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Technology Strategy for Metal-based Additive Manufacturing

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Abstract

Metal-based Additive Manufacturing (AM) technologies are promising for achieving innovations in products and manufacturing processes. Thus, many manufacturing companies have a need to evaluate such technologies' potential but struggle with the complexity of the process and the lack of internal expertise concerning AM, which hinders a structured technology implementation.

To support the strategic implementation of metal-based AM, a methodical approach for developing an *AM Technology Roadmap* is generated on the basis of a company's requirements and product portfolio. The process to obtain the roadmap is divided into three fields of action. Action field A entails gathering technology information, which is then summarized in a *Technology Fact Sheet*. In action field B, suitable applications for AM technology are identified through a combined data- and knowledge-based screening approach. The applications are evaluated on the basis of an *Application Assessment Sheet*, which considers the benefits of AM technology and a technical–economical evaluation. In Action field C, organizational tasks for AM adoption are derived, focusing on the sourcing of the AM technology through a make-or-buy evaluation and measures to generate and exchange knowledge about AM technology. The results of the three action fields are aggregated as connected, time-based planning objects in the *AM Technology Roadmap*.

The applicability in the industrial context is demonstrated through six use cases from various industries. In conclusion, the approach provides a valuable structured support with which to assess the technological potential of metal-based AM for strategic decision-making.

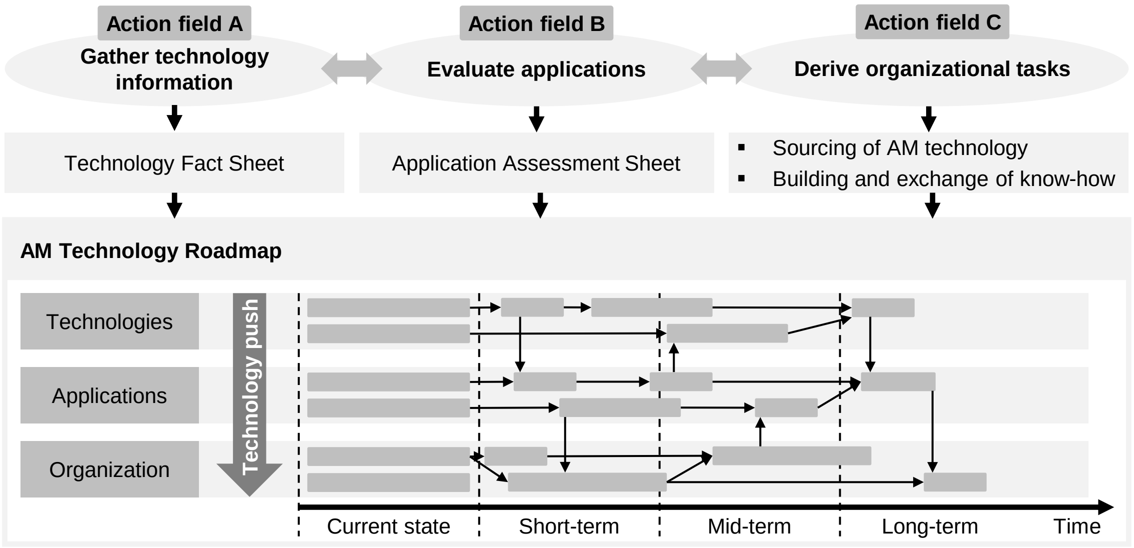

Figure 0.1: Approach to developing an AM Technology Roadmap.

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1 Introduction

1.1 Motivation

Manufacturing companies (also referred to herein as producing companies) must continually innovate to maintain and expand their market position. Innovations generate benefits for customers in form of *product innovations* or yield internal benefits in the manufacturing processes as *process innovations* (EVERSHEIM 2009). Due to the need for continuous innovation and optimization, companies must search and evaluate enabling technologies, which is task for technology management (KLAPPERT ET AL. 2011, SCHUH ET AL. 2011). Following the concept of *lean innovation*, this identification processes must be effective and efficient, which means to avoid all types of waste (SCHUH 2013).

Over the last years, several innovations in the production sector were enabled by *Additive Manufacturing* (AM) technologies (STATISTA 2018). Since the first commercial AM system, the Stereolithography Apparatus SLA-1, was patented in 1987 by Chuck Hall (YANG ET AL. 2017), AM technologies have been matured from processes for prototyping to manufacturing processes for serial parts (GEBHARDT 2016). In contrast to established, conventional manufacturing processes, AM technologies offer profound advantages. As a tool-less production process, AM offers opportunities for flexible production environments and allows to manufacture a new level of geometrical complexity. The first AM processes were based on polymers, but today metallic parts are also made additively. The most common process for metal-based AM is Laser-based Powder Bed Fusion, which utilizes a laser beam to melt a thin layer of metallic powder. Driven by the aerospace and medical sectors, metal-based AM has matured into a production process for serial applications. And since 2013, the demand for metal-based AM technologies has increased considerably (WOHLERS ET AL. 2019). Regarding the rapid development and influence on product differentiation (SCHUH 2013), metal-based AM is a *key technology* for the manufacturing of complex parts for demanding applications.

Hence, manufacturing companies are evaluating the benefits of adopting AM for their product portfolio. Whereas the aerospace sector benefits from new lightweight designs and medical applications from individualized products (NIAKI & NONINO 2018), the benefits of adopting AM are mostly not as straightforward. The main limitations to adopting AM technologies are high investment cost and a lack of internal expertise (MÜLLER & KAREVSKA 2016, MÖHRLE ET AL. 2017). According to MÜLLER & KAREVSKA (2016), only 4% of 900 surveyed companies reported having a holistic strategic approach to implementing AM. By contrast, 76% of the companies reported having *no experience* in AM. In this context, AM is just at the beginning of market diffusion. Moreover, full market diffusion is not expected within the next ten years (CAVIEZEL ET AL. 2017).

In conclusion, metal-based AM technologies are matured manufacturing processes and are considered as key technology for the manufacturing of complex parts in demanding applications. However, due to the novelty of these processes and their fast development, companies face hindrances like high invest cost and missing internal expertise, when trying to adopt these technologies. Thus, supportive approaches need to be developed to unlock the innovation potential of metal-based Additive Manufacturing.

1.2 Research Objective

The research objective of this study is a systematic approach to prepare a technology strategy for metal-based Additive Manufacturing based on the specific requirements of a company. The research objective is concretized through three key questions:

1. How should a company identify metal-based AM processes that meet its requirements?
2. How should a company identify applications in its product portfolio that benefit from AM?
3. How should a company develop a strategy to exploit the full potential of metal-based AM processes?

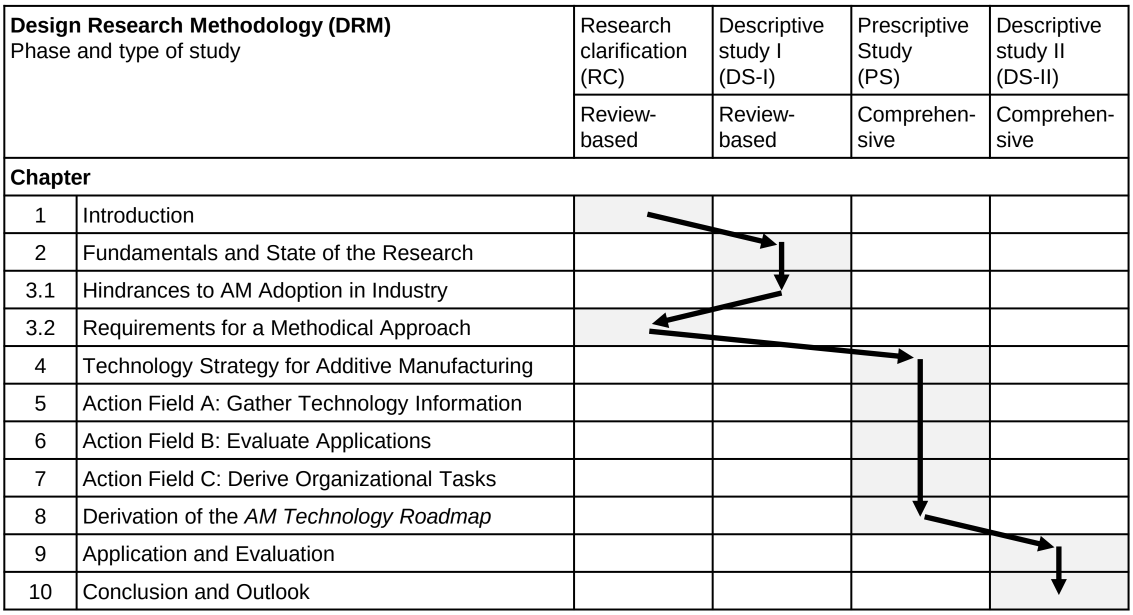
Based on these questions, the subdomains of the research objective were investigated. The first aspect concerns technology identification, and it is necessary to clearly describe the potential and limitations of a technology in a structured form. In addition, the maturity of AM technology must be assessed. Moreover, appropriate sources of information regarding technology potential must be identified. The selection of an AM technology is closely linked to the identification of suitable applications, which is the second aspect of the research objective. Because a production technology is only required when solving a specific production task, the identification of applications and the corresponding AM technology entails matching technology capabilities with production requirements. In addition, general benefits of AM technology must be identified, and the impact on the application must be evaluated. Besides the technical evaluation, economic aspects are crucial for the success of AM implementation. Thus, an appropriate method to identify and evaluate applications in the context of AM technology must be developed. The third part of the research objective is to develop a strategy to exploit the potential of AM technology within the company. For that, a methodical approach must be developed to support the generation of the technology strategy integrating the afore mentioned aspects. The developed methodical approach to generate a technology strategy in metal-based Additive Manufacturing should enable strategic decisions in the field of AM and thus foster the exploitation of the innovation potential of these technologies within the company.

1.3 Research Approach

The research approach is based on the general concept of *Design Research Methodology (DRM)* proposed by BLESSING & CHAKRABARTI (2009). The term *design* is defined as “those activities that actually generate and develop a product from a need, product idea or technology” (BLESSING & CHAKRABARTI 2009). The design process needs to consider all aspects of the whole product life cycle. Because the implementation of AM technologies is inherently linked to the development of products utilizing the AM benefits, the DRM framework is applicable to this research task. Moreover, following the DRM framework, supports the transfer of scientific results into practical application.

The DRM framework consists of four phases, which serve as a generalized structure to develop research findings. The four phases are the *Research Clarification (RC)*, the *Descriptive Study I (DS-I)*, the *Prescriptive Study (PS)* and the *Descriptive Study II (DS-II)*. In addition, BLESSING & CHAKRABARTI (2009) introduce the approach of a *review-based study*, which is only based on literature, and the *comprehensive study*, which uses information from literature and findings of the researcher. Combining the four phases and the study approaches, seven general types of research projects are defined in the DRM. It is emphasized by BLESSING & CHAKRABARTI (2009), that the DRM framework supports the individual, unique research approach and is not a fixed process or set of tools. Thus, the DRM framework allows for several iterations and parallel execution of phases to adopt to the specific requirements of the unique research project.

The research approach to obtain a *Technology Strategy for Metal-based Additive Manufacturing* follows the four development phases of the DRM framework. In particular, considering the applied study approaches, it follows a *Type 6* research project in the DRM framework. In such research project, the existing situation and need for improvement is concluded from literature (RC and DS-I). Then the research results are developed (PS) and evaluated (DS-II). To clarify the research goals (RC), an explorative study can be executed (DS-I) in an iterative process step. The research approach of this study is depicted in Figure 1.1.



Design Research Methodology (DRM) Phase and type of study		Research clarification (RC)	Descriptive study I (DS-I)	Prescriptive Study (PS)	Descriptive study II (DS-II)
		Review-based	Review-based	Comprehensive	Comprehensive
Chapter					
1	Introduction	▨			
2	Fundamentals and State of the Research		▨		
3.1	Hindrances to AM Adoption in Industry		▨		
3.2	Requirements for a Methodical Approach	▨			
4	Technology Strategy for Additive Manufacturing			▨	
5	Action Field A: Gather Technology Information			▨	
6	Action Field B: Evaluate Applications			▨	
7	Action Field C: Derive Organizational Tasks			▨	
8	Derivation of the *AM Technology Roadmap*			▨	
9	Application and Evaluation				▨
10	Conclusion and Outlook				▨

Figure 1.1: Research approach.

For the *Research Clarification*, the background and implications to setup a technology strategy in AM are investigated on the basis of a literature review. To concretize the research goal, the *Descriptive Study I* considers the fundamentals and state of research in metal-based AM technologies, technology management, and existing approaches for AM implementation (chapter 2). Moreover, the hindrances for AM implementation are analyzed by a review of relevant studies (section 3.1). On this basis, the research goals to overcome the limitations in the implementation of metal-based AM technologies are defined (section 3.2). These research goals are also the requirements for the methodical approach, which is developed in the *Prescriptive Study*. The development of the methodical approach is based on the prior investigated literature, experience from industrial use cases and expert discussions on how to implement AM technologies. The finally developed methodology to obtain an *AM Technology Roadmap* consists of three action fields (chapter 4 to 8). The tools and methods to obtain the technology strategy were iteratively developed by the author and continuously tested in producing companies. Thus, the *Prescriptive Study* follows a comprehensive approach, which combines literature review and research findings. In the *Descriptive Study II*, the developed methodology is applied in six manufacturing companies (section 9.1 to 9.5). The project duration to apply the methodology ranges from 3 to 48 months and covers different branches and company sizes. Hence, the research results obtained from the *Prescriptive Study* are transferred into practical application. Based on this practical application, the methodology is evaluated in the context of the requirements (section 9.5). Finally, conclusions are drawn from the practical application of the methodology and they are discussed in the context of the research assumptions and future research.

In general, the methodology to generate a *Technology Strategy in Metal-based Additive Manufacturing* is a methodical approach in the field of technology management. In particular, it can be assigned to the subordinate functions of technology identification and planning. Because the capabilities of metal-based AM technologies are evaluated for potential in a company, the approach entails the technology push principle, which leads to mid- to long-term innovation potential (EVERSHEIM 2009).

2 Fundamentals and State of the Research

The fundamentals and state of the research is analyzed in three thematic sections. First, metal-based AM processes are introduced, and the market development of these technologies is investigated (section 2.1). In the second section, the task of developing a technology strategy is set in the context of technology management (section 2.2). Finally, in the third section, methods to implement AM technologies in an industrial context are investigated (section 2.3), including approaches for part selection and cost modeling.

2.1 Metal-based Additive Manufacturing

Additive Manufacturing is defined in ISO/ASTM 52900 as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies." In light of this definition, AM processes are inherently linked to a 3D data model of the geometry for manufacturing. In the manufacturing process, the geometry is built by adding and joining volume elements. The fundamental additive principles of adding and joining volume elements are realized through manifold processes. These different approaches are categorized into seven process categories of AM (ISO/ASTM 52900). An overview of the AM process categories, which are relevant for the processing of metals, is depicted in Table 2.1.

In metal-based AM processes that utilize the *powder bed fusion* principle, the raw material is supplied as a thin layer of powder, which is then locally melted by an energy source. In *directed energy deposition* processes, raw material and thermal fusion energy are deposited in parallel, which enables a fully 3D toolpath. Processes that utilize the *extrusion* principle work on the basis of a nozzle, in which material is melted and then deposited. In a *binder jetting* process, the deposition unit deposits a binder on a powder bed consisting of another additional material. *Sheet lamination* processes work with a 2D sheet as raw material, which is then shaped and joined to the underlying layers of material. A detailed description of the functional principles is provided in ISO/ASTM 52900, YANG ET AL. (2017), and GEBHARDT (2016). In Table 2.1 metal-based AM processes are listed, including the feedstock material and number of suppliers, which is an indicator for the relevance of the specific AM process for production.

Table 2.1: Metal-based AM processes (ISO/ASTM 52900, MUNSCH ET AL. 2019B).

Process category (ISO/ASTM 52900)	**Single step / Multi step**	**Metal-based Additive Manufacturing Process**	**Feedstock material**	**Number of suppliers**
Powder Bed Fusion	Single	Laser-based powder bed fusion LPBF	Powder	36
	Single	Electron beam powder bed fusion EBM	Powder	4
	Multi	Metal SLS	Powder	1
Directed Energy Deposition	Single	Powder feed laser energy deposition	Powder	18
	Single	Resistance welding	Wire	1
	Single	Plasma arc energy deposition	Wire	2
	Single	Wire arc energy deposition	Wire	7
	Single	Electron beam energy deposition	Wire	2
	Single	Wire feed laser energy deposition	Wire	2
Extrusion	Multi	Metal fused deposition modeling	Filament	7
	Multi	MIM fused deposition modeling	Granulate	2
Binder Jetting	Multi	Binder jetting	Powder	4
	Multi	Hybrid binder jetting	Powder	1
Sheet Lamination	Single	Friction welding	Sheet	1
Process category not defined	Single	Cold spray	Powder	4
	Single	Friction stir welding	Rods	1
	Single	Liquid metal printing	Rods	1
	Multi	Nano-particle jetting	Dispersion	1

In addition to the process categories, AM processes are differentiated by joining process characteristics. ISO/ASTM 52900 distinguishes between a single-step process, in which similar materials are fused, and a multi-step AM process, in which dissimilar materials are joined through adhesion. The single-step process is defined as a process in which “the basic geometry and fundamental properties of the intended material [are acquired] in a single process step.” The multi-step process is defined as a process in which, at first, the geometry is acquired with an AM process and the fundamental properties of the intended material are built in a secondary process step. Figure 2.1 outlines single-step and multi-step processes.

