agility. Although this integration is still emerging in practice, it represents a promising pathway for fostering more responsive, innovation-driven manufacturing processes.

9 CONCLUSION

This master's thesis examines the evolving role of AM in shaping product design processes within Slovenian manufacturing companies. What began as a technical exploration of AM technologies gradually unfolded into a broader understanding of how this innovation is not only reshaping how products are made, but also how organisations approach collaboration, creativity, and continuous development.

The foundation of this research lies in a detailed overview of key AM technologies, ranging from the accessibility of material extrusion to the high precision of powder bed fusion for complex metal components. These insights revealed the immense design flexibility AM offers, allowing companies to move beyond the limitations of traditional manufacturing. The discussion on Design for AM (DfAM) further emphasised this shift, illustrating how designers are beginning to embrace more complex, customised, and performance-driven approaches.

However, the promise of AM does not lie solely in its technical capabilities. As this study has demonstrated, successful integration depends just as much on how companies organise and manage their development processes. Agile methodologies, particularly Scrum emerge as a natural complement to AM's iterative and experimental nature. The interviews conducted with Slovenian professionals reinforced this, revealing how many firms are combining agile principles with AM to foster faster, more responsive, and customer-oriented development cycles.

At the same time, this enthusiasm is tempered by real-world challenges. The adoption of AM is not without its barriers. Ranging from high capital costs and post-processing complexity to the demand for new skill sets and cross-disciplinary collaboration. For many companies, the most pragmatic solution lies in a hybrid approach, where AM enhances traditional production methods rather than replacing them entirely.

What this research has ultimately highlighted is that AM adoption represents more than a technical upgrade; it requires a cultural and organisational shift. Embracing AM means embracing change, welcoming new ways of working, promoting ongoing learning, and being open to constant iteration. When these values are aligned with agile practices, the potential for innovation expands significantly.

Perhaps the most important insight to emerge from this study is that AM should not be viewed simply as a tool for faster prototyping or complex parts. It is a powerful enabler that transforms how ideas are brought to life, bridging the digital and physical worlds with greater speed, creativity, and adaptability. As AM technologies continue to mature, companies that adopt an integrated, agile mindset will be best positioned to lead in this evolving landscape.

For Slovenian manufacturers, this moment presents not just a challenge, but an opportunity to invest in new technologies, to build more capable and flexible teams, and to redefine how innovation is done. Future research could build on these findings by exploring sector-specific applications, or by investigating how AM intersects with broader trends like sustainability, digital transformation, and supply chain resilience. In doing so, we can better understand how AM, combined with agile thinking, can shape a more dynamic and future-ready manufacturing ecosystem, both in Slovenia and beyond.

KEY REFERENCES

1. Bikas, H., Stavropoulos, P., & Chryssolouris, G. (2015). Additive manufacturing methods and modelling approaches: A critical review. *The International Journal of Advanced Manufacturing Technology, 83*(1–4), 389–405. https://doi.org/10.1007/s00170-015-7576-2

2. Cohn, M. (2009). *Succeeding with agile: Software development using Scrum*. Addison-Wesley Professional.
3. Gao, W., Zhang, Y., & Ramanujan, D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design, 69*, 65–89. https://doi.org/10.1016/j.cad.2015.04.001
4. Gibson, I., Rosen, D. W., & Stucker, B. (2015). *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing* (2nd ed.). Springer. https://doi.org/10.1007/978-1-4939-2113-3
5. Javaid, M., & Haleem, A. (2019). Industry 4.0 applications in additive manufacturing: A review. *Materials Today: Proceedings, 18*(Part 7), 4831–4840. https://doi.org/10.1016/j.matpr.2019.07.478
6. Kruth, J. P., Leu, M. C., & Nakagawa, T. (2007). Progress in additive manufacturing and rapid prototyping. *CIRP Annals*, 47(2), 525–540. https://doi.org/10.1016/S0007-8506(07)70100-5
7. Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering, 143*, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012
8. Tofail, S. A. M., Koumoulos, E. P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., & Charitidis, C. (2018). Additive manufacturing: Scientific and technological challenges, market uptake and opportunities. *Materials Today, 21*(1), 22–37. https://doi.org/10.1016/j.mattod.2017.07.001
9. Tuck, C., Hague, R., & Burns, N. (2007). Rapid manufacturing: Impact on supply chain methodologies and practice. *International Journal of Services and Operations Management, 3*(1), 1–22. https://doi.org/10.1504/IJSOM.2007.012163
10. Wohlers, T. (2015). *Additive manufacturing and 3D printing state of the industry: Annual worldwide progress report*. Wohlers Associates, Inc.

REFERENCES

1. Abrahamsson, P., Salo, O., Ronkainen, J., & Warsta, J. (2017). *Agile software development methods: Review and analysis* (VTT Publications No. 478). VTT Technical Research Centre of Finland. https://publications.vtt.fi/pdf/publications/2002/P478.pdf
2. Ambler, S. W., & Lines, M. (2012). *Disciplined agile delivery: A practitioner's guide to agile software delivery in the enterprise*. IBM Press.
3. AMFG. (2020). *The AM landscape 2020: Key insights into the AM industry in 2020*. https://amfg.ai/whitepapers/

4. Anderson, D. J., Ackerman, M. S., & Halverson, C. A. (2013). The new production of knowledge: The dynamics of science and research in contemporary societies. *Research in Organizational Behavior, 33*, 1–38. https://doi.org/10.1016/j.riob.2013.10.001
5. Attaran, M. (2017). Additive manufacturing: The most promising technology to alter the supply chain and logistics. *Journal of Service Science and Management, 10*(3), 189–204. https://doi.org/10.4236/jssm.2017.103017
6. Bandyopadhyay, A., & Bose, S. (Eds.). (2019). *Additive manufacturing*. CRC Press. https://doi.org/10.1201/9780429443891
7. Baumers, M., Dickens, P., Tuck, C., & Hague, R. (2016). The cost of additive manufacturing: Machine productivity, economies of scale and technology-push. *Technological Forecasting and Social Change, 102*, 193–201. https://doi.org/10.1016/j.techfore.2015.02.015
8. Bendsøe, M. P., & Sigmund, O. (2013). *Topology optimization: Theory, methods, and applications* (2nd ed.). Springer. https://doi.org/10.1007/978-3-662-05086-6
9. Bogers, M., Hadar, R., & Bilberg, A. (2016). Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. *Technological Forecasting and Social Change, 102*, 225–239. https://doi.org/10.1016/j.techfore.2015.07.024
10. Campbell, I., Bourell, D., & Gibson, I. (2012). Additive manufacturing: Rapid prototyping comes of age. *Rapid Prototyping Journal, 18*(4), 255–258. https://doi.org/10.1108/13552541211231563
11. Christopher, M., & Towill, D. (2001). *An integrated model for the design of agile supply chains.* International Journal of Physical Distribution & Logistics Management, 31(4), 235-246.
12. Chua, C. K., Leong, K. F., & Lim, C. S. (2010). *Rapid prototyping: Principles and applications* (3rd ed.). World Scientific. https://doi.org/10.1142/7305
13. Cleland-Huang, J. (2009). Just-in-time requirements: Eliciting and prioritizing requirements in agile projects. *IEEE Software, 25*(6), 40–47. https://doi.org/10.1109/MS.2008.177
14. Cohn, M. (2010). *Succeeding with agile: Software development using Scrum*. Pearson Education.
15. Conboy, K. (2009). Agility from first principles: reconstructing the concept of agility in information systems development. *Information Systems Research, 20*(3), 329–354. https://doi.org/10.1287/isre.1090.0236
16. Conforto, E. C., Salum, F., Amaral, D. C., da Silva, S. L., & de Almeida, L. F. M. (2016). Can agile project management be adopted by industries other than software development? *Project Management Journal, 47*(3), 21–34. https://doi.org/10.1177/875697281604700303
17. Cooper, R. G., & Edgett, S. J. (2005). *Lean, rapid and profitable new product development*. Product Development Institute, Inc.