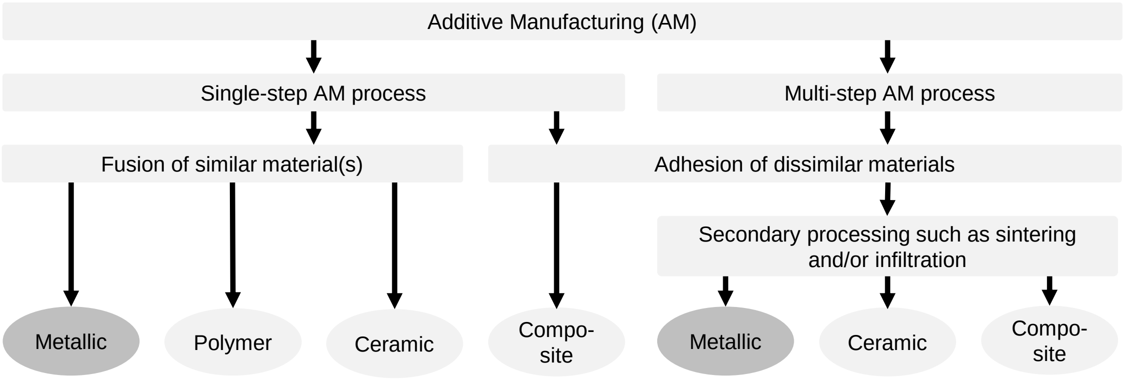
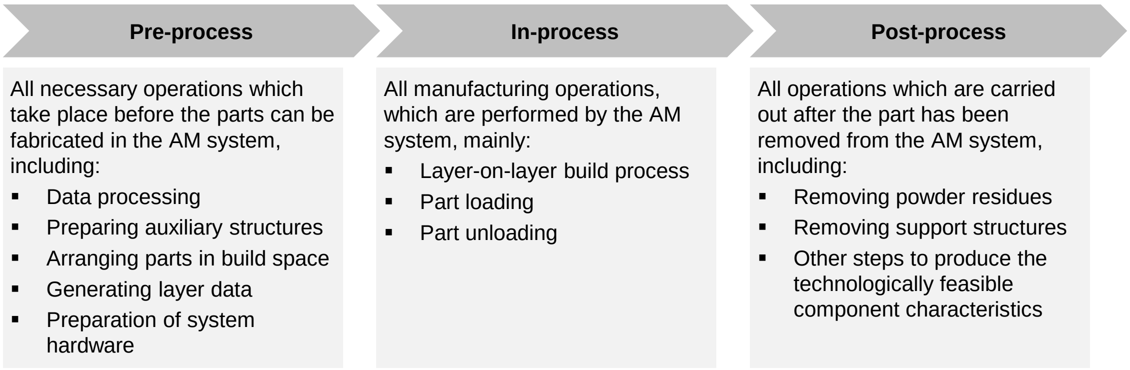


Figure 2.1: Single-step and multi-step AM processes (ISO/ASTM 52900).

Metal-based AM is the manufacturing of metallic parts through an AM production process, as depicted in Figure 2.1. Five out of the seven process categories in ISO/ASTM 52900 apply to the manufacturing of metallic parts. In total, there are 18 different metal-based AM processes (Munsch et al. 2019b). Four of them cannot be clearly assigned to one of the seven categories of AM, and thus, they are listed in Table 2.1 without a process category.

Metal-based AM processes are part of a process chain to manufacture technical products. A generalized process chain of AM processes is defined in the technical specification VDI 3405. The AM process chain is divided into three steps, which are pre-, in-, and post-processing. The definition of the process steps is depicted in Figure 2.2. It is essential to differentiate the multistep AM processes from post-processing of parts manufactured through single-step AM processes. In a multi-step AM process, the process steps are mandatory to obtain the desired part properties and are necessitated by the output of the AM process. For example, an AM part manufactured by binder jetting needs to be sintered to obtain metallic properties. By contrast, the post-processing of an AM part manufactured by a single-step process adjusts already existing material properties to meet the technical specification of the application.



Pre-process

All necessary operations which take place before the parts can be fabricated in the AM system, including:

- Data processing
- Preparing auxiliary structures
- Arranging parts in build space
- Generating layer data
- Preparation of system hardware

In-process

All manufacturing operations, which are performed by the AM system, mainly:

- Layer-on-layer build process
- Part loading
- Part unloading

Post-process

All operations which are carried out after the part has been removed from the AM system, including:

- Removing powder residues
- Removing support structures
- Other steps to produce the technologically feasible component characteristics

Figure 2.2: Generalized process chain for additive manufacturing (VDI 3405).

Several metals can be processed by metal-based AM. Due to the diverse functional principles of AM, each process is suitable for specific materials. For most single-step processes, the weldability of the metal is important because in the AM processes the material is melted locally to fuse it. The most utilized metals in AM are steels, aluminum alloys, titanium alloys, and Ni-based alloys. Moreover, Co-based alloys, hard metals, and precious metals are processed by metal AM (VDI 3405-3, BOURELL ET AL. 2017). BOURELL ET AL. (2017) investigated the range of material properties for metal-based AM by considering the ultimate tensile strength and break elongation of the resultant materials. An additional analysis for steels is provided by BAJAJ ET AL. (2020). The obtained overview of material properties for additively manufactured metals, including specific reference materials, is depicted in Figure 2.3.

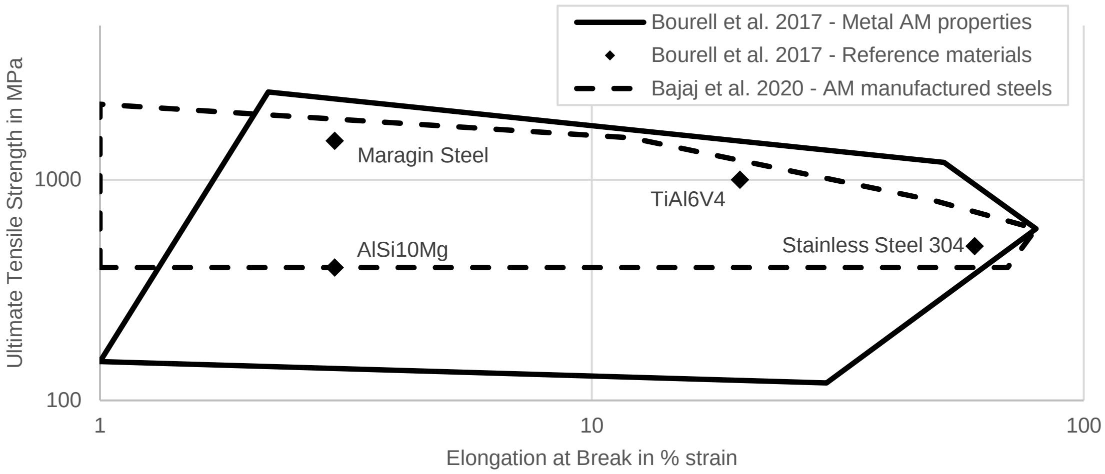


Figure 2.3: Material properties of additively manufactured metals.

The analysis of the market share of the AM process categories highlights the dominance of powder bed fusion (PBF) processes, as evident in Figure 2.4. The market analysis accounted for the total number of installed metal AM systems in 2018 (MUNSCH ET AL. 2019C), the number of metal AM systems sold in 2018 (MUNSCH ET AL. 2019C), and the types of metal AM systems available on the market (FROST & SULLIVAN 2018). Ninety percent of the installed base of metal AM systems in 2018 are systems for PBF processes. Considering the market available metal AM systems, PBF accounts for more than half of all available systems. Thus, currently PBF is the most important process class for metal-based AM. Within this class, the most utilized process is LPBF, which can be seen in the number of technology suppliers, listed in Table 2.1. In general, only four processes are provided from more than five suppliers. These are laser-based powder bed fusion (LPBF), powder-feed laser deposition (LMD), wire arc energy deposition (WAAM), and metal-fused deposition modeling (M-FDM). By contrast, 11 processes are provided by only one or two suppliers, which indicates a small ecosystem for such AM technologies. Although the relevance of other process categories is increasing, as can be seen in the sales numbers for AM systems, PBF remains the most important process category for metal-based AM.

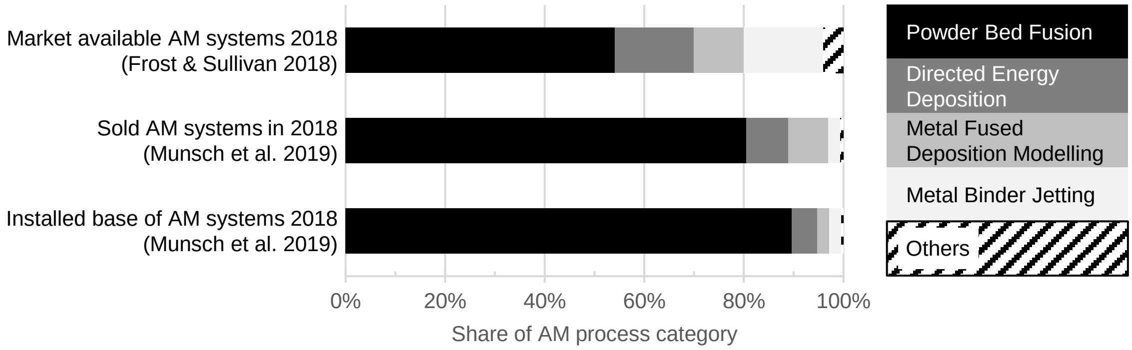


Figure 2.4: Market share of metal-based AM technologies. Data from M*UNSCH ET AL. (2019C) and* F*ROST &* S*ULLIVAN (2018).*

2.1.1 Powder Bed Fusion Processes

Because the process category of PBF is the predominant principle for metal-based AM, these process category is examined in more detail. Powder Bed Fusion is defined in ISO/ASTM 52900 as a “process in which thermal energy selectively fuses regions of a powder bed.” Within the class of PBF, there are two single-step AM processes to produce metal parts:

- Laser-based powder bed fusion (LPBF) and
- Electron beam melting (EBM).

PBF processes, especially LPBF, are the most utilized metal-based AM processes, as depicted in the market analysis in Figure 2.4 and in Table 2.1. In VDI 3405, the process of LPBF is named as laser beam melting, which is often referred to as LBM. Moreover, AM system manufacturers hold trademarks for processes called LaserCusing, Laser Metal Fusion, and Selective Laser Melting. Nevertheless, there are only little differences in the physical process principle among these.

The functional principle of the LPBF process is described in VDI 3405 and depicted in Figure 2.5. The fundamental LPBF principle was first described by MEINERS (1999). In the first step of the LPBF process, a layer of powder is deposited with a coater mechanism (1). The coater mechanism is equipped with a brush, roller, or blade to apply a thin layer of metal powder (commonly with a thickness of 20 – 120 µm). Second, the laser as energy source melts the powder material locally in the solidification zone (2). The laser spot is moved by a laser scanner. The areas for solidification are defined in the build job data in the form of a vector path describing the movement of the laser focal point. In the third step, the build platform is lowered for one layer height (3) before the next layer is applied by the coating mechanism.

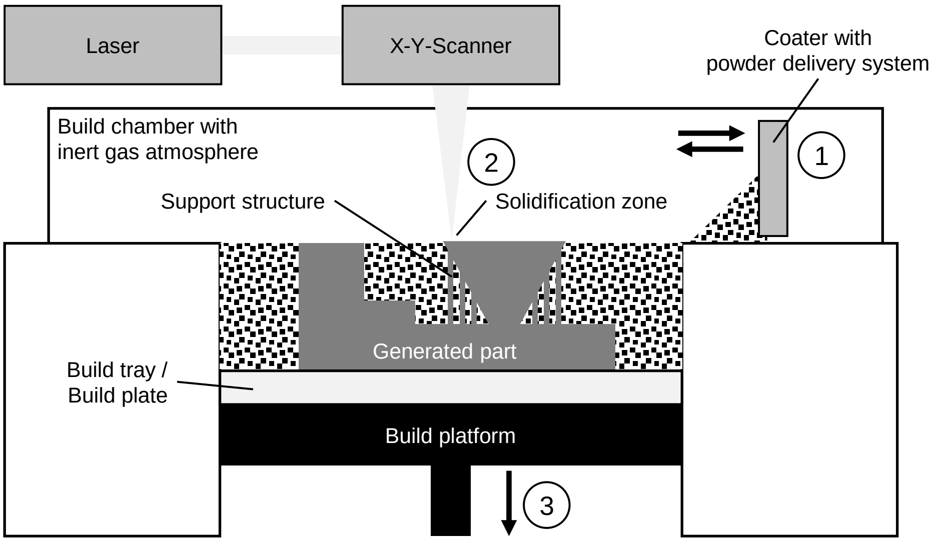


Figure 2.5: Functional principle of the LPBF process based on VDI 3405 and GEBHARDT (2016).

The process chain of the LPBF was investigated in detail by MÖHRLE (2018), who summarized nine literature sources to develop a comprehensive process chain of LPBF. The LPBF process chain is characterized by mandatory process steps, which are required to execute the LPBF manufacturing process. In addition, several process steps are optional, and so, they apply if necessary to manufacture the parts. The LPBF process chain is based on the general AM process chain of VDI 3405 that splits the process into pre-process, in-process, and post-process steps. Figure 2.6 shows the LPBF process chain based on MÖHRLE (2018).

Pre-processing for LPBF consists of three parts: preparation of the LPBF manufacturing system for the production task, the supply of appropriate raw powder material for the manufacturing process, and the preparation of the build job file. Whereas the preparation of the system and the raw material supply are mandatory for each production process, the build job file is created once if a new part is manufactured. The in-process stage covers all steps that are performed in the LPBF manufacturing system. The manufacturing process starts with generating the inert gas atmosphere (inertization) in the build chamber and tempering the build plate. Then, the iterative build process of coating, solidification, and lowering the build platform is executed until all layers of the build job are processed. Finally, the build chamber cools down before the residual powder and the build plate with the manufactured parts are removed from the LPBF manufacturing system. Prior to the start of a further production process, the LPBF manufacturing system needs to be cleaned.

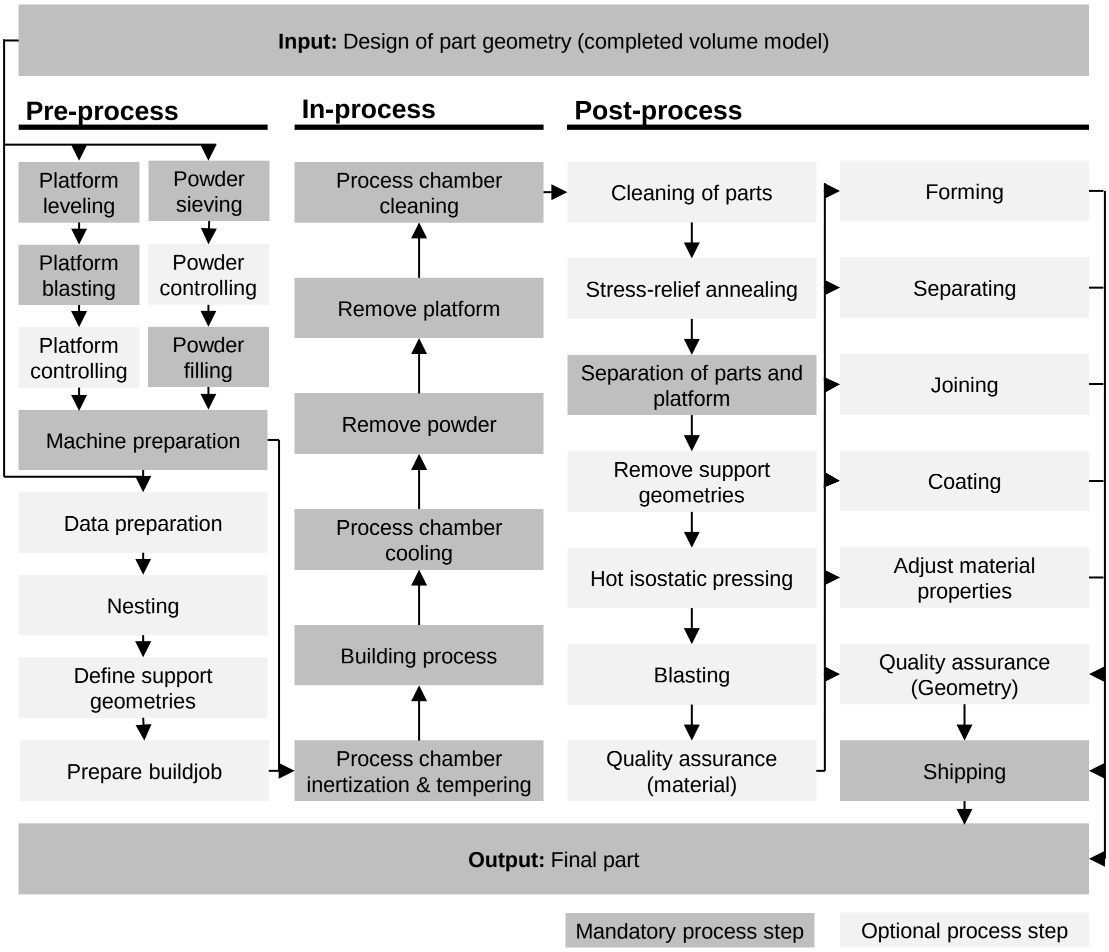


Figure 2.6: Process chain of the LPBF process (based on MÖHRLE 2018).