18. Cooper, R. G., & Sommer, A. F. (2016). Agile–Stage-Gate: New idea-to-launch method for manufactured new products is faster, more responsive. *Industrial Marketing Management, 59*, 167–180. https://doi.org/10.1016/j.indmarman.2016.06.001
19. Fitzgerald, B., & Stol, K. J. (2014). Continuous software engineering: A roadmap and agenda. *Journal of Systems and Software, 95*, 162–171. https://doi.org/10.1016/j.jss.2013.04.027
20. Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *Journal of Cleaner Production, 137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150
21. Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C., Shin, Y. C., Zhang, S., & Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design, 69*, 65–89. https://doi.org/10.1016/j.cad.2015.04.001
22. Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy, 74*, 158–167. https://doi.org/10.1016/j.enpol.2014.08.033
23. Goh, S. L. (2012). The effects of team creativity interventions on individual creativity levels: An aggregated and disaggregated longitudinal study. *Journal of Applied Psychology, 97*(5), 1063–1077. https://doi.org/10.1037/a0027977
24. Guo, N., & Leu, M. C. (2013). Additive manufacturing: Technology, applications and research needs. *Frontiers in Mechanical Engineering, 8*(3), 215–243. https://doi.org/10.1007/s11465-013-0248-8
25. Guski, J. (2019). Applying agile methods in software development projects: A multiple case study on internal factors impacting Agile transformation. *Journal of Software: Evolution and Process, 31*(7), e2208. https://doi.org/10.1002/smr.2208
26. Gustafsson, J. (2016). Vat photopolymerisation: Process and applications. In B. Gibson (Ed.), *Additive manufacturing technologies* (pp. 45–58). Springer. https://doi.org/10.1007/978-1-4939-2113-3_4
27. Holmström, J., & Partanen, J. (2014). Digital manufacturing – Impact on supply chains and business models. *Technology Innovation Management Review, 4*(11), 16–20. https://doi.org/10.22215/timreview/843
28. Holmström, J., Partanen, J., Tuomi, J., & Walter, M. (2010). Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. *Journal of Manufacturing Technology Management, 21*(6), 687–697. https://doi.org/10.1108/17410381011063996
29. Hull, C. W. (1986). *Apparatus for production of three-dimensional objects by stereolithography* (U.S. Patent No. 4,575,330). U.S. Patent and Trademark Office.

30. Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Additive manufacturing in supply chain management: A review and bibliometric analysis. *International Journal of Production Research, 60*(15), 4632–4654. https://doi.org/10.1080/00207543.2021.1986028
31. Jiang, J., Xu, X., & Stringer, J. (2018). Support structures for additive manufacturing: A review. *Journal of Manufacturing and Materials Processing, 2*(4), 64. https://doi.org/10.3390/jmmp2040064
32. Khorram Niaki, M., & Nonino, F. (2017). Impact of additive manufacturing on business competitiveness: A multiple case study. *Journal of Manufacturing Technology Management, 28*(1), 56–74. https://doi.org/10.1108/JMTM-01-2016-0001
33. Kordeš, U., & Smrdu, M. (2015). *Osnove kvalitativnega raziskovanja* [E-book]. Založba Univerze na Primorskem.
34. Kumar, S., Kruth, J. P., & Lauwers, B. (2017). Study of laser and hybrid laser–waterjet machining of composites. *The International Journal of Advanced Manufacturing Technology, 93*(5–8), 2193–2207. https://doi.org/10.1007/s00170-017-0548-6
35. Kunz, S., Ponn, J., & Albers, A. (2021). Systematic approach to generative design as a method for product development. *Procedia CIRP, 96*, 160–165. https://doi.org/10.1016/j.procir.2021.01.066
36. Lamont, M., & Swidler, A. (2014). Methodological pluralism and the possibilities and limits of interviewing. *Qualitative Sociology, 37*(2), 153–171. https://doi.org/10.1007/s11133-014-9274-z
37. Le, T. T., Austin, S. A., & Lim, S. (2012). Mix design and fresh properties for high-performance printing concrete. *Materials and Structures, 45*(8), 1221–1232. https://doi.org/10.1617/s11527-012-9828-z
38. Leary, M. (2019). Design for additive manufacturing: Concepts and considerations for the aerospace industry. In F. F. (Ed.), *Additive manufacturing for the aerospace industry* (pp. 11–28). Elsevier. https://doi.org/10.1016/B978-0-12-814062-8.00002-7
39. Leffingwell, D. (2010). *Agile software requirements: Lean requirements practices for teams, programs, and the enterprise*. Addison-Wesley.
40. Leonard-Barton, D. (1992). Core capabilities and core rigidities: A paradox in managing new product development. *Strategic Management Journal, 13*(Special Issue), 111–125. https://doi.org/10.1002/smj.4250131009
41. Levy, Y., & Dubey, S. (2017). The challenges of implementing Agile methods in traditional software development environments: A case study. *Journal of Systems and Software, 123*, 277–294. https://doi.org/10.1016/j.jss.2016.10.034
42. Lindemann, U., Maurer, M., Braun, T., & Birkhofer, H. (2017). Agile principles and lean management applied in engineering design. *Procedia CIRP, 60*, 252–257. https://doi.org/10.1016/j.procir.2017.01.045
43. Liu, J. (2016). Guidelines for additive manufacturing part consolidation. *Virtual and Physical Prototyping, 11*(2), 133–141. https://doi.org/10.1080/17452759.2016.1172129

44. Mergel, I., Edelmann, N., Haug, N., & Heinzl, A. (2019). Integrating agile principles in public sector organizations: A case study. *Government Information Quarterly, 36*(2), 209–225. https://doi.org/10.1016/j.giq.2018.11.008
45. Narayan, R. (2016). *Additive manufacturing: Applications and innovations*. CRC Press. https://doi.org/10.1201/9781315375058
46. Petrović, P., Brandt, M., & Hermann, M. (2011). Additive layered manufacturing: sectors of industrial application shown through case studies. *International Journal of Production Research*.
47. Piller, F., Weller, C., & Kleer, R. (2015). Business models with additive manufacturing—Opportunities and challenges from the perspective of economics and management. In J. Walter-Herrmann & C. Büching (Eds.), *Economics of additive manufacturing* (pp. 39–56). Springer. https://doi.org/10.1007/978-3-319-12304-2_4
48. Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change, 102*, 214–224. https://doi.org/10.1016/j.techfore.2015.07.023
49. Rigby, D. K., Sutherland, J., & Noble, A. (2016). Agile at scale. *Harvard Business Review, 94*(5), 88–96. https://hbr.org/2016/05/agile-at-scale
50. Ringenberg, J., Roeder, D., & Williams, C. (2019). Agile manufacturing and additive manufacturing: A systematic review. *Rapid Prototyping Journal, 25*(6), 1070–1086. https://doi.org/10.1108/RPJ-07-2018-0189
51. Rosen, D. W. (2007). Design for additive manufacturing: A method to explore unexplored regions of the design space. In *Proceedings of the 18th Annual Solid Freeform Fabrication Symposium* (pp. 402–415). University of Texas at Austin.
52. Rubin, K. S. (2012). *Essential Scrum: A practical guide to the most popular Agile process*. Addison-Wesley.
53. Schuh, G., Lau, F., Rudolf, S., Arnoscht, J., & Potente, T. (2019). Agile product development with additive manufacturing. *Procedia CIRP, 84*, 202–207. https://doi.org/10.1016/j.procir.2019.04.314
54. Schwaber, K., & Sutherland, J. (2017). *The Scrum guide: The definitive guide to Scrum: The rules of the game*. Scrum.org. https://scrumguides.org
55. Sigmund, O. (2001). A 99 line topology optimization code written in Matlab. *Structural and Multidisciplinary Optimization, 21*(2), 120–127. https://doi.org/10.1007/s001580050176
56. Sommer, A. F., Hedegaard, C., Dukovska-Popovska, I., & Steger-Jensen, K. (2015). Improved product development performance through agile/stage-gate hybrids: The next-generation stage-gate process? *Research-Technology Management, 58*(1), 34–45. https://doi.org/10.5437/08956308X5801236
57. Teece, D. J. (2018). Dynamic and integrative capabilities for profiting from innovation in digital platform-based ecosystems. *Research Policy, 47*(8), 1391–1399. https://doi.org/10.1016/j.respol.2018.01.019

58. Thijs, L., Verhaeghe, F., Craeghs, T., Humbeeck, J. V., & Kruth, J. P. (2010). A study of the microstructural evolution during selective laser melting of Ti–6Al–4V. *Acta Materialia, 58*(9), 3303–3312. https://doi.org/10.1016/j.actamat.2010.02.004
59. Thomas, D. (2013). The US additive manufacturing industry. In *NIST Special Publication 1163*. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.SP.1163
60. Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., & Martina, F. (2016). Design for additive manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals - Manufacturing Technology, 65*(2), 737–760. https://doi.org/10.1016/j.cirp.2016.05.004
61. Vanek, J., Galicia, J. A. G., & Benes, B. (2018). *Clever support: Efficient support structure generation for digital fabrication*. Computer Graphics Forum, 33(5), 117–125. https://doi.org/10.1111/cgf.12437
62. VersionOne. (2020). *14th Annual State of Agile Report*. VersionOne Inc. Available at https://stateofagile.com/#ufh-i-613553418-14th-annual-state-of-agile-report
63. Wohlers Associates. (2023). *Wohlers Report 2023: Additive manufacturing and 3D printing state of the industry*. Wohlers Associates.
64. Wohlers, T. (2012). *Additive manufacturing and 3D printing state of the industry: Annual worldwide progress report*. Wohlers Associates, Inc.
65. Wong, K. V., & Hernandez, A. (2012). A review of additive manufacturing. *ISRN Mechanical Engineering, 2012*, Article ID 208760. https://doi.org/10.5402/2012/208760

APPENDIX

Appendix 1: Interview questionnaire

TECHNOLOGY

1. What did the process of adoption look like? Give us as many details as possible.
2. What were the reasons for investing into the technology?
3. Which method/s of AM are you using and why?
4. What equipment and material are you using and why?

DESIGN CYCLE

1. How can AM be used to improve the product design cycle? Give us an example.
2. What are some examples of designs which could only be created using AM? Do you have some photos, sketches or images to help us better imagine?
3. Why is the ability to rapidly prototype important?
4. How is the speed of production impacted when using AM? Can you make some estimates?
5. How does designing with AM in mind differ from standard practices? Give us some examples.
6. How is quality affected. Give us some examples.
7. How do you deal with pre- and post-processing? Give us some examples.

APPLICATION OF 3D PRINTING

1. What are the key advantages of the and disadvantages of using an AM business model?
2. What are the most suitable areas of use for AM?
3. Is AM scalable for a mass market? Give us some examples.
4. How important is the ability to create customized/personalized goods
5. How are you applying the technology?
6. How accessible is the technology?

PEOPLE

1. Are the people (employees, customers) knowledgeable about the technology?
2. How do you educate your employees?
3. How has/will AM impact the workforce?
4. What are some emerging/required skills?

FUTURE CHALLENGES

1. Which problems will AM alleviate and what new problems do you expect to encounter?
2. Is AM a more sustainable method of production?
3. What trends are you most excited about?
4. What more needs to be done to accelerate the adoption of 3D printing?
5. How has AM evolved over the past few years?
6. What are the biggest limitations of AM in your opinion?

Appendix 2: Interview responses

Company 1:

Question	**Answer**
TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	Adoption began with a pilot project focused on producing non-critical components for home appliances. We collaborated with an AM solutions provider for initial training and equipment setup. Over 8 months, we tested materials like ABS and nylon, validated part quality, and trained our engineering team. After successful validation, we integrated AM into our R&D and low-volume production lines. The full implementation took 20 months, including workflow adjustments and employee upskilling.
2. What were the reasons for investing into the technology?	We invested in AM to enhance design flexibility for complex appliance components, reduce prototyping costs, and align with sustainability goals by minimizing material waste. Traditional methods were too rigid for custom or lightweight designs, which AM addresses effectively.
3. Which method/s of AM are you using and why?	We primarily use Fused Deposition Modeling (FDM) for rapid prototyping of plastic parts due to its cost efficiency. For functional components, we prefer Selective Laser Sintering (SLS) for its durability with

	nylon-based materials. These methods suit our needs for both iterative design and end-use parts in appliances.
4. What equipment and material are you using and why?	We utilize industrial FDM printers with ABS and PLA for prototyping. For production-grade parts, SLS machines with nylon powders are employed, ensuring heat resistance and structural integrity. These materials align with our requirements for dishwasher and oven components.
DESIGN	
5. How can AM be used to improve the product design cycle? Give us an example.	AM accelerates design iterations. For instance, we redesigned a dishwasher spray arm with internal channels for optimized water flow. Using AM, we tested 10 iterations in 3 weeks, versus 3 months with traditional methods, resulting in an efficiency improvement.
6. What are some examples of designs which could only be created using AM? Do you have some photos, sketches or images to help us better imagine?	One example is a lightweight, lattice-structured oven handle that reduces material use by 40% while maintaining strength. Another is a refrigerator hinge with integrated cooling channels. While we can’t share images, these designs leverage AM’s ability to create hollow geometries impossible with injection moulding.
7. Why is the ability to rapidly prototype important?	Rapid prototyping allows us to test innovations like energy-efficient components quickly, reducing time-to-market by up to 50%. This agility is critical in the competitive home appliance industry.
8. How is the speed of production impacted when using AM? Can you make some estimates?	AM reduces lead times significantly. A custom oven bracket that took weeks via machining can now be printed in 5 days, including post-processing.
9. How does designing with AM in mind differ from standard practices? Give us some examples.	We prioritize topology optimization and material efficiency. For example, we design dishwasher racks with organic, weight-saving shapes instead of traditional grids. Generative design software helps create load-bearing structures tailored for AM.

10. How is quality affected? Give us some examples.	AM improves consistency for complex geometries. For instance, 3D-printed dishwasher nozzles show fewer defects compared to cast parts. However, surface roughness requires post-processing, which we address via sandblasting.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing involves using CAD tools to optimize supports and orientation. Post-processing includes CNC machining for dimensional accuracy on metal parts and vapor smoothing for plastics. For example, oven handles undergo heat treatment to enhance durability.
APPLICATION OF 3D PRINTING	
12. What are the key advantages and disadvantages of using an AM business model?	**Advantages:** Reduced tooling costs, on-demand spare parts production, and customization for niche markets. **Disadvantages:** High upfront equipment costs, slower speeds for mass production, and post-processing complexity.
13. What are the most suitable areas of use for AM?	AM excels in prototyping, low-volume custom appliances (e.g., premium kitchen modules), and tooling for injection moulds. It’s also ideal for legacy spare parts no longer in mass production.
14. Is AM scalable for a mass market? Give us some examples.	For mass production, AM is limited but scalable in hybrid models. For example, we use AM for custom oven knobs in limited editions, while traditional methods handle high-volume.
15. How important is the ability to create customized/personalized goods?	Critical for premium segments. We offer personalized panels and ergonomic handles tailored to user preferences, enhancing brand value.
16. How are you applying the technology?	We apply AM for prototyping new appliance concepts, producing jigs and fixtures for assembly lines, and manufacturing bespoke components for high-end product lines.

17. How accessible is the technology?	Industrial-grade AM systems remain costly, but we partner with service providers for smaller projects. In-house equipment is reserved for high-priority R&D and production.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Our engineers and designers are highly trained, while other departments are gradually gaining familiarity. Customers in B2B segments appreciate AM's potential, but consumer awareness is still growing.
19. How do you educate your employees?	We conduct quarterly workshops, collaborate with AM institutes for certifications, and use digital platforms for software training (e.g., CAD tools). Cross-departmental shadowing is encouraged.
20. How has/will AM impact the workforce?	AM shifts focus to digital design and materials engineering. While some traditional roles decline, new opportunities emerge in AM machine maintenance and generative design.
21. What are some emerging/required skills?	Proficiency in topology optimization software, material science expertise, and knowledge of multi-material printing processes are essential. Soft skills like adaptability are equally critical.
FUTURE CHALLENGES	
22. Which problems will AM alleviate and what new problems do you expect to encounter?	**Alleviated:** Waste reduction, supply chain resilience for spare parts. **New Challenges:** Intellectual property risks with digital designs, regulatory hurdles for certified components.
23. Is AM a more sustainable method of production?	Yes, AM reduces material waste by 30-50% compared to machining. However, energy-intensive printers and post-processing need optimization to maximize sustainability benefits.

24. What trends are you most excited about?	Multi-material printing for integrated appliance components (e.g., combining rigid and flexible parts) and AI-driven design optimization tools.
25. What more needs to be done to accelerate the adoption of 3D printing?	Industry-wide material standardization, government incentives for AM R&D, and collaboration with universities to bridge the skills gap.
26. How has AM evolved over the past few years?	AM transitioned from prototyping to functional part production. Advances in metal AM (e.g., aluminium alloys) now allow us to print heat-resistant components previously unattainable.
27. What are the biggest limitations of AM in your opinion?	High costs for industrial systems, limited material options for food-safe appliance parts, and slower speeds for high-volume production remain key barriers.

Interview findings – Company 1:

Main AM Applications:

- Prototyping appliance components → Dishwasher arms, oven handles, refrigerator hinges, enabling rapid design iteration.
- Small-batch production of custom appliance parts → Premium and limited-edition oven knobs, personalized refrigerator panels.
- On-demand spare parts production → Reducing inventory storage needs, especially for legacy components.

Key benefits:

- Faster Product Development → AM reduces prototyping time by 50%, accelerating innovation.

- More Complex & Efficient Designs → AM allows for internal cooling channels, weight-saving lattice structures, and organic shapes.

- Reduced Material Waste → Compared to machining, AM minimizes waste by 30-50%, aligning with sustainability goals.

Challenges:

- High Initial Equipment Costs → Industrial-grade AM machines require significant investment.
- Post-Processing Complexity → Many parts require heat treatments, vapor smoothing, or CNC machining for final use.
- Material Limitations → Food-safe and heat-resistant AM materials for appliances are still limited.