In the post-process stage, the only mandatory process step is to separate the manufactured parts and the build plate. However, in most cases, support structures also need to be removed from the manufactured parts. The finishing of the manufactured parts is dependent on the application purpose. Here, a variety of manufacturing processes can be applied to ensure the material, geometric, and surface requirements.

The second single-step AM process utilizing the PBF principle is EBM. Although the fundamental process cycle is the same as that for the LPBF process, the energy source for material solidification is an electron beam. This causes several points of differentiation with LPBF with respect to the process, manufacturing system, and suitable applications. A qualitative comparison of LPBF and EBM processes was presented by SCHNABEL ET AL. (2017) and is listed in Table 2.2. In conclusion, EBM offers a higher build rate than LPBF does, leading to lower cost per part for specific manufacturing tasks. However, EBM has limitations such as lower geometrical complexity, lower dimensional accuracy, and fewer available materials.

Table 2.2: Comparison of LPBF and EBM process (SCHNABEL ET AL. 2017).

	Laser-based Powder Bed Fusion (LPBF)	**Electron Beam Melting (EBM)**
Energy source	Laser (up to 1 kW per laser, up to 4 lasers per machine)	Electron beam (up to 3.5 kW)
Range of materials	Tool steels, stainless steels, Aluminum alloys, Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys	Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys
Controlled atmosphere	Nitrogen; Argon	Vacuum
Process temperatures	No pre-heating of each layer or process chamber, build plate optionally heated up to 250 °C or even higher	Pre-heating of each layer up to 1000 °C (e.g. for TiAl)
Susceptibility to residual stresses	High	Low
Stress-relief heat treatment required	Yes (in most cases)	No (in most cases)
Complexity of parts	High	Medium
Size of powder particles (typical range)	10 – 45 µm	45 – 105 µm
Part surface roughness (as-built)	Rz = 30 – 140 µm	Poorer than LPBF
Dimensional accuracy	0.1 mm	Poorer than LPBF (~ 0.5 mm)
Process speed	Poorer than EBM (single laser machines)	High (very high scan rates)
Typical applications	Components for all industrial sectors	Limited applicability due to limited complexity and accuracy of components; still low variety of materials
Residual powder	Flowable	Slight adhesion (powder cake)

2.1.2 Additive Manufacturing Market Development

Annual market data are published by WOHLERS ET AL. (2020). Based on this data, different aspects of market development are investigated.

The AM market size is estimated to be $11.9bn in 2019 (WOHLERS ET AL. 2020). In comparison to the global production market size, AM accounts for 0.077% of global manufacturing (WOHLERS ET AL. 2019). In addition, NIAKI & NONINO (2018) state that the global AM market is less than 2% of total manufacturing, and MUNSCH ET AL. (2019A) estimate a share of 0.2% for metal-based AM.

Even though the AM market is small compared to the global manufacturing market, it has seen significant growth over recent years, which is depicted in Figure 2.7. In the recent decade, each year the AM market continued to growth. Except 2016, the annual growth rate exceeded 20% in this timespan.

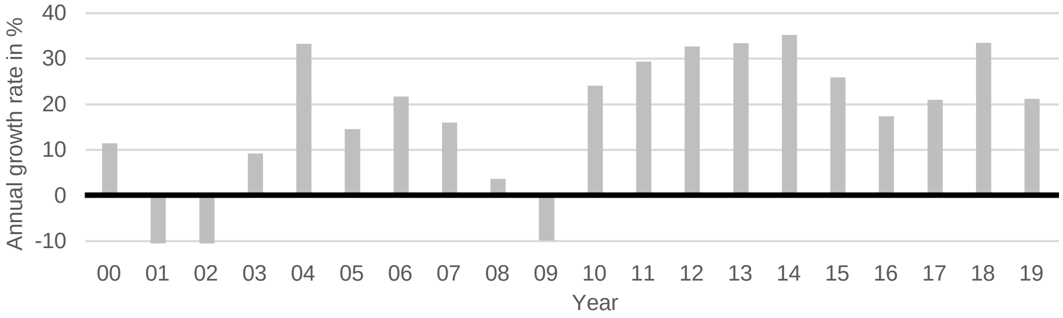


Figure 2.7: Overview of AM market growth. Data from W*OHLERS ET AL*. *(2020).*

The market growth is caused by AM system sales, which is a precondition for additive manufactured products, and material revenue, which is a measure for the real AM production. These indicators for the total AM market and the metal-based segment are depicted in Figure 2.8. The annual growth rate for the number of AM systems sold, including all AM systems with a sales price over $5,000, is 14.4% over the 10-year period of 2009 to 2018. Material revenue grew annually by 20.2% in the same time span. For metal-based AM, a turning point was reached in 2013 – 2014. Since then, in the years 2014 – 2018, the number of metal AM systems sold increased by 45.4% per year, and the material revenue with metallic materials increased by 51.5% annually. In addition, the market share of metal-based AM increased. In 2018, more than 10% of all AM systems sold were metal-based AM systems. Considering the growth rates for AM systems sold and material revenue, it is evident that metal-based AM has exceeded the growth rate of the total AM market. Nevertheless, since 2015 – 2016, the growth rate has decreased slightly.

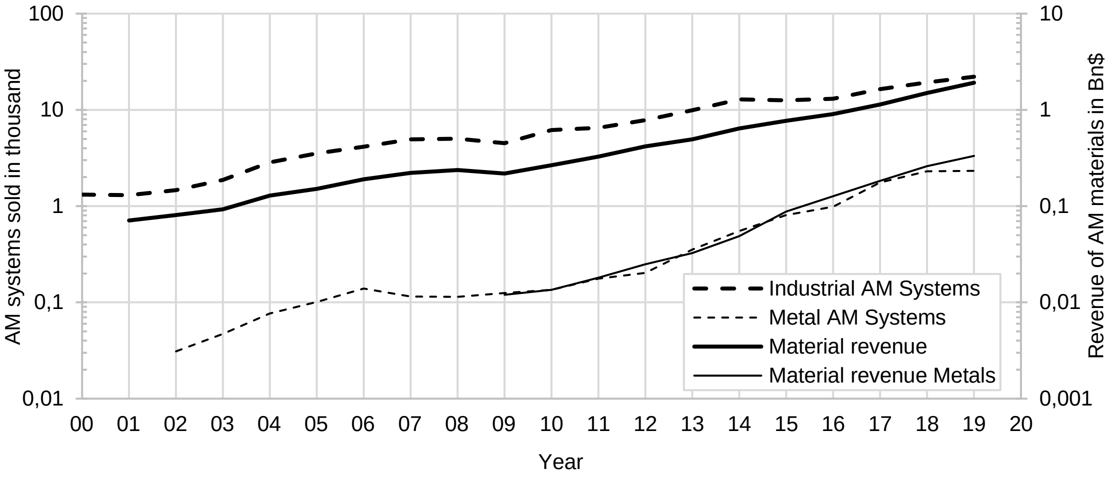


Figure 2.8: AM system sales and material revenue for total AM market and metal-based AM. Data from W*OHLERS ET AL*. *(2020).*

AM is a small market today but offers advantages for several domains of industry, which has fostered its growth over the last years. It is expected that the market growth will continue. Estimates of AM market growth until 2025 range from an annual 8% proposed by LuxResearch to 53% proposed by McKinsey (SEIDEL & SCHÄTZ 2019). The forecast of WOHLERS ET AL. (2019) foresees an annual market growth of 29.4% up to 2024. Taking a long-term perspective, WOHLERS ET AL. (2019) estimates AM will capture 5% of the manufacturing market, which would result in a 65-times larger AM market compared to 2018.

In conclusion, metal-based AM is a new and fast growing manufacturing technology, which offers advantages to producing companies. Metal-based AM can be realized by several functional principles of AM, however the most relevant process in industrial application is LPBF. In LPBF, thin layers of metallic powder are locally fused by a laser beam. The use of LPBF is part of a process chain, which consists of pre-, in- and post-processing steps to manufacture a technical product.

2.2 Technology Management

In the following section, the task to develop a technology strategy is discussed in the context of technology management. At first, definitions and functions of technology management are presented. Then the characteristics of a technology strategy are investigated. Finally, approaches for technology roadmapping are compared.

The term *technology* is defined as “the individual or common, explicit or implicit, scientific knowledge regarding solutions for technical problems” (SCHUH 2013). Thus, a *technology strategy* is a plan that defines actions to reach the long-term goal of utilizing a technology to generate advantages (SCHULTE-GEHRMANN ET AL. 2011). Hence, to establish a technology strategy is a task for technology management. The following section introduces the framework conditions and tasks of technology management.

The St. Gallen Management Concept (SGMK) is a holistic framework for the management of an organization. The SGMK proposes three levels for management activities: normative, strategic, and operational management (BLEICHER 2017). The advanced fourth version of the SGMK focuses on the framework conditions for successful management and integrates external influences on an organization (RÜEGG-STÜRM & GRAND 2017). The SGMK addresses the management of value creation and improvements in organizational structure (RÜEGG-STÜRM & GRAND

2017, Bleicher 2017). Due to its general approach, the conceptual framework is adaptable to subsystems within an organization. Eversheim et al. (2009) proposed the Aachen Innovation Model (AIM) for innovation management, which is based on the SGMK concept. Furthermore, Schuh & Klappert (2011) and Abele (2006) set the tasks of technology management in the context of the SGMK. Technology and innovation management cannot clearly be distinguished and intersect in several aspects. Technology management focuses on the capability of technologies, but innovation management is more focused on specific products (Klappert et al. 2011). Based on the SGMK concept, the tasks of technology management are integrated into the management context of an organization, as depicted in Figure 2.9 (Schuh et al. 2011).

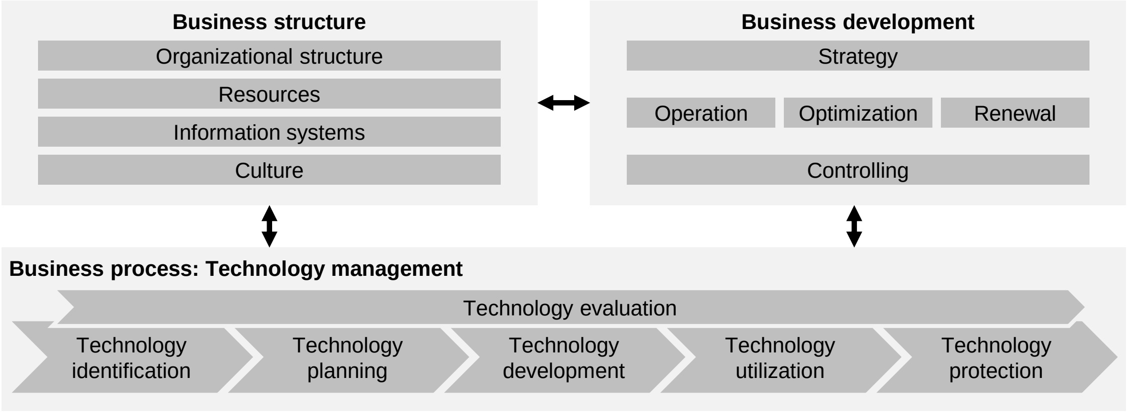


Figure 2.9: Framework for technology management. Based on Schuh et al. (2011).

According to Schuh et al. (2011), technology management consists of six processual phases, which are summarized in the following. The first step is *technology identification*, which addresses the screening for relevant technologies and their development in the context of the organization. In this phase, information about new technologies and the capability of existing technologies is collected and summarized to provide a data foundation for decision-making. In *technology planning*, all actions, processes, costs, resources, and deadlines to utilize an identified technology are established. Thus, it is the operationalization of the goals described in the technology strategy. Outcomes of the planning phase are precisely described and realizable requirements for technology development and utilization. The goal of *technology development* is the efficient realization of the defined requirements. Hence, a particular technological capability must be developed with available resources and within the predefined time span. Technology development follows a development process, which provides transparency about the development state. The next phase is *technology utilization*. In this phase, there are two basic concepts for technology utilization: internal use of the technology capability and external use. Internal exploitation of technological capabilities focuses on the generation of product benefits through the technology and thus provides an advantage for the company. Externalization tries to maximize economic benefits by providing the technology to third parties, including strategic alliance partners, licensees, or buyers. For developed technologies, the aspect of *technology protection* is an important task of technology management. With appropriate and systematic measures, a leakage of know-how is prevented. Moreover, mechanisms to protect internal technological know-how are developed. In parallel to the five introduced phases, continuous *technology evaluation* is executed. Having effective and efficient evaluative processes to assess technological capabilities is a base competence of technology management. The evaluative approaches need to deliver profound background information to inform decisions in all other technology management phases.

With a focus on production technologies and the underlying process chains for production tasks, REINHART ET AL. (2012) and GREITEMANN (2016) have proposed an approach to identify suitable production technologies. In this approach, search fields are established to describe the required production task. To identify suitable technologies for the production task, a model integrating several information sources is established and delivers technology information based on the definition of relevant search fields and corresponding search queries. Finally, the generated information about the technology is aggregated into a formalized onepager document. This onepager document can be utilized for further technology planning.

A methodical evaluation approach for the strategic planning of entire process chains for production tasks was developed by REINHART ET AL. (2011) and SCHINDLER (2014). The approach focuses on deriving a maturity level for the process chain and integrating various interconnected technologies. Based on qualitative and quantitative criteria, the maturity level of the process chain is described by seven maturity grades. As a subpart of the methodology, a questionnaire that is answered by technology experts, is used to assess the maturity of a specific technology.

The maturity of a technology is described by several approaches. The time-based development of technological maturity is categorized into three phases: pacemaker, key, and base technology (SCHUH 2013). The model is known as *S-shaped-model of technology performance*, as depicted in Figure 2.10. Key characteristic of these phases are investigated in ABELE (2006). A *pacemaker technology* is in an early development phase. It has high potential, but availability and applicability are limited. Therefore, the influence of a pacemaker technology on the market is low. A *key technology* exhibits rapid development in technological performance, and there is still a high potential for further development. A key technology has a strong influence on the products and cost structure of a company adopting the key technology. A *base technology* is an established technology in the market, offering high and well-grounded technological performance but having limited technological potential. Because a base technology is established in the market, it is easy to access. Thus, there are only few competitive advantages and the risk of technology substitution is high.

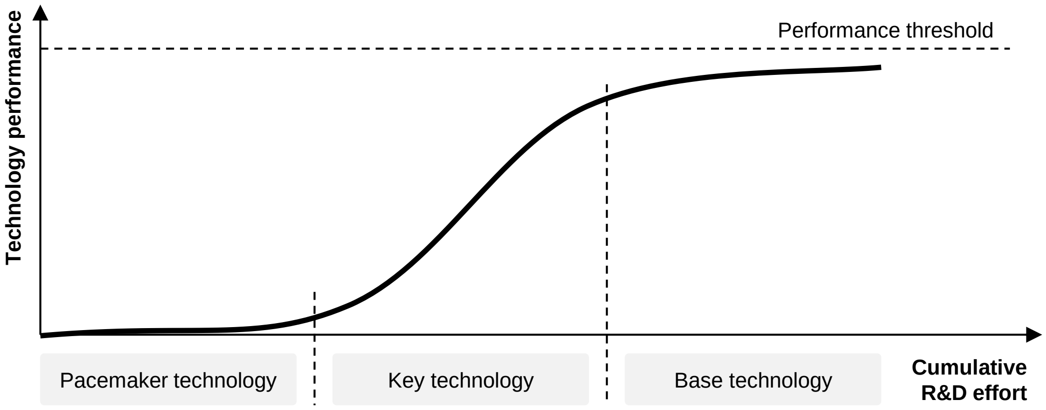


Figure 2.10: S-shaped-model of technology performance (SCHUH 2013).