Company 2:

TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	The adoption process was gradual, starting with research and small-scale prototyping. We began with pilot projects to assess feasibility, collaborated with external partners, and trained our engineers. Over time, we integrated AM into our production workflow.
2. What were the reasons for investing into the technology?	Our key reasons were faster prototyping, cost reduction, greater design flexibility, and the ability to produce complex geometries that traditional methods couldn't achieve. It also supports sustainability by reducing material waste.
3. Which method/s of AM are you using and why?	We primarily use Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM). SLS allows us to create complex, strong, and functional prototypes without support structures, while FDM is useful for rapid prototyping with cost-effective materials.
4. What equipment and material are you using and why?	We use industrial-grade 3D printers such as EOS and Stratasys machines. Our materials include PA12 for SLS due to its durability and ABS/PLA for FDM due to ease of use. We also experiment with composite materials for enhanced properties.
DESIGN	

5. How can AM be used to improve the product design cycle? Give us an example.	AM enables iterative design, allowing us to test multiple versions of a product quickly. For example, in automotive sensor housings, we can rapidly modify designs, print prototypes, and validate them in days instead of weeks.
6. What are some examples of designs which could only be created using AM? Do you have some photos, sketches or images to help us better imagine?	Internal cooling channels in injection molds, lightweight lattice structures, and bio-inspired geometries are only possible with AM. We cannot share design images under unless under NDA.
7. Why is the ability to rapidly prototype important?	It accelerates innovation, reduces costs, and minimizes risk. Quick iterations allow us to refine designs before investing in costly tooling.
8. How is the speed of production impacted when using AM? Can you make some estimates?	Prototyping speed is significantly increased—what used to take weeks with traditional methods now takes days or even hours. However, AM for end-use parts is still slower compared to injection molding.
9. How does designing with AM in mind differ from standard practices? Give us some examples.	AM allows for more complex and organic designs. Unlike traditional methods, we don't have to consider machining limitations. Examples include lattice structures for lightweighting and consolidated multi-part assemblies.
10. How is quality affected? Give us some examples.	Quality depends on the AM process used. SLS and SLA provide high detail and strength, while FDM can have lower surface quality. We use post-processing techniques like smoothing and coating to enhance quality.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing involves CAD optimization and slicing for print efficiency. Post-processing includes support removal, sanding, chemical smoothing, and sometimes painting or coating for functional and aesthetic improvements.
APPLICATION OF 3D PRINTING	

12. What are the key advantages and disadvantages of using an AM business model?	Advantages include design freedom, lower inventory needs, and rapid prototyping. Disadvantages include slower mass production speeds and material limitations.
13. What are the most suitable areas of use for AM?	Prototyping, spare parts, tooling, lightweight structures, and customized products like medical implants or automotive components.
14. Is AM scalable for a mass market? Give us some examples.	AM is currently best suited for low-to-mid volume production. In industries like aerospace and healthcare, where customization is key, it's already scalable. However, for high-volume consumer goods, traditional manufacturing remains more efficient.
15. How important is the ability to create customized/personalized goods?	Extremely important, especially in medical, dental, and high-performance industries where tailored solutions offer better performance and fit.
16. How are you applying the technology?	We use AM for rapid prototyping, functional testing, production of custom tooling, and in some cases, low-volume production of specialized components.
17. How accessible is the technology?	While AM is becoming more accessible, high-quality industrial 3D printing still requires significant investment in equipment and expertise. Entry-level solutions are widely available for prototyping.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Knowledge levels vary. Engineers and designers are well-versed in AM, while broader adoption among customers and production teams requires ongoing education.
19. How do you educate your employees?	We provide hands-on training, workshops, and access to AM courses. Collaboration with universities and tech partners also helps in skill development.

20. How has/will AM impact the workforce?	AM shifts the focus from traditional machining skills to digital design and process optimization. It reduces manual labor but creates demand for skilled engineers and technicians.
21. What are some emerging/required skills?	CAD design for AM, material science, process optimization, and post-processing expertise. Understanding of topology optimization and simulation is increasingly valuable.
FUTURE CHALLENGES	
22. Which problems will AM alleviate and what new problems do you expect to encounter?	AM reduces lead times, enables localized production, and minimizes waste. Challenges include material costs, consistency, and the need for standardized processes.
23. Is AM a more sustainable method of production?	Generally, yes. It reduces material waste and transportation emissions. However, some processes consume significant energy, which needs to be managed.
24. What trends are you most excited about?	Multi-material printing, metal AM advancements, and AI-driven generative design for highly optimized components.
25. What more needs to be done to accelerate the adoption of 3D printing?	Continued cost reduction, better material availability, and industry-wide standards to ensure repeatability and reliability.
26. How has AM evolved over the past few years?	It has moved from prototyping to functional part production. New materials and faster printers have made it more viable for end-use applications.
27. What are the biggest limitations of AM in your opinion?	Print speed, material costs, part size constraints, and quality consistency. Post-processing remains a bottleneck in many applications.

Interview findings – Company 2:

Main AM Applications:

- Prototyping electronic components, sensors, and industrial automation parts.
- Small-batch production of specialized housings and connectors.
- Customization of automation system components for specific industrial needs.

Key Benefits:

- Faster R&D cycles, reducing time to market.
- Minimized material waste, making production more sustainable.
- High customization capabilities for niche industrial applications.

Challenges:

- Material limitations (especially for conductive and insulating materials).
- Post-processing complexity (ensuring final parts meet industrial standards).
- Higher costs compared to traditional moulding for mass production.

Company 3:

TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	The adoption of AM at our company started with experimental prototyping for high-performance exhaust components. We collaborated with research institutions and technology partners to explore AM's potential for heat-resistant and lightweight materials. Initially, we focused on small-scale testing before integrating AM into our R&D and production workflows.
2. What were the reasons for investing into the technology?	The primary reasons were to push the boundaries of performance, reduce development cycles, and create complex, lightweight designs that traditional manufacturing methods couldn't achieve. AM also enables rapid iteration and custom solutions for motorsports and high-end applications.

3. Which method/s of AM are you using and why?	We primarily use Laser Powder Bed Fusion (LPBF) for metal components. This method allows us to create high-strength titanium and Inconel parts with optimized geometries, which are crucial for our lightweight and heat-resistant exhaust systems.
4. What equipment and material are you using and why?	We use industrial metal 3D printers from EOS and Renishaw. Titanium is our preferred material due to their high strength-to-weight ratio and heat resistance, essential for motorsport applications.
DESIGN	
5. How can AM be used to improve the product design cycle? Give us an example.	AM allows us to prototype exhaust system components quickly and test them in real-world conditions. For example, we can develop and test new exhaust designs within days, allowing racing teams to optimize performance mid-season.
6. What are some examples of designs which could only be created using AM? Do you have some photos, sketches or images to help us better imagine?	Internal lattice structures for optimized weight reduction and customized aerodynamic exhaust tips are only possible with AM. We have proprietary designs that showcase these innovations, though sharing images is limited due to confidentiality.
7. Why is the ability to rapidly prototype important?	In motorsports, rapid prototyping allows us to iterate designs quickly and test them under extreme conditions. This provides a competitive edge by enabling faster adaptation to changing regulations and performance needs.
8. How is the speed of production impacted when using AM? Can you make some estimates?	Prototyping speed is drastically improved—what used to take weeks can now be achieved in days. However, full-scale production is still slower compared to CNC machining or hydroforming, so AM is used selectively for high-performance parts.
9. How does designing with AM in mind differ from standard practices? Give us some examples.	AM allows us to optimize designs beyond traditional constraints. For instance, we can integrate cooling channels inside exhaust pipes, reducing weight while

	improving thermal efficiency—something impossible with traditional welding techniques.
10. How is quality affected? Give us some examples.	Quality is excellent when AM is used correctly. For example, AM-produced titanium components have comparable strength to conventionally manufactured parts, but require post-processing like heat treatment and surface finishing for optimal durability and appearance.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing involves advanced simulation and topology optimization. Post-processing includes CNC finishing, heat treatments, and surface polishing to ensure mechanical and aesthetic quality, especially for high-end exhaust systems.
APPLICATION OF 3D PRINTING	
12. What are the key advantages and disadvantages of using an AM business model?	Advantages include design freedom, material efficiency, and reduced tooling costs. The main disadvantage is the time and cost of post-processing, as well as material availability constraints.
13. What are the most suitable areas of use for AM?	High-performance automotive and motorsport parts, aerospace components, and custom, low-volume production where weight and thermal efficiency are critical.
14. Is AM scalable for a mass market? Give us some examples.	Not yet for large-scale production, but it works well for premium, low-volume applications. For example, we use AM for bespoke exhaust components in supercars and high-end motorcycles.
15. How important is the ability to create customized/personalized goods?	Very important in our market. AM allows us to produce custom exhausts tailored to specific racing teams or luxury vehicle manufacturers, improving both performance and exclusivity.
16. How are you applying the technology?	We use AM for rapid prototyping, small-batch production of complex components, and developing

	high-performance, weight-optimized parts for racing and supercars.
17. How accessible is the technology?	Industrial AM is still expensive and requires specialized knowledge, but costs are decreasing. We have dedicated teams working with the latest AM technologies to push the limits of performance.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Our engineers and designers are well-trained in AM, but educating customers on the benefits of 3D-printed components is an ongoing process. Motorsport teams understand the advantages, while general consumers still need more awareness.
19. How do you educate your employees?	We invest in specialized training, collaborate with universities, and provide hands-on experience with AM machines. Internal R&D teams also continuously test and validate new AM techniques.
20. How has/will AM impact the workforce?	AM shifts the focus from manual labor to digital design, simulation, and post-processing. It requires highly skilled engineers rather than traditional welders or machinists for certain applications.
21. What are some emerging/required skills?	Advanced CAD modeling, simulation-based design, material science for AM, and expertise in post-processing techniques such as heat treatment and surface finishing.
FUTURE CHALLENGES	
22. Which problems will AM alleviate and what new problems do you expect to encounter?	AM helps eliminate tooling costs and reduces weight in performance applications. However, challenges remain in scaling production, ensuring repeatability, and optimizing post-processing.
23. Is AM a more sustainable method of production?	Yes, as it minimizes material waste compared to subtractive methods. However, energy consumption for metal 3D printing is still high and needs optimization.

24. What trends are you most excited about?	Multi-material printing, hybrid manufacturing (combining AM with traditional methods), and AI-driven generative design to create ultra-optimized performance parts.
25. What more needs to be done to accelerate the adoption of 3D printing?	Improvements in print speed, lower material costs, and better post-processing automation will drive wider adoption.
26. How has AM evolved over the past few years?	It has transitioned from an experimental technology to a key tool for performance engineering, with major advances in metal AM for high-strength applications.
27. What are the biggest limitations of AM in your opinion?	Print speed, high material costs, and the need for extensive post-processing remain barriers for broader adoption.

Interview findings – Company 3:

Main AM Applications:

- Lightweight, high-strength titanium exhaust systems for motorcycles and performance vehicles.
- Custom aerodynamic components that optimize heat dissipation and airflow.
- Production of complex internal geometries that traditional methods cannot achieve.

Key Benefits:

- Significant weight reduction, improving vehicle performance.
- Enhanced aerodynamics and durability with advanced material use.
- Shorter lead times for product development in the motorsport sector.

Challenges:

- High costs of titanium powders and specialized printing technology.
- Intensive post-processing (machining, surface finishing, heat treatments).
- Difficulties in scaling production for mainstream automotive applications.

Company 4:

TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	We began exploring AM to accelerate our prototyping and optimize lightweight structures for our aircraft. Initially, we tested AM for rapid iteration of aerodynamic components and tooling. Over time, as the technology improved, we expanded its use to small-scale production of lightweight, high-performance parts.
2. What were the reasons for investing into the technology?	The main drivers were reducing weight, increasing design flexibility, lowering production costs for small-batch components, and accelerating our development cycle. It allows us to create complex, aerodynamically optimized parts that would be difficult or impossible to manufacture conventionally.
3. Which method/s of AM are you using and why?	We primarily use Selective Laser Sintering (SLS) for strong, lightweight polymer parts and Laser Powder Bed Fusion (LPBF) for metal components. These methods provide the strength and precision required for aerospace applications while maintaining low weight.
4. What equipment and material are you using and why?	We use industrial 3D printers from EOS and Stratasys. Materials include carbon-fiber-reinforced composites for non-structural components, and titanium or aluminum alloys for structural parts, ensuring strength while keeping weight minimal.
DESIGN	
5. How can AM be used to improve the product design cycle? Give us an example.	AM allows us to iterate designs quickly, testing multiple versions of an aircraft component in a short time. For example, when developing aerodynamic fairings, we can rapidly produce and test prototypes in wind tunnel simulations before committing to final production.
6. What are some examples of designs which could only be created using AM? Do you have some	Lightweight, lattice-structured aircraft brackets and optimized ducting systems for cooling and airflow are only possible with AM. These designs reduce weight

photos, sketches or images to help us better imagine?	while maintaining structural integrity, which is critical for aviation. We have internal documentation showcasing these innovations, though sharing is limited due to proprietary considerations.
7. Why is the ability to rapidly prototype important?	Rapid prototyping shortens development cycles and reduces the cost of traditional tooling. In aviation, every gram counts, so being able to quickly test different design iterations helps us create more efficient aircraft.
8. How is the speed of production impacted when using AM? Can you make some estimates?	For prototyping, AM reduces production time from weeks to days. However, for large-scale manufacturing, traditional composite molding and machining are still faster for most structural components.
9. How does designing with AM in mind differ from standard practices? Give us some examples.	AM allows for organic, weight-optimized designs that traditional manufacturing cannot achieve. For example, structural brackets with lattice geometries maintain strength while being significantly lighter than milled aluminum alternatives.
10. How is quality affected? Give us some examples.	Quality is generally excellent, but post-processing is required to meet aviation safety standards. For example, 3D-printed titanium parts undergo heat treatment and machining to ensure precision and durability.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing involves CAD optimization and stress simulations. Post-processing includes surface finishing, heat treatments, and testing to ensure components meet aerospace safety regulations.
APPLICATION OF 3D PRINTING	
12. What are the key advantages and disadvantages of using an AM business model?	The main advantages are design flexibility, weight reduction, and rapid iteration. The disadvantages are high material costs, slower production for large parts, and stringent post-processing requirements.
13. What are the most suitable areas of use for AM?	Lightweight brackets, aerodynamic fairings, custom avionics enclosures, cooling ducts, and tooling for

	composite layups are ideal applications for AM in aviation.
14. Is AM scalable for a mass market? Give us some examples.	For aerospace, AM is primarily used for high-performance, low-volume production. While it is not yet suitable for mass-producing large aircraft parts, smaller components such as brackets and housings are already being integrated into commercial production.
15. How important is the ability to create customized/personalized goods?	Customization is highly valuable, especially for experimental aircraft and special-use cases where tailored designs improve efficiency and performance.
16. How are you applying the technology?	We use AM for prototyping, producing lightweight non-critical components, and manufacturing customized tooling to support composite manufacturing.
17. How accessible is the technology?	While AM technology is improving in accessibility, high-end aerospace applications still require significant investment in specialized equipment and materials.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Engineers and designers are well-versed in AM, but wider adoption in the aerospace industry requires continued education. Customers are becoming more aware of AM benefits, especially in the high-performance aviation sector.
19. How do you educate your employees?	We conduct in-house training, collaborate with universities, and provide access to industry-leading AM research. Hands-on experience with 3D printing technologies is also emphasized.
20. How has/will AM impact the workforce?	AM shifts manufacturing jobs towards digital design, simulation, and post-processing expertise. While some traditional fabrication jobs are reduced, new roles in advanced engineering and materials science are emerging.

21. What are some emerging/required skills?	Topology optimization, material science for AM, CAD design tailored for additive processes, and expertise in post-processing techniques such as polishing and heat treatment.
FUTURE CHALLENGES	
22. Which problems will AM alleviate and what new problems do you expect to encounter?	AM reduces waste, speeds up innovation, and enables weight reduction. However, challenges include certification for aerospace use, material consistency, and high production costs.
23. Is AM a more sustainable method of production?	Yes, as it reduces material waste compared to traditional subtractive methods. However, energy-intensive processes and material supply chain challenges still need to be addressed.
24. What trends are you most excited about?	Multi-material printing, high-performance composite 3D printing, and AI-driven generative design to create ultra-lightweight, aerodynamically optimized aircraft structures.
25. What more needs to be done to accelerate the adoption of 3D printing?	Advances in material certification, better automation for post-processing, and increased adoption of AM in large-scale aerospace manufacturing.
26. How has AM evolved over the past few years?	It has progressed from primarily being a prototyping tool to an essential part of aerospace R&D and limited production, with improvements in material performance and print quality.
27. What are the biggest limitations of AM in your opinion?	Scalability, high material costs, and the need for extensive certification and post-processing remain the biggest challenges for wider aerospace adoption.

Interview findings – Company 4:

Main AM Applications:

- Lightweight structural components for electric and hybrid aircraft.
- Rapid prototyping of aerodynamic parts to improve efficiency.
- Custom UAV (drone) components with integrated sensor housings.

Key Benefits:

- Weight savings improve fuel efficiency and extend battery life for electric aircraft.
- Faster iteration cycles for new aircraft models.
- Complex geometries allow for optimized aerodynamics and performance.

Challenges:

- Aerospace certification requirements are strict and time-consuming.
- Material limitations in high-stress environments (fatigue resistance issues).
- Scalability issues when producing large aircraft parts using AM.