A widespread measure for technology maturity is the *Technology Readiness Level*, also referred to as *TRL*, standardized in DIN ISO 16290. The TRL is derived and used by the US National Aeronautics and Space Administration (NASA) to assess the maturity of technologies. It defines nine levels of technology readiness for the use of a particular technology in a space mission, stated in Table 2.3.

Closely linked to the TRL is the *Manufacturing Readiness Level (MRL)*. Whereas the TRL defines the maturity of a product technology (especially for applications in space missions), the MRL describes the maturity of the manufacturing capability. The MRL is not standardized, but an open access definition is provided by the DEPARTMENT OF DEFENCE (2018). The MRL corresponds to the nine levels of the TRL model; in addition, there is a tenth level defining the technology state of full rate production and lean production practices in place. The definition of MRL is given in Table 2.3.

Table 2.3: Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) (DIN ISO 16290, DEPARTMENT OF DEFENCE 2018).

	Technology Readiness Level (TRL)	**Manufacturing Readiness Level (MRL)**
1	Basic principles observed and reported	Basic Manufacturing Implications Identified
2	Technology concept or application formulated	Manufacturing Concepts Identified
3	Experimental and analytical critical function and characteristic proof of concept	Manufacturing Proof of Concept Developed
4	Component or breadboard validation in a laboratory environment	Capability to produce the technology in a laboratory environment
5	Component or breadboard validation in a relevant environment	Capability to produce prototype components in a production relevant environment
6	System or subsystem model or prototype demonstrated in a relevant environment	Capability to produce a prototype system or subsystem in a production relevant environment
7	System prototype demonstration in an operational environment	Capability to produce systems, subsystems, or components in a production representative environment
8	Actual system completed and “flight qualified” through test and demonstration	Pilot line capability demonstrated; ready to begin Low Rate Initial Production (LRIP)
9	Actual system “flight proven” through successful mission operations	Low rate production demonstrated; Capability in place to begin Full Rate Production (FRP)
10	[does not exist]	Full Rate Production demonstrated and lean production practices in place

2.2.1 Technology Strategy

A *technology strategy* is a plan defining actions to reach the long-term goal of utilizing a technology to generate advantages (SCHULTE-GEHRMANN ET AL. 2011). Thus, it defines goals and the fundamental approach to achieve them. The five aspects of a technology strategy with the underlying characteristics, following SCHULTE-GEHRMANN ET AL. (2011), are summarized in Figure 2.11.

Aspect of strategy	**Characteristics**		
Technology focus	Used in company	Market available	Completely new
Technology performance	Technological leadership	Technological presence	
Technology source	Internal	External	
Technology timing	Pioneer	Early follower	Late follower
Technology utilization	Internal	External	

Figure 2.11: Aspects of a technology strategy. Based on SCHULTE-GEHRMANN ET AL. (2011).

At first, the focal technologies of the strategy are defined. These can be technologies that are already in use in the company, market available, but not used within the company, or are completely new. The second aspect considers technological performance in reference to the market benchmark. If it is a technological leader, a company builds and maintains an advantage through unique technological capabilities. Mostly, the company executes fundamental research in the technology. If a technology is utilized in the company on the level of market available technology performance, it follows a technical presence approach. The third aspect of the technology strategy is sourcing the technology. Here, the main choice is to decide on developing an internal supply or choosing an external supplier. An internal supply requires the realization of technology development with internal resources. By contrast, an external supply is realized through various forms of cooperation or acquisition—for example, buying licenses or forging an R&D cooperative venture. Technology timing covers all time-based aspects of the technology strategy, especially the start for technology development and market entry. A pioneer introduces a technology to the market first, whereas an early follower enters the market with a short time delay. Late follower enter the market when a technology and the market are stabilized to reduce risks. Finally, the technology strategy considers the aspect of technology utilization. Internal technology utilization is mostly applied for core competencies of the company and enables long-lasting economic benefits. External utilization includes intercompany cooperation or sale.

To establish a technology strategy, SCHULTE-GEHRMANN ET AL. (2011) proposed five steps, as depicted in Figure 2.12. At first, internal technologies of the company are analyzed, encompassing product and process technologies. In the second step, the environment is analyzed and externally available technologies are evaluated. In the third step, the identified technologies are clustered into technology fields on the basis of shared properties. Finally, the technology strategy is formulated to address previously introduced aspects. In the final step, the consistency of the technology strategy is approved.

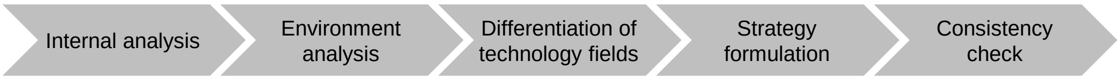


Figure 2.12: Process to develop a technology strategy. Based on SCHULTE-GEHRMANN ET AL. (2011).

In general, two main technology strategies can be distinguished when considering the technology potential and the market demand (EVERSHEIM 2009). The strategy of *market pull* tries to identify and exploit market opportunities as basis for product development. In contrast, a *technology push* strategy focusses on strengthening the internal technology potential (e.g., patents, licenses) and to transform this potential into products. A market pull approach generates mostly short-term potentials, whereas the technology push strategy leads to mid- to long-term innovation potentials.

2.2.2 Technology Roadmap

The concept of roadmapping is commonly used in industry, but there is no consistent structure for roadmaps (SCHUH 2013). Nevertheless, constituent elements of a roadmap were defined by SCHUH (2013), which are depicted in the generic structure of a roadmap in Figure 2.13; these include the following:

1. *Timeline* for chronological ordering of planning elements.
2. *Planning levels* for a content-based structure of the roadmap (e.g., markets, products, technologies).
3. *Planning objects* as elements covering a period on the timeline.
4. *Connections* between planning objects on different planning levels to visualize interdependencies.

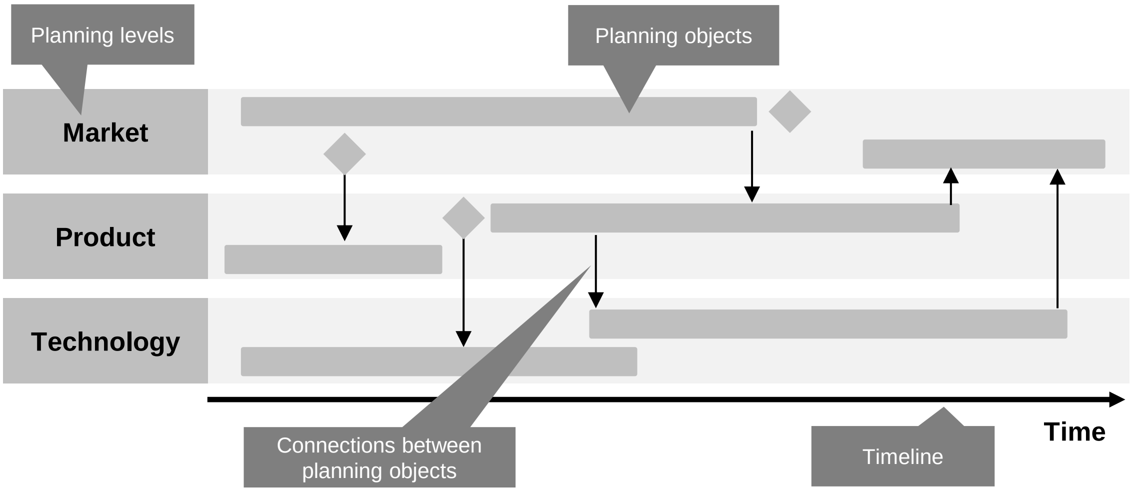


Figure 2.13: Constituent elements of a roadmap. Based on SCHUH (2013).

To avoid uncertainty in a longer forecast period, SCHUH (2013) recommended reducing the detail of long-term forecasts. Based on a study, SCHUH (2013) determined that 96% of investigated roadmaps covered a time period of up to 10 years and 66% focused on periods up to 6 years. SCHUH (2013) defined roadmaps through constituent elements, but EVERSHEIM (2009) defined *technology road mapping* based on purpose:

> "Technology road mapping enables the prognosis, analysis and visualization of future technology developments. The goal is the prognosis and evaluation of future developments in a certain field of activity. Road mapping is made up of the generation of the roadmap and the actual result presentation as a roadmap." (EVERSHEIM 2009)

In addition, Möhrle & Isenmann (2017) defined a technology roadmap as a graphical representation of technologies and their linkages over time, which is more generic but equivalent to the definition of Schuh (2013). Based on the definition of Eversheim (2009), roadmapping consists of the two steps of *generation of the roadmap* and *actual result representation*. This definition is supplemented by Schuh (2013), who identified the three steps of *obtain the goal of the roadmap, gather and analyze information*, and *set up the roadmap*.

One major limitation of a roadmap is its dependency on the involved experts. As stated by Schuh (2013), interdisciplinary experts must be integrated into the roadmapping process to obtain a reliable result. The importance of internal technology experts was also demonstrated by Greitemann (2016), who investigated the relevance of 15 information sources in reference to technology performance development. Based on a study with 55 participants, the information sources for each technology phase were evaluated. The five highest-ranked information sources from the study are shown in Figure 2.14.

In every phase of technology maturity, internal experts are the most valuable information source. In the early technology development phases, formal information (e.g., scientific publications, technology studies) are of higher relevance than in later developmental phases. Therefore, informal sources become more important in later technology phases (e.g., external experts and business partners, personal contacts). For the establishment of a technology roadmap, the identification of suitable information sources is an important task. Moreover, internal experts are a valuable information source in every phase of technology development and have a major influence on the result of a roadmapping process.

		Pacemaker technology	**Key technology**	**Base technology**
Ranking of information source	**1**	Internal Experts	Internal Experts	Internal Experts
	2	Internet	Internet	External experts and business partner
	3	Research institutions and universities	External experts and business partner	Internet
	4	Scientific publications	Scientific publications	Personal contacts
	5	Technology studies	Personal contacts	Commercial events

Figure 2.14: Ranking of information sources based on the phase of technology performance. Based on data from Greitemann (2016).

In conclusion, the setup of a technology strategy is a task of technology management. In the framework of technology management, the setup of a strategy is addressed in the steps of technology identification and technology planning. The technology strategy defines actions to utilize the evaluated technology in the company. A roadmapping approach is appropriate to setup and visualize a technology strategy. To obtain a reliable roadmap, interdisciplinary experts must be involved in the roadmapping process.

2.3 Implementation of Additive Manufacturing

The evaluation and introduction of AM technologies in an industrial context is often referred to as AM implementation (cf. Deradjat & Minshall 2018, Lutter-Günther et al. 2015a, Grund 2015, Mellor 2014). In the following section, approaches for AM implementation are introduced. Moreover, the current state of research on the subordinate tasks of identification and evaluation of suitable parts and cost calculation is presented.

According to Beskow et al. (1999), a change process consists of the steps of planning, implementation, and evaluation. In the *normalized introduction process* proposed by Haberstroh (2018), which was derived from the investigation of five change process models, the preparation and execution phase is part of implementation. Both approaches are depicted in Figure 2.15.

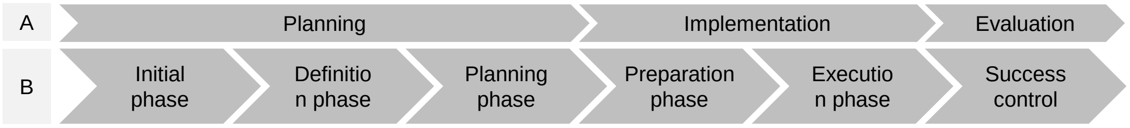


Figure 2.15: Generalized change processes. Based on Beskow et al. (1999) (A) and Haberstroh (2018) (B).

Based on these generalized change processes, the term *implementation* denotes a phase in which a predefined plan is executed, whereas the derivation of the plan or strategy is part of the planning phase. By contrast, the use of the term *AM implementation* in literature describes the evaluation and introduction of AM technologies in an industrial context, including all subordinate aspects. Thus, there is mostly no precise separation between planning and execution phases. In the following, the term *implementation* includes all previously mentioned aspects.

Methodical approaches, which describe the implementation of AM, address all steps of technology evaluation and introduction. Thus, a holistic view of the topic is adopted from the perspective of an organization that introduces AM technologies. The AM implementation approaches discussed in the literature can be clustered by the structure of the suggested approach. Some approaches describe AM implementation as a time-based process, expressed by steps following each other. In contrast, other approaches focus on the challenges to an organization deriving fields of action that must be considered for AM implementation. Based on these classifications, Table 2.4 presents an overview of AM implementation approaches in the literature. Moreover, it is indicated whether an approach includes supporting tools for AM implementation, such as checklists, cost models, or design guidelines.

Table 2.4: Overview of AM implementation approaches.

	Process approach	**Action field approach**	**Supporting tools**
Rohde 2019 Büsching & Koch 2017	✓		✓
Leutenecker-Twelsiek 2019 Klahn et al. 2018	✓		✓
Ilg 2019 Ilg et al. 2019	✓		✓
Illgner 2018	✓		
Lakomiec 2018	✓		✓
Lindemann 2017		✓	✓
Feldmann & Pumpe 2016	✓		✓
Grund 2015		✓	
Lutter-Günther et al. 2015	✓	✓	✓
Mellor 2014 Mellor et al. 2014		✓	✓
Cotteleer 2014		✓	

The literature review shows that most AM implementation approaches utilize a process-based structure for implementation. However, there are also approaches that describe implementation on the basis of action fields within a company. Most approaches integrate supporting tools to facilitate AM implementation. Selected AM implementation approaches are summarized in the following section, ranked by descending publication date.

Rohde (2019) and Büsching & Koch (2017) develop a process for the integration of AM into serial production, which is depicted in Figure 2.17. The process integrates a technical and economic part evaluation and the linkage to the product development processes of the applying company. The integration process utilizes the part identification methods of LINDEMANN (2017) and KRUSE ET AL. (2017). A data-based part screening approach is mentioned, but not presented in detail. Moreover the external supply of parts is insufficiently addressed. Thus, the approach focusses on establishing a serial production for selected parts.

Figure 2.16: Seven phases of AM technology integration. Based on ROHDE (2019).

LEUTENECKER-TWELSIEK (2019) proposed an Experience-based Transfer Model (ETM) for the implementation of AM technologies. The model covers three phases for building know-how and developing first applications with AM. Figure 2.17 presents an overview of the ETM model, which consists of the three phases of *theory* explanation, *application* and *feedback*. These phases are gone through twice. At first, the focus is on part identification, whereas the second run sets the focus on the realization of specific applications in AM. To facilitate part identification and the design of applications, LEUTENECKER-TWELSIEK (2019) offered tools and guidelines to execute different tasks in the ETM model.

The benefits of AM are summarized in four potential clusters, covering *functional integration*, *lightweight design*, *increase of performance*, and *individualization/small batch size*. A specific application is evaluated in four aspects: technical feasibility, effort for post-processing, customer benefits, and original equipment manufacturer benefits. Based on rating criteria, a point score for each aspect is obtained and aggregated into a final point score of the application. The evaluation result is summarized in an onepager document.

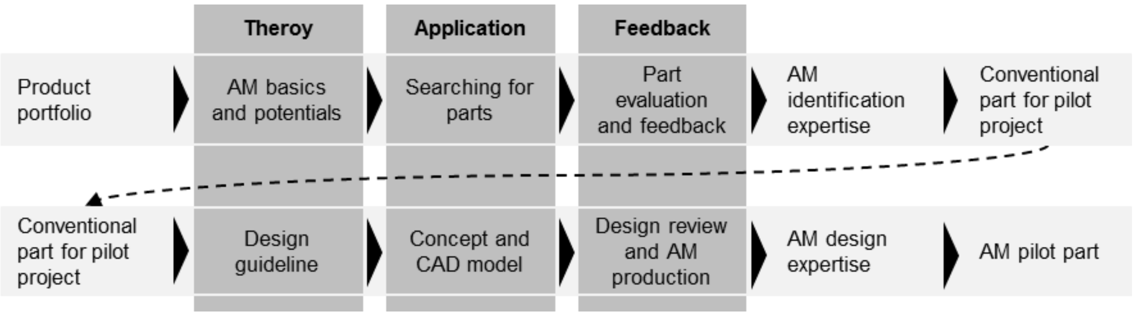


*Figure 2.17: ETM model to implement AM technologies (*LEUTENECKER-TWELSIEK *2019).*

The implementation model of ILG (2019) is focused to small and medium-sized enterprises (SMEs). The aim of the model is to provide a structured and user-friendly approach to test the suitability of AM processes. It includes the selection of materials and processes and a procedure for technical and economical evaluation. The model distinguishes a *selection level* where appropriate processes, materials, and applications are selected and an *analysis level* in which the findings are gathered from the selected case studies in terms of quality, manufacturability, and economical aspects, depicted in Figure 2.7. Moreover, the model was validated through application to an SME in the medical sector.