Company 5:

TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	The company has been an early adopter of AM, integrating it into multiple divisions, including energy, industrial automation, and mobility. The process started with prototyping and gradually expanded to spare parts production and digital inventory solutions. We first tested AM in repair and maintenance applications, and once we saw the cost and time benefits, we scaled up its use in industrial component manufacturing.
2. What were the reasons for investing into the technology?	The main reasons were to reduce lead times, lower inventory costs, enable on-demand production, and create highly optimized components. AM allows us to produce complex geometries that improve efficiency in

	power generation, industrial automation, and mobility applications.
3. Which method/s of AM are you using and why?	We use multiple methods depending on the application. Selective Laser Melting (SLM) for metal components in power turbines, Fused Deposition Modeling (FDM) for industrial prototypes, and Selective Laser Sintering (SLS) for producing functional polymer parts. Each method is selected based on material requirements and production scale.
4. What equipment and material are you using and why?	We use industrial 3D printers from EOS, Stratasys, and HP. Materials include metal powders (nickel alloys, stainless steel, titanium) for high-performance components, and engineering-grade polymers (PA12, PEEK) for durable functional parts. The choice of materials is driven by application-specific requirements such as heat resistance, strength, and conductivity.
DESIGN	
5. How can AM be used to improve the product design cycle? Give us an example.	AM accelerates product development by enabling rapid iteration. For example, in gas turbine design, we use AM to create new cooling structures that improve efficiency. Instead of waiting months for traditional casting, we can produce testable prototypes within weeks.
6. What are some examples of designs which could only be created using AM? Do you have some photos, sketches or images to help us better imagine?	Internal cooling channels in gas turbine blades and lightweight bionic structures for industrial automation components are only possible with AM. These complex geometries improve performance and efficiency. While we have many examples, some are proprietary and confidential.
7. Why is the ability to rapidly prototype important?	Rapid prototyping allows us to test new industrial designs quickly, shortening development cycles and reducing costs. This is especially critical for custom components in energy and mobility solutions, where

	failure analysis and performance validation must be done quickly.
8. How is the speed of production impacted when using AM? Can you make some estimates?	AM significantly reduces lead times for complex parts. A traditionally cast turbine component can take 6-12 months to manufacture, while AM reduces this to weeks. However, large-scale production is still faster with traditional methods.
9. How does designing with AM in mind differ from standard practices? Give us some examples.	AM allows for topology optimization, meaning we design for strength while minimizing weight. For example, lightweight brackets in industrial robots use a lattice structure that is impossible with machining but reduces weight while maintaining durability.
10. How is quality affected? Give us some examples.	AM can achieve high precision and mechanical strength, but post-processing is required to meet industrial standards. In power plant applications, we ensure AM-produced turbine parts meet heat resistance and fatigue life requirements through testing and surface treatments.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing involves digital twin simulations and stress analysis before printing. Post-processing includes heat treatment, CNC machining, and surface finishing. For example, AM-produced turbine blades go through HIP (Hot Isostatic Pressing) to eliminate porosity and improve durability.
APPLICATION OF 3D PRINTING	
12. What are the key advantages and disadvantages of using an AM business model?	Advantages: On-demand production, reduced warehousing costs, and improved design capabilities. Disadvantages: High initial investment, material costs, and the need for specialized workforce training.
13. What are the most suitable areas of use for AM?	Energy (turbines, heat exchangers), industrial automation (robotic parts), rail and mobility (custom spare parts), and healthcare (custom medical implants).

14. Is AM scalable for a mass market? Give us some examples.	It’s not yet ideal for mass production, but it excels in customization and low-volume high-value parts. For example, Siemens Mobility uses AM to produce spare parts for trains, reducing lead times for discontinued components.
15. How important is the ability to create customized/personalized goods?	Very important, especially in industries requiring custom-fit parts (e.g., railway maintenance, medical prosthetics, and energy-efficient turbine components).
16. How are you applying the technology?	We use AM for prototyping, spare parts manufacturing, tooling, and complex industrial components such as heat exchangers in power plants.
17. How accessible is the technology?	AM is becoming more accessible, but high-end industrial applications still require significant investment in machines, materials, and post-processing.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Our engineers and R&D teams are well-versed in AM, but some industries require more education on its benefits and limitations.
19. How do you educate your employees?	We have internal training programs, partnerships with universities, and hands-on workshops for employees to understand AM design, simulation, and post-processing.
20. How has/will AM impact the workforce?	AM reduces manual labor in some areas but creates new roles in digital design, simulation, and post-processing. The workforce needs to shift towards automation, material science, and AI-driven design.
21. What are some emerging/required skills?	CAD for AM, generative design, materials science, machine operation, and quality assurance for AM-produced parts.
FUTURE CHALLENGES	

22. Which problems will AM alleviate and what new problems do you expect to encounter?	AM will help reduce supply chain dependencies and enable decentralized manufacturing. However, challenges remain in material qualification, repeatability, and certification for critical applications.
23. Is AM a more sustainable method of production?	Yes, as it reduces material waste and transportation costs. However, energy consumption for metal AM processes is still high and needs further optimization.
24. What trends are you most excited about?	AI-driven generative design, hybrid manufacturing (AM + CNC), and automation of post-processing.
25. What more needs to be done to accelerate the adoption of 3D printing?	Improved print speed, material costs, and certification processes will help integrate AM more widely into industrial production.
26. How has AM evolved over the past few years?	AM has moved from prototyping to full-scale production in certain industries. Improvements in multi-material printing and automation are making AM more viable for critical applications.
27. What are the biggest limitations of AM in your opinion?	Slow production speed, high material costs, and the need for extensive post-processing are the biggest hurdles for widespread adoption.

Interview findings – Company 5:

Main AM Applications:

- On-demand spare parts for industrial machinery to reduce downtime.
- Custom components for automation solutions, tailored to specific factory needs.
- Optimized heat exchangers and fluid control components for energy efficiency.

Key Benefits:

- Minimizes inventory needs with digital manufacturing.
- Reduces lead times for replacement parts, lowering downtime costs.
- Design flexibility enables better integration with smart factory systems.

Challenges:

- High material costs compared to traditional casting and milling.
- Ensuring long-term durability of printed industrial components.
- Lack of standardization in AM-produced parts across industries.

Company 6:

TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	At our company, we started exploring AM to improve prototyping, tooling, and small-batch production in the automotive and industrial sectors. Initially, we tested AM for rapid iteration of engine components and heating system parts. As we saw improvements in efficiency, material savings, and design flexibility, we expanded its use for functional parts, jigs, and fixtures.
2. What were the reasons for investing into the technology?	The key drivers were reducing production lead times, optimizing part geometries for performance, lowering material waste, and improving energy efficiency in our solutions. AM enables us to manufacture complex geometries that enhance heat transfer and fluid dynamics, critical for heating and cooling systems.
3. Which method/s of AM are you using and why?	We primarily use Selective Laser Melting (SLM) for metal parts in engine components and thermal management systems. We also use Fused Deposition Modeling (FDM) for prototyping and tooling, and Selective Laser Sintering (SLS) for durable polymer parts used in industrial automation.
4. What equipment and material are you using and why?	We utilize EOS and Trumpf industrial 3D printers for metal components and Stratasys for polymer applications. Materials include aluminum alloys for lightweight heat exchangers, stainless steel for high-temperature components, and engineering-grade plastics for durable, non-metallic parts.
DESIGN	

5. How can AM be used to improve the product design cycle? Give us an example.	AM allows for faster iteration of complex parts. For example, in developing heat exchangers for electric vehicles, we rapidly test different internal cooling channel designs to maximize efficiency before committing to mass production.
6. What are some examples of designs which could only be created using AM? Do you have some photos, sketches or images to help us better imagine?	Complex heat exchanger structures, optimized airflow ducts, and lightweight metallic supports for automotive components are only possible with AM. These designs improve efficiency and durability while reducing weight. Due to proprietary restrictions, we cannot publicly share all examples.
7. Why is the ability to rapidly prototype important?	It reduces R&D time, minimizes costs, and allows us to test different geometries for fluid dynamics and heat management before committing to full-scale production.
8. How is the speed of production impacted when using AM? Can you make some estimates?	AM significantly reduces prototyping time from months to weeks. However, for high-volume production, traditional casting and machining are still faster and more cost-effective.
9. How does designing with AM in mind differ from standard practices? Give us some examples.	AM enables organic, optimized structures that reduce weight and improve performance. For example, we designed a lightweight aluminum manifold with internal cooling channels, reducing material usage while improving thermal performance.
10. How is quality affected? Give us some examples.	AM parts match or exceed conventional standards, but post-processing is needed. For example, metallic glow plug housings for diesel engines require heat treatment and precision machining after printing.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing includes topology optimization and thermal simulations. Post-processing includes heat treatment, CNC finishing, and surface smoothing to ensure durability and performance in automotive applications.