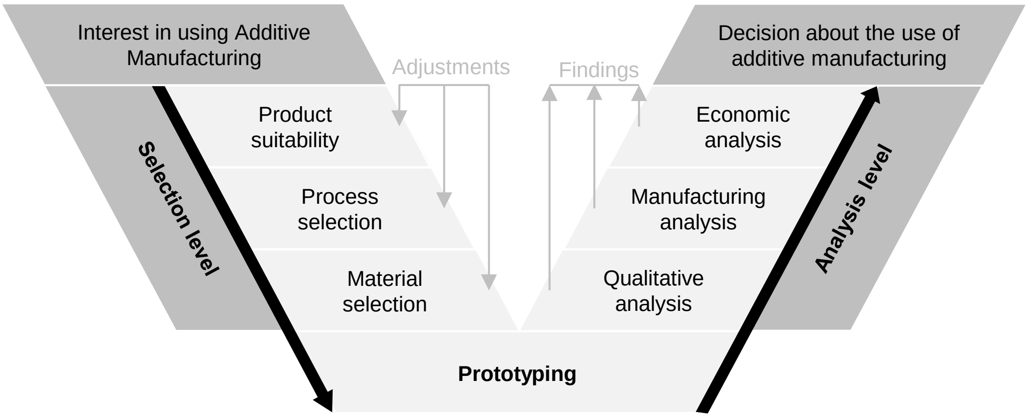


Figure 2.18: Systematical evaluation of AM processes for SME (ILG ET AL. 2019).

LAKOMIEC (2018) proposed three phases of AM implementation based on the products to be manufactured, see Figure 2.19. In the first phase, *development hardware*, toolings, and fixtures are manufactured additively to gain first experience with the manufacturing process. These products are only for internal applications to reduce the impact in case of part failure. The second phase, *substitution*, is based on conventionally manufactured products that can also be manufactured by AM without changes in design. In the third phase, *new design*, opportunities achievable through AM are exploited. In this phase, products are developed that use the full potential of AM. In all three phases, *overall factors* are considered to obtain a business case in AM based on the company's situation and market demand. The approach of LAKOMIEC (2018) was validated in the aerospace industry: AM is stated to be a production process for "expensive, highly-complex industrial applications in low numbers," which meets the demand of the aerospace industry, but application of AM in further branches is expected in the near future.

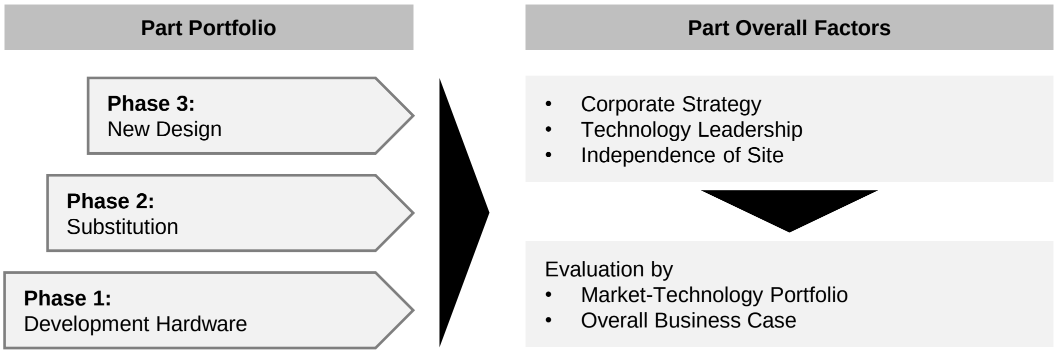


Figure 2.19: Implementation and part identification approach of LAKOMIEC *(2018).*

ILLGNER ET AL. (2018) proposed an approach for the systematic evaluation of AM technologies within a company. Figure 2.20 shows the five steps of the systematic process. At first, the *frame conditions and focus* of the evaluation have to be clarified. Then, the AM technology and *business cases are defined*. In the third step, a *combined part identification* is proposed, consisting of a data-based analysis, a knowledge-based analysis, and an evaluation of the identified parts. The fourth step is to *develop functional prototypes* and approve the technical feasibility of the identified parts. Finally, the fifth step covers the *planning and layout* of the AM process chain, which covers the setup of a production facility as well as establishing a supplier network. During all process steps, it is important to support the building of know-how through trainings and know-how transfer. All information produced during the process are collected into a roadmap for AM technologies, thus providing an overview and tool for implementation planning. The approach focusses on the process description, whereas tools or guidelines to execute the process are not discussed.

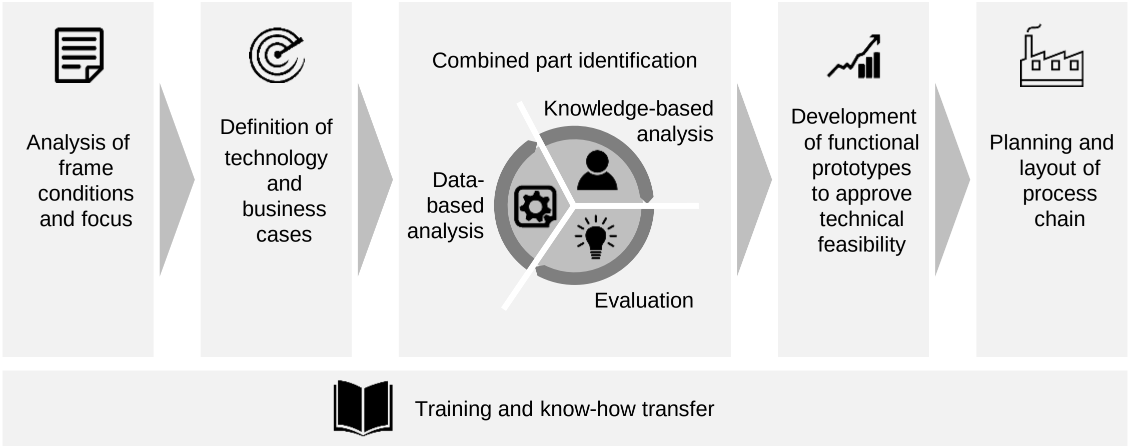


*Figure 2.20: Systematic evaluation of AM technologies (*ILLGNER ET AL. *2018).*

LUTTER-GÜNTHER ET AL. (2015A) described a process model for the implementation of AM. The model consists of five steps to identify and implement an AM business case and is depicted in Figure 2.21. The focus is on economic use of AM within the company. The model is based on the typology of five business models derived from AM technology characteristics. The business models are

1. Enabler for design optimization,
2. Value-add by customization,
3. Cost-efficient production method,
4. New supply chain concepts, and
5. Repair by AM.

In conclusion, three fields of action for AM implementation in a company have been identified, which cover the product, the process chain, and the organization. Moreover, it is recommended to establish a responsible team for AM implementation and business case development consisting of company executives and AM experts.

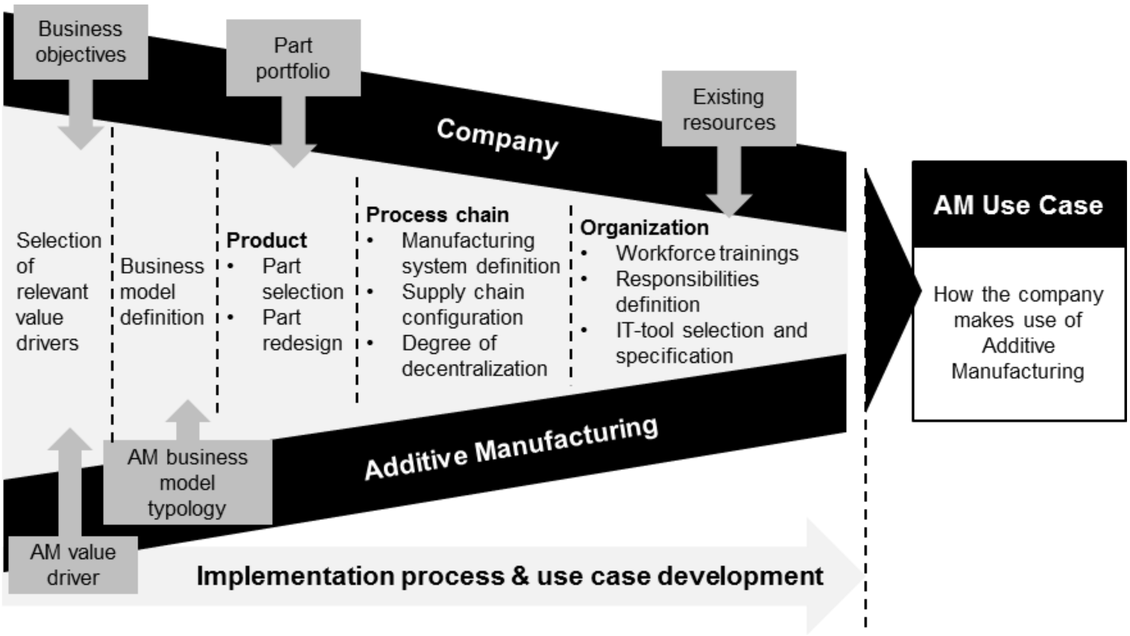


Figure 2.21: Process model for AM implementation (LUTTER-GÜNTHER ET AL. 2015A).

MELLOR (2014) and MELLOR ET AL. (2014) proposed a normative AM implementation framework based on a socio-technical study in seven companies. The derived model of AM implementation covers five key dimensions of AM implementation and influential external forces, as shown in Figure 2.22. Additionally, four key phases of AM implementation were derived. These phases are the development of the business case, the organizational action plan, an operational action plan, and the establishment of an AM supply chain. In the evaluation, the chances and risks of the AM business cases are identified along the AM process chain. The main findings in the study were that AM implementation should be treated as "a manufacturing strategy implementation process" and that it is indispensable that AM managers "understand how to build the business case for AM technologies," which highlights the importance of internally available knowledge about AM technology.

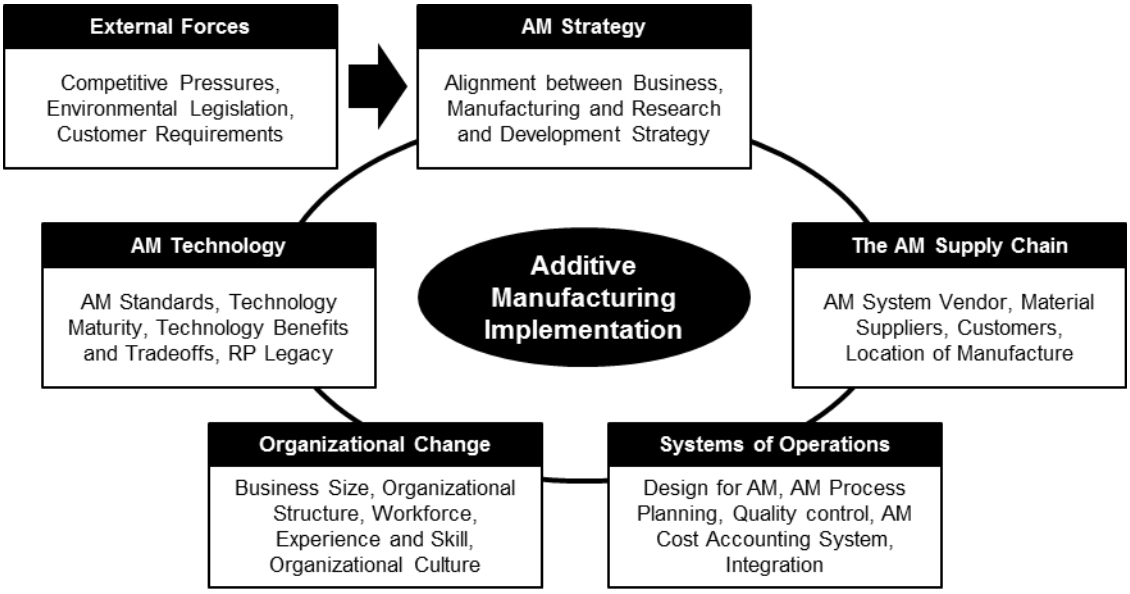


Figure 2.22: Framework for AM implementation (MELLOR ET AL. 2014).

2.3.1 Identification and Evaluation of Applications

Companies that implement AM technologies pursue two main goals: finding and exploiting business cases or compiling knowledge of the technology (LEUTENECKER-TWELSIEK 2019). Following MELLOR (2014), the understanding of the business case is the most important ability of AM managers. A business case is when the cost of AM production is lower than the conventional cost or the added value in the product justifies the higher AM production cost (THOMPSON ET AL. 2016). In summary, a business case is an economic use of AM for a specified production task. Thus, it is an important step in AM technology implementation to identify and evaluate parts that benefit from AM technology.

The fundamental approach to select suitable AM applications is a matching of production task and production technology, both described by individual characteristics. The generalized approach is depicted in Figure 2.23. On the one hand, there is an existing part, idea, or functional description that characterizes the production task. On the other hand, there is the AM process and AM process chain, which is defined by process characteristics. To clarify if the AM process is suitable for the production task, the part and process characteristics are compared. This comparison can be supported by different approaches of decision support methodologies. There are three outcomes that result from the comparison: the AM process is suitable for the production task, the AM process is not suitable for the production task, or the data are insufficient for a decision. In the last case, the characteristics of the production task and production process must be updated with additional information until a decision can be made. Depending on the point of view, different aspects of AM implementation are covered by the scheme in Figure 2.23. When starting with the process characteristics and searching for parts to manufacture, it is a *part identification* approach. By contrast, when starting with a production task and evaluating different AM processes, it is a *process selection* approach.

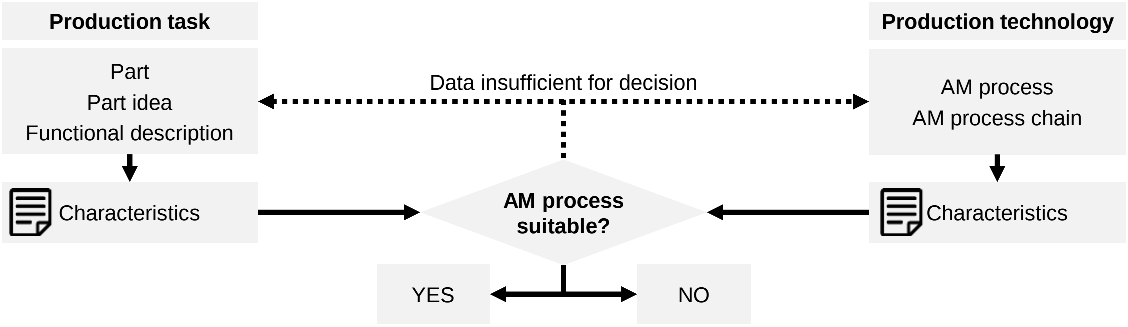


Figure 2.23: Part and process identification methodologies.

The evaluation of AM suitability for a specific production from a design perspective is described in ISO/ASTM 52910. *Design for Additive Manufacturing (DfAM)* is defined as “the design of all types of products, devices, systems, components or parts that are fabricated by any type of AM system” (ISO/ASTM 52910). An introduction to design approaches for AM is provided in KUMKE (2018), KRANZ (2017), BOOTH ET AL. (2016), and VDI 3405-3. KUMKE (2018) assigns the task of part and process selection to DfAM *in a broad sense* in contrast to the design of specific applications, which is defined as DfAM *in a strict sense*.

Because the adoption of a geometry in the AM process is a necessity for a successful AM application, appropriate design expertise is a key factor for implementation. Therefore, it is closely linked to the identification of suitable AM applications. ISO/ASTM 52910 provides a general approach for the identification of AM potential, which is the first step in the superordinate process *Overall Strategy for Design of AM*. The identification procedure is shown in Figure 2.24. After the identification of a general AM potential or an idea for an application, the systematic approach involves identifying a suitable AM material and checking for the build volume. Then, a checklist of six AM benefits is provided to rate the potential as low, medium, or high in each category. If the overall rating is medium or high, AM is recommended. If the rating is low, the identification of an AM material fails or the build volume is insufficient, and in that case, conventional manufacturing is preferred. In conclusion, the process defined in ISO/ASTM 52910 provides a generic approach for the identification of AM benefits for design tasks. The proposed evaluation steps are a comprehensive guideline but need to be enhanced with detailed information on processes and materials to be applicable for a specific application.

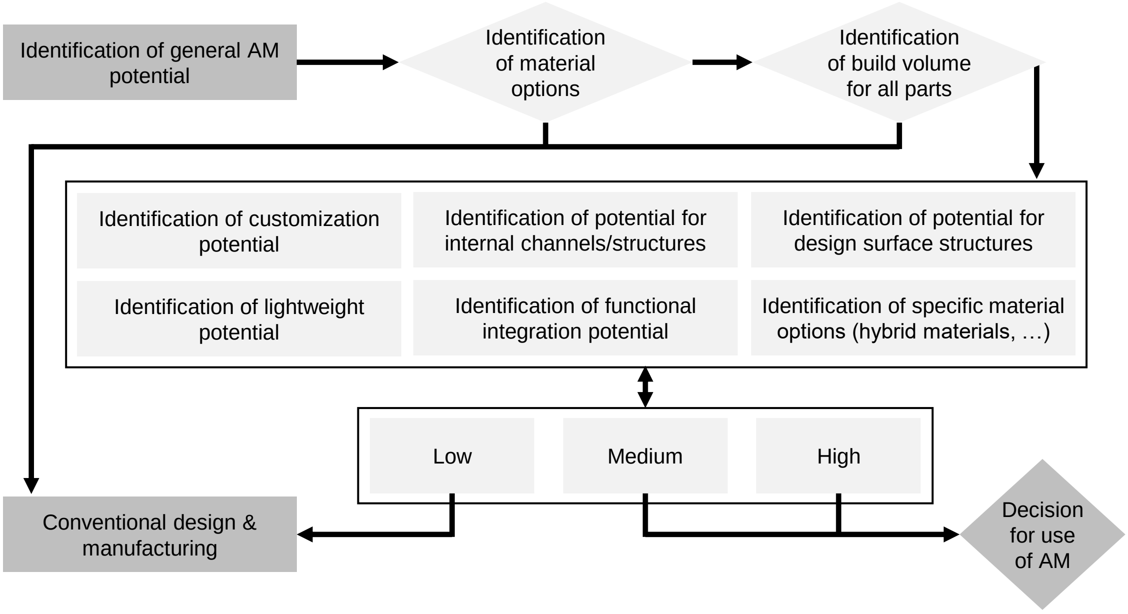


Figure 2.24: Procedure for identification of AM potential (based on ISO/ASTM 52910).

The identification of AM applications is based on two strategies: a knowledge-based and a data-based approach. The *knowledge-based approach* tries to identify parts on the basis of individual suggestions of the company's experts. Therefore, employees are trained in AM technology and encouraged to propose suitable applications. Finally, an AM expert reviews the proposals and selects suitable applications. Because the approach involves interdisciplinary experts within the company, it is also named as bottom-up approach. The *data-based approach* is based on the evaluation of part criteria provided in databases. Therefore the technology performance must be described in key figures that are appropriate for an automated screening. Then the part information stored in the database is evaluated in the context of the technology. Due to the ability to screen large datasets with this approach, it is also referred to as top-down approach. Table 2.5 provides a review of literature for part identification approaches.

Table 2.5: Literature review of part identification approaches.

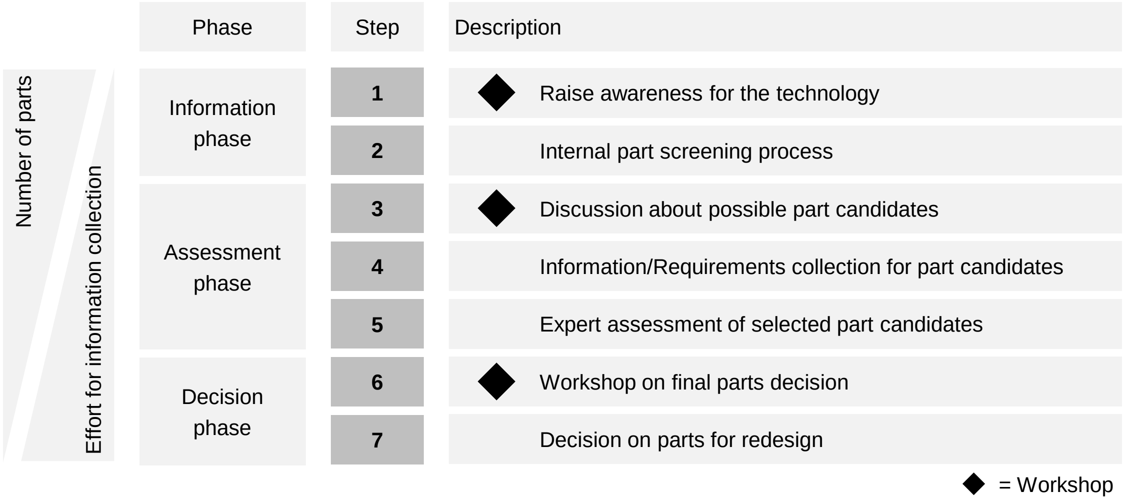
	Knowledge-based approach	**Data-based approach**	**Summary**
Deppe 2019	✓		Decision support system to select spare parts based on Promethee-method using preference functions
Ilg 2019	✓		Checklist for suitability of AM parts, process selection based on pairwise comparison and benefit analysis
Haas 2019	✓		Six step decision system including process selection and evaluation of AM potential
Munsch et al. 2019	✓	✓	Overview on five step process for top down and bottom up approach
Lakomiec 2018	✓		Three step approach: 1. Geometric complexity, 2. Manufacturing cost, 3. Additional value and life cycle benefits
Kumke 2018	✓	✓	Provides a methodology guideline for part identification
Wang et al. 2018 Wang et al. 2017	✓		Decision support system (DSS) using preference functions for rating criteria
Rudolph 2018	✓		Web-based tool to evaluate manufacturability restrictions, cost and lightweight potential
Illgner et al. 2018		✓	Generic process for databased part selection based on three detailing levels
Kruse et al. 2017 Lindemann 2017 Lindemann et al. 2014	✓		Workshop-based part selection process supported by a Trade-off Matrix (TOM) for part evaluation
Schmidt 2016	✓		Rating methodology for LPBF process for lightweight design, function integration and cost
Knofius et al. 2016		✓	Method to obtain a numerical ranking of spare parts based on weighted rating criteria
Achillas et al. 2015	✓		Decision support framework to obtain a production strategy, compares AM with conventional processes
Merkt et al. 2012	✓		Process to select AM process and evaluate technical and economic potential
Ghazy 2012	✓		Decision support system (KBS) using databases for process, material, post-processing and machines
Kushnarenko 2009	✓		Three level decision system to select an AM process including pre- and post-processing steps

The literature review is clustered in knowledge-based and data-based approaches. It is obvious that the knowledge-based approach is more represented in the literature. Moreover, only MUNSCH ET AL. (2019A) and KUMKE (2018) mentioned both approaches, although the data-based identification process was not explained in detail. Because the approaches complement each other, a combination of the approaches offers the opportunity for a holistic and detailed evaluation of AM technology, which is mentioned by KNOFIUS ET AL. (2016), but not represented in the literature review. In the following section, exemplary methods of both approaches are introduced.

2.3.1.1 Knowledge-based Part Identification Approaches

Knowledge-based or bottom-up part identification consists of two approaches to build up knowledge for part identification. One approach is based on workshops to involve employees and AM experts. The knowledge is transferred during the discussion and by using supportive tools, such as presentation slides, cost models, or structured documents to report ideas. The other approach tries to model an AM expert's suggestion in a tool to support the user's evaluation of the suitability of AM technology. This approach uses preference functions to model the AM expert's knowledge in AM technologies.

LINDEMANN ET AL. (2014) suggested a workshop-based concept for part identification. The basic concept was then explained in more detail by KRUSE ET AL. 2017 and LINDEMANN (2017). Figure 2.25 gives an overview of the workshop-based concept suggested by LINDEMANN ET AL. (2014).



Phase	Step		Description
Information phase	1	◆	Raise awareness for the technology
	2		Internal part screening process
Assessment phase	3	◆	Discussion about possible part candidates
	4		Information/Requirements collection for part candidates
	5		Expert assessment of selected part candidates
Decision phase	6	◆	Workshop on final parts decision
	7		Decision on parts for redesign

◆ = Workshop

Figure 2.25: Workshop-based part identification concept (LINDEMANN ET AL. 2014).

The concept consists of seven steps in three phases, each starting with a workshop for employees and AM experts. The goal of the first workshop is to understand the principles of AM and acquire the ability to begin part screening. In the first phase, information about application ideas is collected. In the second workshop, the identified ideas are discussed, and a list of possible parts is generated. Moreover, the participants deepen their knowledge about AM technology. The third workshop focuses on the decision of which parts to produce with AM technology after a redesign of the part. The decision is based on detailed information about each candidate part collected during the prior identification phases. In addition to the workshop-based part identification concept, LINDEMANN ET AL. (2014) proposed a

Trade-off Matrix (TOM) to evaluate the collected part candidates. The TOM follows the decision phases of the workshop concept and contains several rating criteria combined with a point scoring system. The TOM was refined in following publications (LINDEMANN 2017, KRUSE ET AL. 2017) but not published in detail.

The second approach for knowledge-based part identification is a tool to support the user in evaluating AM technologies. This approach was followed by DEPPE (2019), WANG ET AL. (2017), ACHILLAS ET AL. (2015), and GHAZY (2012). Although differences in the rating criteria and calculation method exist, the common element is to obtain a preference function for each rating criteria defined by the user. The general principle of these rating systems is depicted in Figure 2.26a. It consists of a preference evaluation based on user input, a performance evaluation based on data relating to AM processes, and a rating system to compare the performance and preference functions. WANG ET AL. (2017) distinguished the rating systems according to the level of detail of the results: the *judgement of feasibility* considers only the lowest acceptable level for the rating criteria, and the obtained result is binary (feasible or not feasible), whereas the *judgement of suitability* weights the rating criteria, and so, the result is a ranking between different options.

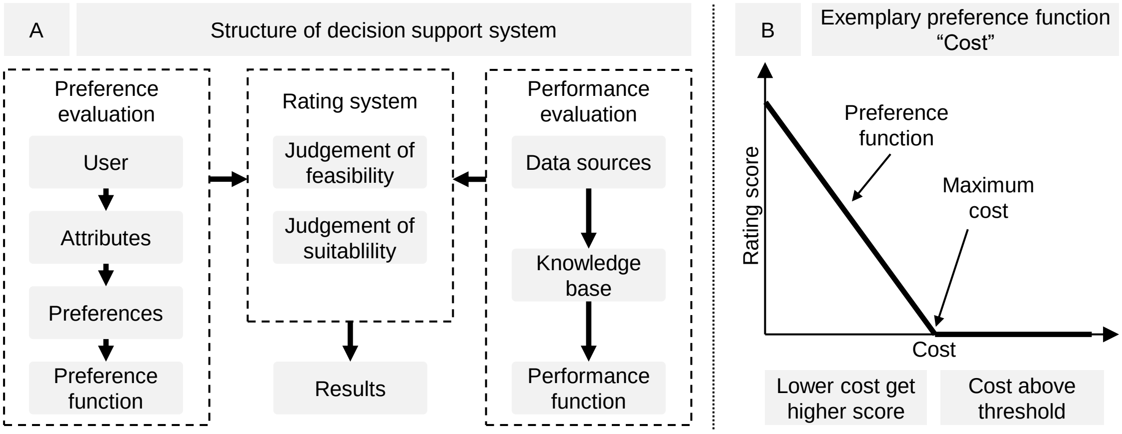


Figure 2.26: Structure of a decision support system (A) and exemplary preference function (B). Based on WANG ET AL. (2017).

The user preference function models the requirements for a specific application. Figure 2.26b shows an exemplary preference function using the example of costs. The function describes a linear advantage of lower costs and a cost maximum. In a rating system, user input is the maximum cost value. For a specific solution, the score of the solution is then calculated with the obtained cost function. There are two main limitations on a decision support system for the task of part and process matching. The performance evaluation requires a precise model of the AM process capabilities, and the setup of accurate user preference functions is complex and time consuming (WANG ET AL. 2018).

2.3.1.2 Data-based Part Identification Approaches

Part identification based on a data screening process has been considered less often in the literature than the knowledge-based approach (see Table 2.5). The approach of using data-based screening to identify suitable AM applications was mentioned by Munsch et al. (2019a), who suggested five steps for a data-based part identification, and Kumke (2018), who provided an overview of part identification approaches in general. A detailed approach for selection of spare parts is proposed by Knofius et al. (2016).

The top-down part identification process of Munsch et al. (2019a) is depicted in Figure 2.27. Motivation for the top-down screening process is to achieve fast results on the suitability of AM technologies on the basis of a large dataset of parts. Moreover, this approach generates objective results, due to the automated evaluation process. Precondition for this approach is the availability of reliable data and the setup of meaningful search criteria. Besides the process steps itself, further information on how to execute the process steps is not described by Munsch et al. (2019a).

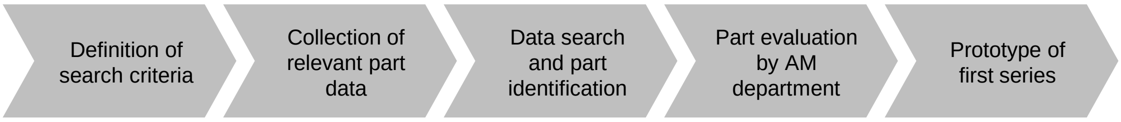


Figure 2.27: Five step process for top-down part screening. Based on Munsch et al. (2019a).

Kumke (2018) proposes a general process for identifying suitable parts for AM, which is depicted in Figure 2.28. For the substep *screening*, different methods to identify parts are proposed, e.g. a data analysis. The data analysis covers a pull and push approach. A push data analysis identifies parts in formalized documents, like part lists. The push approach, screens for actual hindrances in the production process and tries to overcome them by an AM part, e.g. bottleneck spare parts.

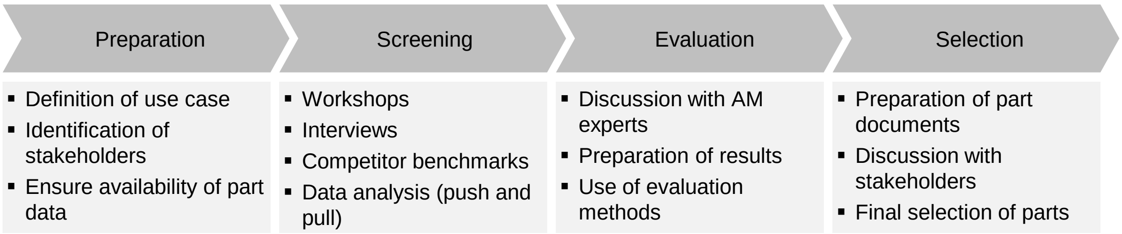


Figure 2.28: Generalized part identification process. Based on Kumke (2018).

KNOFIUS ET AL. (2016) proposed a data-based screening method to identify business cases for AM technology in the spare parts supply. The method was based on an analytic hierarchy process and allows for adoption by a specific company. The result is a ranking of spare parts based on the potential benefit when produced with AM. The main advantage is the assessment of a large number of spare parts simultaneously.

The ranking methodology of KNOFIUS ET AL. (2016) is shown in Figure 2.29. To obtain a ranking, KNOFIUS ET AL. (2016) proposed gathering data from a spare part assortment from the company’s databases. The ranking approach defines go/no-go attributes to exclude parts that are not feasible for production with the AM process. The go/no-go attributes obtain a binary scoring, where “1” is assigned to suitable and “0” to not suitable parts. If one of the no-go attributes gets a score of 0, the part is excluded from the ranking and obtains an overall score of 0. All other attributes are ranked by linear scoring, setting the best value in the database to 1 and the worst to 0. In addition, the linear scoring is multiplied by weight factors obtained from the company’s goals. Therefore, the company’s goals are weighted by a pairwise comparison, and the spare part attributes are then assigned to the company’s goals. Finally, both scoring methods are summarized into an overall score for the spare part, delivering a suitability score of the spare part ranging between 0 and 1. The ranking methodology is validated with a sample of spare parts, rated by an AM expert. Typically, the rating of the AM expert is stricter than the ranking methodology because the AM expert considers additional experienced-based information. Nevertheless, the ranking methodology is considered a valid approach for part screening, because more than 1000 business cases for AM have been identified with the ranking methodology in a field study in the aerospace industry (KNOFIUS ET AL. 2016).