APPLICATION OF 3D PRINTING	
12. What are the key advantages and disadvantages of using an AM business model?	Advantages: Faster product development, reduced material waste, and the ability to create optimized, high-performance parts. Disadvantages: High material costs, slower production for large-scale manufacturing, and extensive post-processing requirements.
13. What are the most suitable areas of use for AM?	Automotive components (heat exchangers, engine parts), industrial heating systems, electronic enclosures, and customized production tools.
14. Is AM scalable for a mass market? Give us some examples.	Not yet for large-volume production, but it is ideal for custom or high-performance applications. For example, customized thermal management solutions for electric vehicles can be 3D printed in small batches.
15. How important is the ability to create customized/personalized goods?	Very important, especially in heating and cooling applications where optimizing airflow and heat dissipation improves energy efficiency.
16. How are you applying the technology?	We use AM for prototyping, small-batch production, and custom tooling in automotive and industrial heating applications.
17. How accessible is the technology?	While AM for prototyping is widely accessible, high-end metal printing for industrial applications still requires significant investment in equipment and training.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Our R&D and engineering teams are well-trained in AM, but customers and traditional manufacturers still require education on its benefits.
19. How do you educate your employees?	Through in-house training programs, industry workshops, and collaborations with universities to stay updated on AM advancements.

20. How has/will AM impact the workforce?	It shifts jobs from manual machining to digital design and post-processing, creating demand for new skills in AM engineering and material science.
21. What are some emerging/required skills?	Topology optimization, thermal analysis, CAD design for AM, and advanced post-processing techniques.
FUTURE CHALLENGES	
22. Which problems will AM alleviate and what new problems do you expect to encounter?	AM helps reduce material waste and enables design flexibility, but challenges remain in certification, repeatability, and production scaling.
23. Is AM a more sustainable method of production?	Yes, as it minimizes material waste and enables lightweight designs that improve energy efficiency. However, high energy consumption for metal printing is a challenge.
24. What trends are you most excited about?	Multi-material printing, automated post-processing, and AI-driven generative design for optimized structures.
25. What more needs to be done to accelerate the adoption of 3D printing?	Lowering material costs, improving print speeds, and streamlining certification processes for industrial applications.
26. How has AM evolved over the past few years?	It has shifted from basic prototyping to functional industrial components, with improved material options and precision.
27. What are the biggest limitations of AM in your opinion?	High costs, slow production speeds for mass manufacturing, and the need for extensive post-processing remain key challenges.

Interview findings – Company 6:

Main AM Applications:

- Heat exchangers and cooling systems for HVAC (heating, ventilation and air conditioning) and automotive applications.

- Prototyping electric motor components to improve energy efficiency.
- Production of optimized metal structures for fluid and thermal management.

Key Benefits:

- More efficient heat dissipation, improving overall system performance.
- Lighter, optimized parts for electric vehicle (EV) applications.
- Reduces material waste, contributing to sustainability goals.

Challenges:

- AM components require extensive post-processing (machining, heat treatments).
- Scaling AM for high-volume automotive production is difficult.
- Strict certification processes for HVAC (heating, ventilation and air conditioning) and automotive applications.

Company 7:

TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	We first adopted AM for tool and fixture prototyping to speed up our R&D process. Over time, we expanded into custom tool production and small-batch manufacturing of complex machine parts. We focused on metal and polymer AM to complement our traditional forging and machining processes.
2. What were the reasons for investing into the technology?	Our main reasons were to reduce prototyping costs, shorten development cycles, and create highly optimized custom tools that improve our efficiency in hand tools, forging, and special machinery manufacturing. AM also helps us reduce material waste and explore lightweight but strong tool designs.
3. Which method/s of AM are you using and why?	We use Selective Laser Melting (SLM) for metal parts, Fused Deposition Modeling (FDM) for rapid prototyping, and Selective Laser Sintering (SLS) for durable polymer parts. SLM allows us to create custom cutting tools and durable spare parts, while FDM and

	SLS are great for functional prototypes and manufacturing aids.
4. What equipment and material are you using and why?	We use EOS and Renishaw metal 3D printers for high-strength steel components, and Stratasys and HP for polymer printing. Our materials include tool steels for durability, aluminum for lightweight structures, and high-performance polymers for mechanical components. These materials are chosen based on strength, wear resistance, and cost-effectiveness.
DESIGN	
5. How can AM be used to improve the product design cycle? Give us an example.	AM allows us to rapidly iterate tool designs, improving ergonomics and performance before investing in expensive molds or machining. For example, we developed a new ergonomic wrench handle using AM, testing multiple variations within weeks instead of months.
6. What are some examples of designs which could only be created using AM? Do you have some photos, sketches or images to help us better imagine?	Lightweight tool handles, bionic structures in custom frames, and internal cooling channels in metal cutting tools are some examples. These designs improve performance, weight distribution, and durability—features that would be impossible or too costly with traditional manufacturing.
7. Why is the ability to rapidly prototype important?	It allows us to test multiple design versions quickly, reducing R&D time and helping us bring new tools to market faster and at lower cost. This is especially valuable in custom tool development for the automotive and aerospace industries.
8. How is the speed of production impacted when using AM? Can you make some estimates?	AM can reduce production time for prototypes and custom parts by 50-70%. However, for high-volume production, traditional forging and CNC machining remain faster.

9. How does designing with AM in mind differ from standard practices? Give us some examples.	AM allows for topology-optimized designs that reduce weight while maintaining strength. For example, we redesigned a customized torque wrench using a lattice structure, reducing weight by 30% while maintaining durability.
10. How is quality affected? Give us some examples.	AM parts match or exceed standard quality, but require post-processing. For instance, AM-printed metal cutting inserts undergo heat treatment and grinding to meet precision standards.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing includes design simulation and stress analysis. Post-processing involves heat treatment, CNC machining, and surface finishing. For example, AM-produced punches for forging dies are heat-treated for improved hardness.
APPLICATION OF 3D PRINTING	
12. What are the key advantages and disadvantages of using an AM business model?	Advantages: Faster prototyping, reduced material waste, and highly optimized tool designs. Disadvantages: High initial investment, slow production speeds for large-scale manufacturing, and post-processing requirements.
13. What are the most suitable areas of use for AM?	Custom tools, lightweight ergonomic designs, spare parts for machinery, and rapid prototyping in the hand tool and automotive sectors.
14. Is AM scalable for a mass market? Give us some examples.	AM is ideal for low-volume, high-precision manufacturing but is not yet cost-effective for mass production. However, we use it for custom wrenches, forging dies, and special fixtures in small batches.
15. How important is the ability to create customized/personalized goods?	Very important, especially for custom hand tools and special-purpose manufacturing equipment, where small design tweaks can significantly improve user experience.

16. How are you applying the technology?	We use AM for prototyping, tooling, spare parts production, and ergonomic tool design.
17. How accessible is the technology?	It’s becoming more accessible, but high-end metal printing still requires significant investment in equipment and expertise.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Our R&D and production teams are trained in AM, but customers often need education on the benefits of 3D-printed tools and fixtures.
19. How do you educate your employees?	We offer in-house training, workshops, and collaborations with technical universities to develop AM-specific skills.
20. How has/will AM impact the workforce?	AM reduces manual machining but creates new roles in design, material science, and post-processing. Workers must adapt to digital design and simulation.
21. What are some emerging/required skills?	CAD for AM, generative design, material science, and post-processing techniques.
FUTURE CHALLENGES	
22. Which problems will AM alleviate and what new problems do you expect to encounter?	AM helps reduce waste and enables lightweight designs, but challenges include material costs, certification, and print speed limitations.
23. Is AM a more sustainable method of production?	Yes, as it minimizes material waste and energy usage, but metal AM processes still have high energy consumption.
24. What trends are you most excited about?	Hybrid manufacturing (AM + CNC), AI-driven generative design, and improved metal printing techniques.
25. What more needs to be done to accelerate the adoption of 3D printing?	Lower material costs, faster print speeds, and standardized certification for industrial applications.

26. How has AM evolved over the past few years?	AM has moved from prototyping to functional industrial parts, with better materials and precision enabling more applications in tooling and automotive sectors.
27. What are the biggest limitations of AM in your opinion?	High costs, slow production speeds for mass manufacturing, and the need for extensive post-processing remain key challenges.

Interview findings – Company 7:

Main AM Applications:

- Ergonomic, lightweight hand tools with improved grip designs.
- Custom tool inserts for machining and specialized cutting applications.
- Rapid prototyping for new tool designs, reducing development time.

Key Benefits:

- Weight reduction improves user comfort and efficiency.
- Faster iteration and testing of new tool designs.
- More sustainable production, as AM reduces material waste.

Challenges:

- High cost of metal AM for mass tool production.
- Additional reinforcement needed for AM-printed tools.
- Integration with traditional manufacturing workflows is complex.

Company 8:

TECHNOLOGY	
1. What did the process of adoption look like? Give us as many details as possible.	We began exploring AM to optimize the development of HVAC components, particularly valves and actuators. Initially, we used AM for rapid prototyping, but as the technology advanced, we integrated it into functional testing and small-batch production of complex components. Our adoption process involved

	extensive R&D, material testing, and validation to ensure AM parts met our strict quality standards.
2. What were the reasons for investing into the technology?	We invested in AM to reduce lead times, enhance product performance, and improve design flexibility. The ability to quickly prototype, test, and modify valve designs is critical for fluid dynamics optimization and energy efficiency. Additionally, AM enables us to create lightweight, high-performance internal structures for our products.
3. Which method/s of AM are you using and why?	We use Selective Laser Sintering (SLS) and Stereolithography (SLA) for polymer parts, primarily for prototyping and testing valve housings. For metal components, such as complex heat exchangers or optimized internal channels, we use Selective Laser Melting (SLM).
4. What equipment and material are you using and why?	We use EOS and Stratasys industrial 3D printers for high-precision prototyping. Materials include PA12 and PEEK for durable polymer parts and stainless steel and aluminum for heat-resistant and corrosion-resistant components. These materials ensure mechanical strength and long-term durability in HVAC applications.
DESIGN	
5. How can AM be used to improve the product design cycle? Give us an example.	AM allows us to test multiple valve designs simultaneously, shortening the design cycle from months to weeks. For instance, when designing a new differential pressure control valve, we printed multiple internal flow channel configurations to optimize fluid dynamics before committing to injection molding.
6. What are some examples of designs which could only be created using AM? Do you have some	Complex internal flow channels in valves, bionic lattice structures for heat dissipation, and optimized actuator housings are only possible with AM. These designs

photos, sketches or images to help us better imagine?	help us achieve higher energy efficiency and better system control.
7. Why is the ability to rapidly prototype important?	It allows us to validate designs quickly, reduce costs, and improve product performance before committing to full-scale production. This is especially important in fluid control applications, where minor design changes can significantly impact efficiency.
8. How is the speed of production impacted when using AM? Can you make some estimates?	AM can reduce prototyping lead times by up to 70%. However, for large-scale production, traditional manufacturing remains faster and more cost-effective.
9. How does designing with AM in mind differ from standard practices? Give us some examples.	It enables organic, optimized designs that improve fluid dynamics. For example, we developed a valve housing with internal lattice structures, reducing weight by 30% while maintaining strength. Traditional manufacturing could not achieve this complexity.
10. How is quality affected? Give us some examples.	Quality is on par or better than traditional manufacturing when proper post-processing is applied. For example, AM-produced stainless steel valve components undergo precision machining and surface finishing to meet industry standards.
11. How do you deal with pre- and post-processing? Give us some examples.	Pre-processing includes CAD modeling and flow simulation, while post-processing involves heat treatment, machining, and surface finishing. For example, AM-printed manifolds for district heating systems are polished internally to reduce friction and improve flow efficiency.
APPLICATION OF 3D PRINTING	
12. What are the key advantages and disadvantages of using an AM business model?	Advantages: Faster development cycles, reduced material waste, and highly optimized designs. Disadvantages: High material costs, slower production speeds for mass manufacturing, and certification challenges.

13. What are the most suitable areas of use for AM?	HVAC components, heat exchangers, customized actuator housings, and rapid prototyping for fluid control systems.
14. Is AM scalable for a mass market? Give us some examples.	Not yet for high-volume manufacturing, but ideal for customized or high-performance applications. We use AM to develop and test new hydronic balancing solutions before scaling to traditional manufacturing.
15. How important is the ability to create customized/personalized goods?	Very important, especially for specialized HVAC systems that require tailored solutions for different buildings and industrial applications.
16. How are you applying the technology?	We use AM for prototyping, small-batch production, and developing optimized internal flow geometries in our HVAC products.
17. How accessible is the technology?	AM is becoming more accessible for prototyping, but high-end metal printing still requires significant investment in equipment and expertise.
PEOPLE	
18. Are the people (employees, customers) knowledgeable about the technology?	Our engineering teams are well-versed in AM, but customers still need education on its advantages in fluid dynamics and HVAC optimization.
19. How do you educate your employees?	We provide internal training, industry seminars, and partnerships with universities to keep our workforce updated on AM applications in HVAC.
20. How has/will AM impact the workforce?	AM reduces manual prototyping but creates demand for new skills in simulation, CAD, and materials science.
21. What are some emerging/required skills?	Topology optimization, thermal and fluid dynamics simulation, CAD for AM, and post-processing techniques.
FUTURE CHALLENGES	

22. Which problems will AM alleviate and what new problems do you expect to encounter?	AM helps reduce waste and improves energy efficiency in HVAC, but challenges include high costs, certification, and production scaling.
23. Is AM a more sustainable method of production?	Yes, as it reduces material waste and allows for more energy-efficient product designs. However, metal printing remains energy-intensive.
24. What trends are you most excited about?	Multi-material printing, AI-driven generative design, and improved AM materials for heat resistance and corrosion protection.
25. What more needs to be done to accelerate the adoption of 3D printing?	Lower material costs, faster print speeds, and industry-wide certification standards for AM-produced HVAC components.
26. How has AM evolved over the past few years?	AM has shifted from simple prototyping to functional, high-performance components, with better material properties and precision enabling more applications in HVAC and industrial automation.
27. What are the biggest limitations of AM in your opinion?	High costs, slow production speeds for mass manufacturing, and post-processing requirements remain key challenges.

Interview findings – Company 8:

Main AM Applications:

- Hydronic valves and actuators with optimized flow channels.
- Custom heat exchangers for improved energy efficiency.
- Small-batch production of highly specialized HVAC components.

Key Benefits:

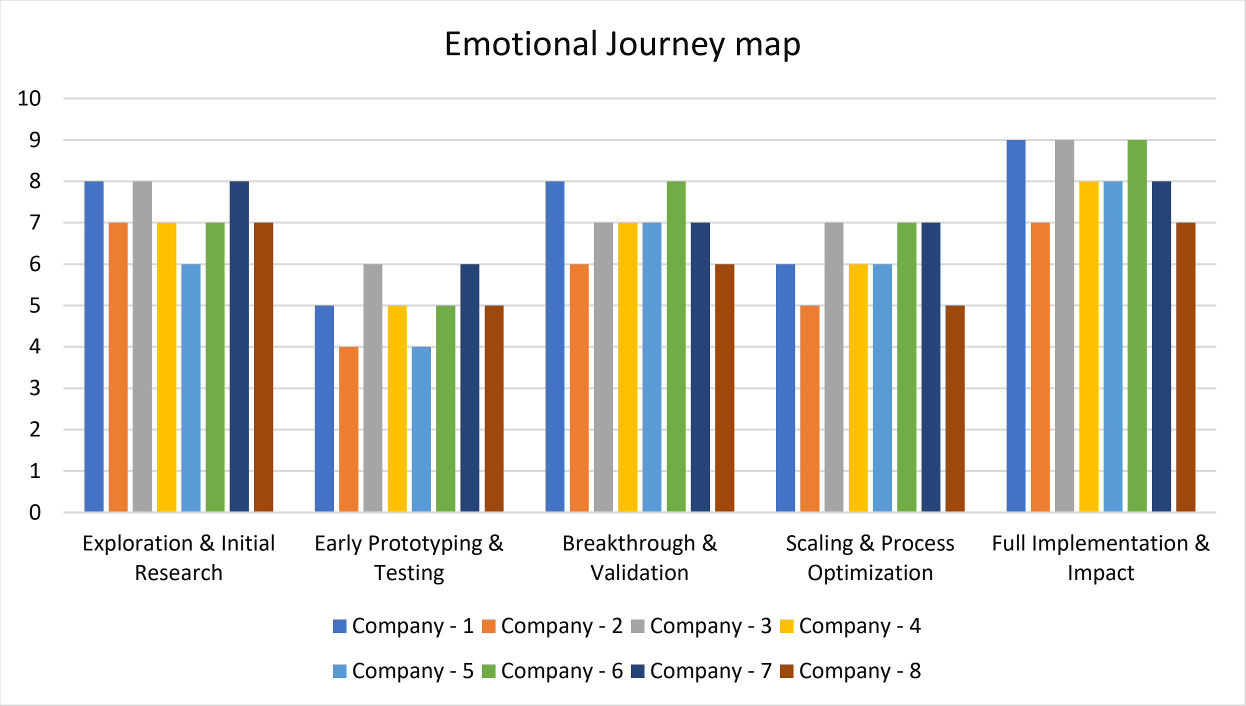
- Enhances energy efficiency and fluid dynamics in HVAC systems.
- Reduces material waste, aligning with sustainability initiatives.
- Allows rapid customization of components for unique installations.

Challenges:

- High-performance materials are costly.
- Certification requirements for HVAC components are stringent.
- Scaling metal AM production remains a challenge.

Appendix 3: Emotional journey map:

Figure 6: Emotional journey map



Source: Own work