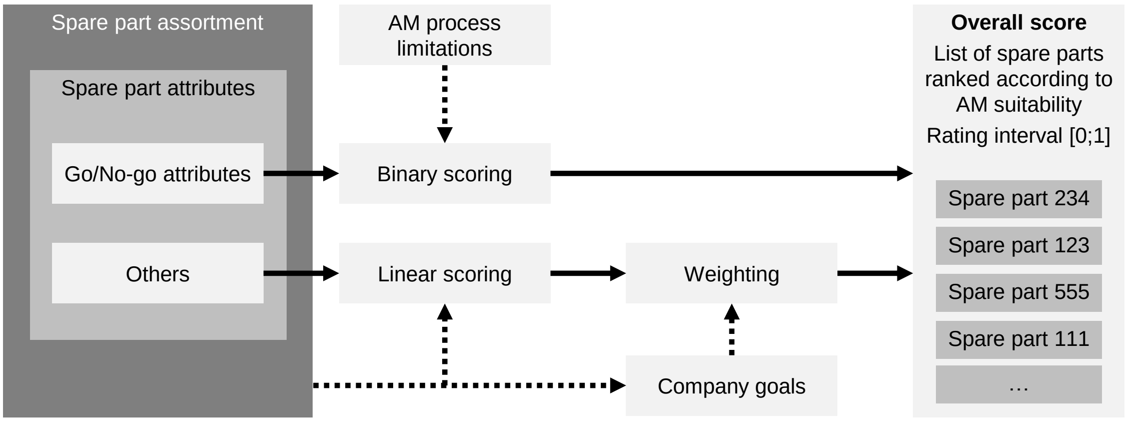


Figure 2.29: Ranking methodology for spare parts. Based on the description of KNOFIUS ET AL. (2016).

2.3.2 Cost Calculation

The calculation of cost in AM is an important task for business case evaluation (BAUMERS & TUCK 2019). It is closely linked to a make-buy evaluation, because cost can be calculated with an analytical model for an internal production, *make scenario*, or by benchmarking external supplier costs, *buy scenario* (SCHNECK ET AL. 2020). An overview of the cost literature for metal-based AM processes is provided in Table 2.6. A comprehensive analysis of make-cost for LPBF and an additional overview of costing literature are provided in LINDEMANN (2017).

Table 2.6: Overview of cost literature for metal-based AM processes.

Reference	AM Process	Make	Buy	Summary
Schneck et al. 2020	LPBF	✓	✓	Cost comparison of cost model and external buy cost; Sensitivity analysis investigates the most important input parameter for AM costs
Baumers & Tuck 2019	General	✓		Review publication; Classification of cost modelling approaches; Steps to setup a cost model; Summary of 11 cost models
Kamps et al. 2018	LPBF	✓		Resource-efficiency and consumption of AM system; Process chain for gear components
Klahn et al. 2018	LPBF	✓		Cost model to obtain volume-based cost
Rudolph 2018	LPBF	✓		Cost calculation for automated quotes of AM parts; Including process chain; Including geometry analysis from STL file
Lindemann 2017 (incl. prior publications)	LPBF	✓		Comprehensive analysis of process cost for LPBF with a life cycle costing approach; Table with 27 references on cost literature (years 2003 – 2015)
Cunningham et al. 2017	WAAM	✓		Time activity based cost model for Wire-Arc Additive Manufacturing (WAAM)
Munsch et al. 2017	LPBF; EBM	✓	✓	Comparison of make and buy cost; Cost along the process chain
Kranz 2017	LPBF	✓		Action-based cost model for LPBF; Scalable approach depending on development phase of AM product
Hällgren et al. 2016	LPBF	✓		Cost comparison of AM and high speed machining
Baldinger 2016 Baldinger et al. 2016	LPBF		✓	Investigation of external cost for buy based on cost matrices; Materials: stainless steel, aluminum
Barclift et al. 2016	LPBF	✓		Extension of an existing cost model with an depreciation approach for the feedstock material; powder reuse
Baumers et al. 2016	LPBF; EBM	✓		Cost comparison of LPBF and EBM process
Schmidt 2016	LPBF	✓		Cost calculation for lightweight parts; Comparison of AM cost, AM cost of optimized design, CNC machining and precision casting
Lutter-Günther et al. 2015	LMD hybrid	✓		Cost model for a hybrid additive manufacturing with Laser Metal Depostion and machining
Poprawe et al. 2015	LPBF	✓		Cost analysis of multi-laser systems
Schröder et al. 2015	LPBF; EBM; LMD	✓		Multi process approach which compares the cost of several AM processes
Thomas & Gilbert 2014	General	✓		Review publication; States several references on AM costing;
Rickenbacher et al. 2013	LPBF	✓		Focus on cost split between different parts in one build job
Baumers et al. 2013 Baumers 2012	LPBF	✓		Focus on resource consumption and split of build cost to the individual manufactured parts
Atzeni & Salmi 2012	LPBF	✓		AM design optimization of a reference part; Comparison to high-pressure die casting process
Krauss et al. 2011	General	✓		Action-based model with integration of process chain

2.3.2.1 Cost Calculation for Internal Production

The cost calculation for an internal production is addressed by several references in literature, see Table 2.6. Depending on the goal of the cost calculation, a cost model bears different complexities and needs to be adopted to the specific application. Especially during development of an AM design, cost estimation has to include more input variables to increase accuracy with progressing development steps (Kranz 2017). Simple models build on a number of assumptions and simplifications, thus their realism is diminished (Baumers & Tuck 2019). It is therefore necessary to clarify the application of the cost model in advance. In general, cost estimation techniques can be categorized into qualitative and quantitative approaches. The most utilized approaches for the cost estimation of AM are activity-based models and parametric techniques. The different approaches for cost modeling are depicted in Figure 2.30.

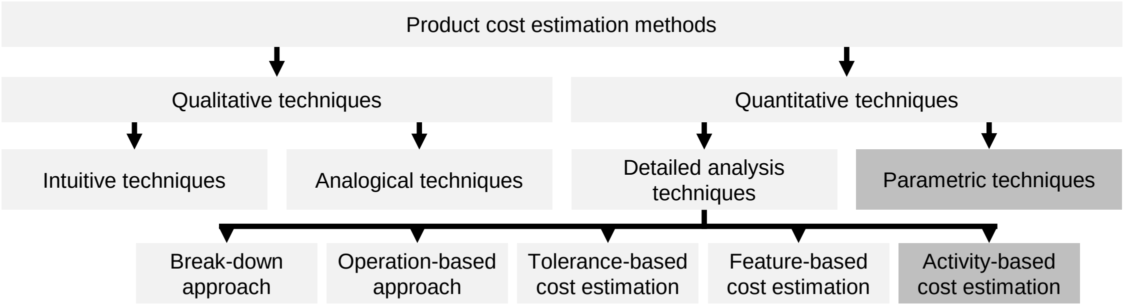


Figure 2.30: Classification of cost estimation techniques (Baumers & Tuck 2019).

To develop an activity-based cost model, Baumers & Tuck (2019) proposed a five-step process, as shown in Figure 2.31. In the first step, the scope of the cost model is defined, considering the application purpose of the cost model and the integrated steps of the AM process chain. In the next step, a build time estimation for the AM process is derived. Then, an indirect cost rate is calculated by assessing all indirect costs on an annual basis and splitting them into the annual productive hours of the AM production system. The indirect costs cover the depreciation of the AM system, labor costs, and overhead costs. In the fourth step, the direct costs of the production process are investigated. These costs are caused by all physical inputs to the AM process, especially raw materials. Finally, in the last step, the total cost per build is derived and split into the single parts of the build.

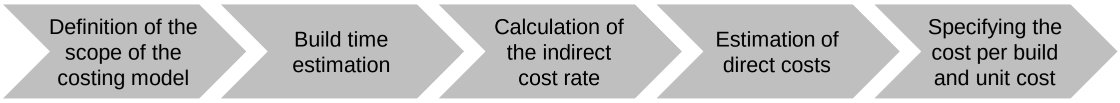


Figure 2.31: Process to develop an activity-based model (Baumers & Tuck 2019).

An alternative approach to assess the cost of AM is parametric approaches. A parametric cost estimation tries to derive a cost factor to represent the cost of the AM process. Parametric AM cost estimation uses mostly volume- or mass-based parameters (LEUTENECKER-TWELSIEK 2019). To estimate the cost of a specific part, the obtained cost factor is multiplied by the part's mass or volume. A parametric approach allows a coarse cost estimation and is especially applicable in the early development phases of a product or for novice users who prefer easily applicable tools (KUMKE ET AL. 2018).

A cost model to derive a volume-based cost factor was developed by KLAHN ET AL. (2018). The input parameters of the model are split into five sections covering machine data, material, build job parameter, consumables, and operating cost. With this input data, the time for layer deposition, preheating, exposure, and machine preparation are calculated. Based on the derived time steps, the overall build rate is derived, expressing the production volume over time, which is a key figure for the productivity of the AM system. Together with depreciation cost, material cost, consumption cost, and labor cost, an overall cost factor is calculated, expressing the cost per volume unit.

The basic dependency between part cost and AM system utilization for PBF processes was investigated by RUFFO ET AL. (2006), who developed a cost model for the polymer-based laser sintering process (LS). Based on a calculation of direct and indirect costs, RUFFO ET AL. (2006) obtained the cost for a single part produced by LS over the production volume. As shown in Figure 2.32, the cost per part follows a logarithmic function superposed by a sawtooth curve, which is caused by the process characteristics of the powder bed. The cost per part reaches a local minimum when the build volume utilization is maximized. This is the case if one layer is filled with parts, producing the most parts for a fixed height of the build job (z axis). When the build volume is fully utilized, the cost per part reaches a global minimum.

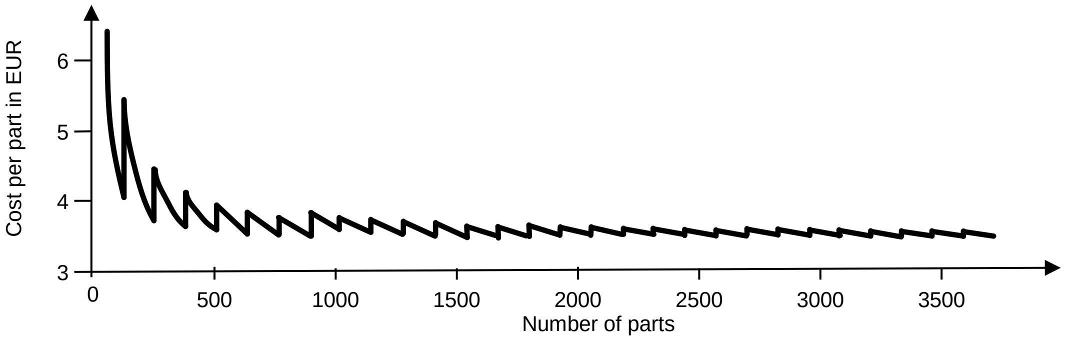


Figure 2.32: Schematic cost per part for a PBF process (RUFFO ET AL. 2006).

From the investigation of RUFFO ET AL. (2006), it is also obvious that the cost scale effect for large production volumes is limited by the logarithmic regression to the global minimum of cost per part. However, the obtained logarithmic regression with a superposed sawtooth curve is valid for all PBF processes and is referred to by many AM cost literature.

2.3.2.2 Cost calculation for External Supply

The investigation of external supply cost of AM parts has been negligibly addressed in the literature (BALDINGER ET AL. 2016) compared with several cost estimation approaches for the make-option (see Table 2.6). The cost literature investigating external supply cost for LPBF is BALDINGER (2016), MUNSCH ET AL. (2017), and SCHNECK ET AL. (2020). A comparison of these approaches is stated in Figure 2.33 for the reference material 1.4404 (316L).

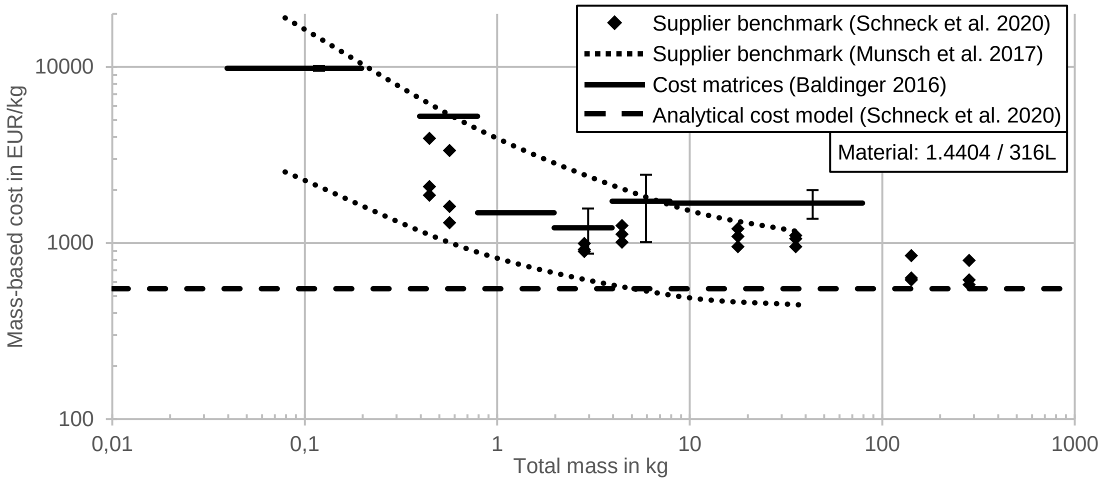


Figure 2.33: Schematic supplier benchmarking. Data for 1.4404 from BALDINGER (2016), MUNSCH ET AL. (2017), and SCHNECK ET AL. (2020).

BALDINGER (2016) evaluated 499 quotations from AM suppliers, including those for LPBF-produced parts in 316L (1.4404) and aluminum alloy AlSi10Mg. The dataset of supplier quotes was divided into classes on the basis of the total volume of parts and packing ratio. The result of this classification was *cost matrices*, stating an average price depended on order volume. BALDINGER ET AL. (2016) recommended the cost matrices as an appropriate tool to estimate cost in an early design phase. In comparison with a linear regression of supplier quotes, the cost matrices offer more precise cost information (BALDINGER ET AL. 2016). MUNSCH ET AL. (2017) compared make and buy costs with respect to overall order volume. For low order volumes, a buy option is preferable to the make option. The external cost stated by MUNSCH ET AL. (2017) covers a broad range. In addition, there is no additional information provided, such as how the data were obtained and analyzed. The comparison of an analytical cost model for the make option and a supplier benchmark study for the buy option were presented by SCHNECK ET AL. (2020). The analytical cost model derives AM cost for 316L (1.4404), which is met by supplier quotes for high order volumes. As a consequence, SCHNECK ET AL. (2020) recommended relying on supplier quotes when evaluating the cost of an AM part.

2.4 Conclusion

The state of the research was analyzed in terms of three aspects, namely metal-based AM processes, technology management, and the implementation of AM in an industrial context. In the following, the state of the research is summarized and evaluated in the context of the research objective.

AM processes are at the beginning of market diffusion (CAVIEZEL ET AL. 2017). With respect to metal-based AM, there are different functional principles to generate a metallic part through additive technology. Five out of seven process classes in ISO/ASTM 52900 apply to the generation of metallic parts. The most established processes are PBF processes, especially LPBF. However, most of the metal-based AM processes are in an early development phase and are offered by only a few technology providers. Despite the small market volume of AM (0.077% of the total production market in 2018), the interest in AM technology is high, which resulted in market growth of 33.5% in 2018 (WOHLERS ET AL. 2019).

To obtain a technology strategy is a task for technology management. The six processual-linked tasks of technology management are embedded in the organizational structure of the company (SCHUH ET AL. 2011). An appropriate method to obtain and represent a technology strategy is a technology roadmap. A technology roadmap is defined as a time-based visualization of planning objects, which are interconnected and clustered in different planning levels (SCHUH 2013).

The evaluation and introduction of AM technologies in an industrial context is referred to as AM implementation. Approaches that support AM implementation are process-based, describing implementation as a process, or action-field oriented, describing relevant topics to address. The most important task in AM implementation is the identification of business cases, defined as technically and economically feasible applications (THOMPSON ET AL. 2016). To identify business cases, knowledge-based (bottom-up) and data-based (top-down) approaches are applied. As learned from the literature review, the data-based approach is considered less than the knowledge-based approach. A combined data- and knowledge-based approach was not identified in the literature review. Considering the cost of AM, several aspects have been investigated in detail by numerous cost studies, but mostly on an analytical basis. As investigated by SCHNECK ET AL. (2020), analytically obtained cost are realizable in the market only for high order volumes. The investigation of external supply cost for AM has negligibly been addressed in the literature (BALDINGER ET AL. 2016).

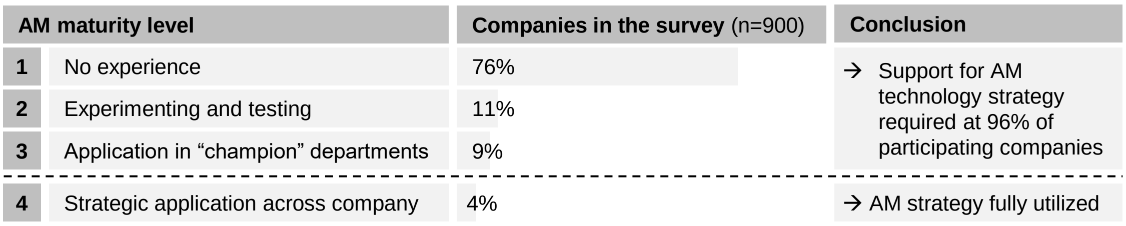
In summary, metal-based AM processes are a production technology in an early and dynamic development phase. Thus, the aspects of a technology strategy (performance, source, timing, and utilization) are difficult to evaluate for a company. Depending on the availability of a holistic technology strategy in a company, the task of AM implementation can be assigned to the derivation of the technology strategy or technology planning to concretize one aspect of the superordinate technology strategy. For that, technology roadmapping is an appropriate approach. The existing methods to implement AM technologies do not focus on the strategic aspects of technology introduction. A holistic approach to identify suitable applications based on a combined data- and knowledge-based approach has not been described in the literature. Moreover, the external sourcing of AM technology has only been marginally investigated in the literature.

3 Need for Action and Requirements

Considering the state of research discussed in chapter 2, hindrances to the adoption of AM technologies in a producing company were investigated. Studies that have evaluated the adoption of AM were summarized, and general hindrances to AM implementation were identified. Given this background context, the requirements for developing a technology strategy in AM are derived. The requirements for a methodical approach to develop the technology strategy need to address the identified implementation hindrances to overcome the current limitations to AM technology adoption.

3.1 Hindrances to AM Adoption in Industry

The current state of AM adoption was evaluated by MÜLLER & KAREVSKA (2016) through a global survey covering 900 companies. They proposed four maturity levels for AM adoption, which are depicted in Figure 3.1. Of the surveyed companies, 76% were at the first maturity level and had only little or no experience in AM, and only 4% of the companies followed an exhaustive strategic approach adopted by the entire company. The survey revealed that 96% of the involved companies were in need of AM implementation support, either as a starting point to evaluate AM technologies or to extend already-established AM structures within the company. Because only 4% of the companies had an exhaustive AM strategy in 2016, most companies presumably still do not follow a comprehensive strategic approach in AM, even if the further diffusion of AM technology since 2016 has been considerable.



AM maturity level		Companies in the survey (n=900)	Conclusion
1	No experience	76%	→ Support for AM technology strategy required at 96% of participating companies
2	Experimenting and testing	11%	
3	Application in “champion” departments	9%	
4	Strategic application across company	4%	→ AM strategy fully utilized

Figure 3.1: Survey on AM adoption (MÜLLER & KAREVSKA 2016).

In a study of 77 participating companies, the value-add potential of AM was investigated along the product life cycle (PFÄHLER ET AL. 2019). The result of the study is depicted in Figure 3.2. Among companies that use AM technologies, the highest value-add potential of AM is expected in the early phases of the product life cycle. In these phases, AM is used to create demonstrators and prototypes (referred to as rapid prototyping). As the origin of AM technologies, this applications field still offers the most value-add potential in an industrial context. By contrast, the value-add potential in the life cycle phases of *production* and *use* is expected to be less than that in the early life cycle phases. Figure 3.2 indicates that among the participating companies, the opportunities of an AM production approach were not utilized for serial products and to gain benefits during the product use phase. It can be concluded that AM technologies are established for prototyping purposes in the product development phase, but hindrances prevent the transfer of value-add potential to the production and use phases of an AM product.

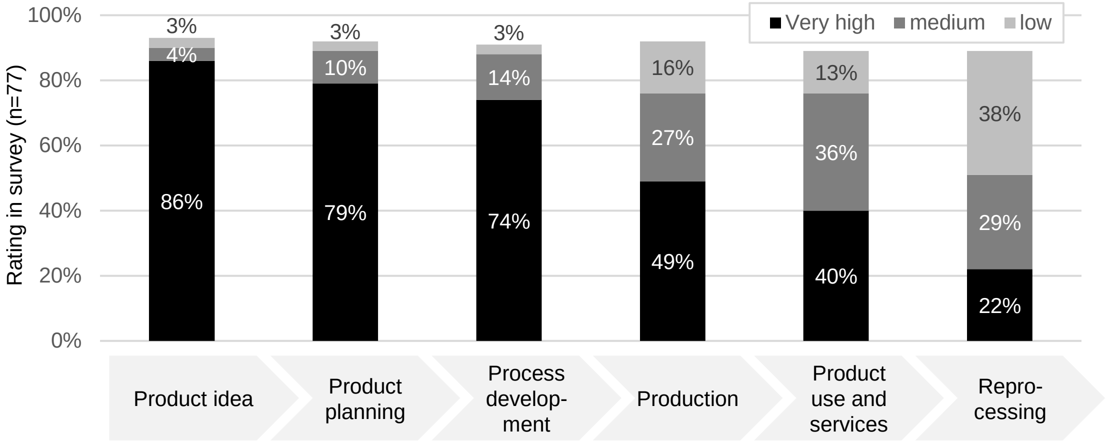


Figure 3.2: Potential for AM technologies to add value along the product life cycle (PFÄHLER ET AL. 2019).

With a focus on the German AM market, CAVIEZEL ET AL. (2017) summarized the current state and outlook for AM technology. In the comprehensive study, the AM ecosystem was analyzed, including the reference to international market development. Part four of the study focused on the use of AM technologies in industry. This part of the study was based on a publication and patent analysis and 18 qualitative expert interviews. Moreover, the result was finalized in an expert workshop.

The study proposes 18 theses regarding the current state of and outlook for AM technologies. An excerpt from the identified thesis is presented in Table 3.1. The German AM market has a strength in development and production of AM systems, whereas its weaknesses are in application and industry adoption. Primarily, adoption is driven by process specialists utilizing AM technology for products in low batch sizes. Currently, AM is in the beginning of market diffusion. Thus, it is expected, that the adoption of AM in industry will continuously proceed within the next years. Indeed, full market diffusion is not expected within the next ten years.

Nevertheless, AM, and especially metal-based AM, presents high potential as an enabler for innovative products. Current limitations have been identified with respect to the production of medium and large batch sizes and material availability. As explicit hindrances for further technology adoption, the availability of necessary competences and the identification of applications, business models, and the suitable technology were identified. These hindrances limit the adoption of AM technologies in an industrial company, especially for SMEs.

Table 3.1: Theses concerning the current state of and adoption of AM technologies. Excerpt from CAVIEZEL ET AL. *(2017).*

Topic	**Number of thesis**	**Thesis** (Focus on German market)
Current state analysis	3	Strength in development and production of AM systems. Weaknesses in application and utilization in industry.
	5	AM adoption is mainly driven by process specialists with low production batch sizes.
Outlook	1	AM is in the beginning of market diffusion for serial production.
	2	A full market diffusion for serial production is not expected within the next 10 years.
	4	Metal AM bears high potential for AM market development.
	7	Hybrid manufacturing processes are an important factor for AM series production.
	8	Technical limitations hinder the production of medium and large batch sizes by AM within the next 10 years.
	9	Further market diffusion of AM series production needs increased material availability.
Hindrances for AM implementation	10	Necessary competences for AM adoption are not widely accessible, especially for SMEs.
	11	Many SMEs struggle with the identification of applications, business models and suitable AM technology.
	13	Focusing on the most promising AM technologies by application potential and fostering standardization on a industrial basis supports market diffusion of AM technologies.

ILG (2019), LINDEMANN (2017), and MÖHRLE ET AL. (2017) have investigated the adoption of AM technologies and implementation hindrances. ILG (2019) conducted a study in the medical field and identified a lack of knowledge and a unstructured suitability analysis for AM technologies as main hindrances. The focus of the survey of LINDEMANN (2017) was the cost of AM, and results revealed that knowledge of cost is a crucial factor in technology utilization. This was supported by the study of MÖHRLE ET AL. (2017), which also revealed cost information to be an important hindrance to technology adoption. Moreover, knowledge of AM technology was identified as a limitation.

An overview of implementation hindrances is provided in Figure 3.3. Three generalized hindrances for the implementation of AM technology are concluded: limited availability of technology information, insufficient support to develop AM applications, and restrictions from existing organizational structures.

Limited availability of technology information	**Insufficient support to develop AM applications**	**Restrictions from existing organizational structure**
▪ Benefits and limitations not fully renowned ▪ Design guideline unavailable ▪ Cost structure unclear ▪ No appropriate standards ▪ …	▪ Identification methods for applications unavailable ▪ Insufficient planning of application development ▪ Quality assurance measures unclear ▪ …	▪ Unstructured AM implementation process with insufficient mastering of project complexity ▪ Incidental building of know-how and knowledge exchange ▪ Low AM technology acceptance ▪ …
→ Technology	**→ Applications**	**→ Organization**

Figure 3.3: Analysis of generalized AM implementation hindrances.

The limited availability of technology information covers two aspects. At first, there is the available knowledge in general, but secondly, also the accessibility of this knowledge is crucial. Because of the novelty of AM processes, it is relatively difficult to obtain reliable information regarding its benefits and limitations, including design restrictions and cost structure. A standard is a technical document that defines requirements, specifications, or guidelines and is a valuable source of information. Therefore, the lack of standards is a critical barrier to the more general adoption of AM (MONZÓN ET AL. 2019).

When implementing AM technologies, the most important task is identifying and developing technically feasible and economically viable applications. Because comprehensive methods for such identification and development are incomplete or may be complex to apply, the implementation of AM remains limited. Moreover, uncertainty regarding the quality of additively manufactured parts hinders the use of AM as a production process.

Organizational hindrances result from the lack of a structured implementation process that would allow for managing the complex task of implementation. Moreover, the compilation and exchange of knowledge limits the implementation because structured measures for building and exchanging knowledge are not applied. Additionally, limited know-how precludes technology acceptance.

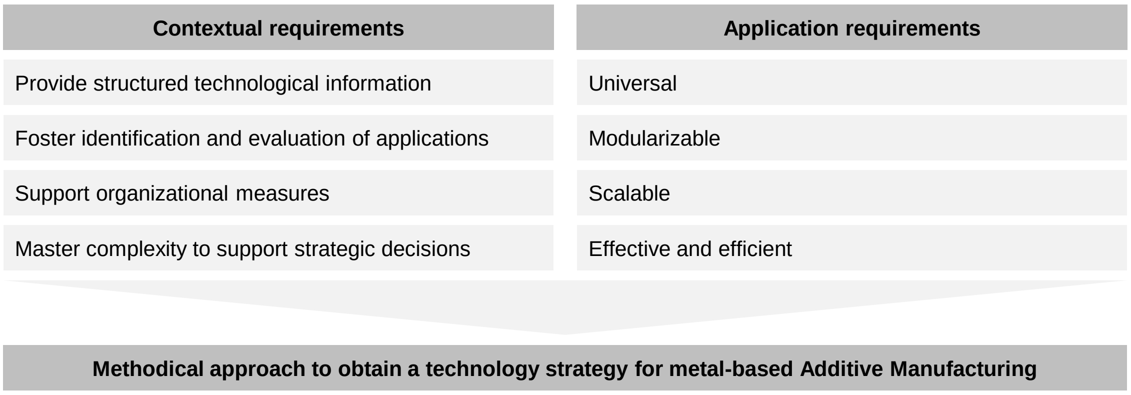
In conclusion, AM technologies are utilized as production processes but are mostly used for specialized products and niche applications in low production volumes. For a broader application of AM technology, three hindrances must be overcome:

the availability of AM technology information, the evaluation of AM applications, and the setup of an appropriate organizational structure.

3.2 Requirements for a Methodical Approach

As stated before, AM is in the beginning of market diffusion (CAVIEZEL ET AL. 2017). Thus, several production companies are in need to investigate the potential of AM and implement these processes in their organization within the next years. During the evaluation and implementation process, they are confronted with the hindrances derived in section 3.1, which are the availability of information, the evaluation of applications, and appropriate organizational measures. The existing methodical approaches support the AM implementation in specific tasks (e.g, the design of AM parts), but lack a superordinate strategical perspective. Especially for metal-based AM technologies, this strategic approach for implementation is required, because these technologies are mostly utilized to produce complex parts for demanding applications. To develop and produce such AM applications demands for a long-term planning perspective, which is necessary to allocate the personnel, financial and structural resources. On this basis, strategical decision about the AM implementation can be taken. Hence, a methodical approach is required to obtain a technology strategy for metal-based AM.

The requirements for such an approach can be categorized in terms of contextual requirements that describe the challenges to be addressed from a technical perspective and application requirements that describe the needs arising from the application of the methodical approach in an industrial context. The requirements are summarized in Figure 3.4.



Contextual requirements	Application requirements
Provide structured technological information	Universal
Foster identification and evaluation of applications	Modularizable
Support organizational measures	Scalable
Master complexity to support strategic decisions	Effective and efficient

Methodical approach to obtain a technology strategy for metal-based Additive Manufacturing

Figure 3.4: Contextual and application requirements for methodical approach.

The method to develop a technology strategy must fulfil contextual requirements and overcome current hindrances to AM technology adoption. The contextual requirements are as follows:

- *Provide structured technology information:* To overcome the limitation of information availability, the methodical approach must provide a structured form of technology information. Such structured information must clearly describe the current technology performance, limitations, and outlook for technology development. The maturity of an AM technology must be evaluated.

- *Foster identification and evaluation of applications:* Appropriate tools and methods for identifying and evaluating applications must be included. The identification approach must provide specific AM-suitable applications as well as an overview of the technology's potential in the product portfolio. The evaluation approach must be based on reliable rating criteria and use technology performance data. Moreover, the evaluation must integrate quantitative and qualitative aspects.

- *Support organizational measures:* An organizational change toward AM technologies must be supported through the methodical approach. In this context, approaches to establish the required know-how within the organization must be integrated. Moreover, the accessibility of relevant AM technologies must be ensured in consideration of technical and economic aspects.

- *Master complexity to support strategic decisions:* Finally, all prior requirements must be integrated into one methodical approach that covers the interconnections of the aspects of implementation. This approach must provide an overview of the complex implementation process and thus enable well-grounded strategic decisions, e.g. developing AM applications or investing in an internal AM production environment.

In addition to content-related requirements, further requirements arise from the application of the method in an industrial context. The application requirements are as follows:

- *Universal:* The method to obtain a technology strategy in metal-based AM must focus on production companies and be universally applicable to various industrial domains and organizational sizes. Moreover, the approach must consider the progressive developments in AM technologies, thus enabling information to remain up to date and the integration of new emerging AM technologies.

- *Modularizable:* The approach must consist of various sections that can be applied as separate steps. This allows for customization in the evaluation process according to the company's needs. Because a company has limited capacity to execute the methodical approach, the concept must be modular and support a company focusing on relevant evaluation steps.

- *Scalable:* The methodical approach must be adjustable to input data granularity, which allows for integration of information that is difficult to access or is imprecise. Thus, the evaluation steps must be scalable with respect to the level of detail of input information. This allows for iterations within the process when more detailed input information becomes available.

- *Effective and efficient:* Finally, the approach needs to be effective. Thus, each step must generate a relevant outcome for the final result of the technology strategy. Moreover, the dependency between steps must be clear. Due to limited capacity within an organization to execute the methodical approach, it must also be efficient. This demands for prioritization and selection to focus capacity on the most relevant evaluation steps.

4 Technology Strategy for Additive Manufacturing

In the following chapter the approach to obtain a technology strategy for metal-based AM is introduced. The approach addresses the requirements, which are derived in chapter 3. Moreover, the frame conditions to apply the approach are discussed.

As stated in section 2.2.1, page 20, a *technology strategy* is defined as a plan that defines actions to reach the long-term goal of utilizing a technology (SCHULTE-GEHRMANN ET AL. 2011). A *technology strategy for metal-based additive manufacturing* is therefore a structured approach to implementing or progressing in the use of metal-based AM technologies to exploit the potential of these technologies. Furthermore a *technology roadmap* can be utilized as representation of a technology strategy (EVERSHEIM 2009). In the context of the presented methodical approach, the technology strategy and its representation as a technology roadmap for metal-based AM are treated as synonyms.

Successful application of the methodical approach to create a technology roadmap in an organization demands the integration of the organization's background and individual requirements. Roadmapping is a process of collecting and evaluating information in the context of the organization that will apply it. It is dependent on available information, which typically consists of technology information from internal and external information sources, the current and future product portfolio, and the organizational structure as well as prior experience in AM technologies (input). This information is collected and evaluated through the process to obtain the technology strategy. Finally, the technology strategy that is obtained through this process is represented as a technology roadmap (output). In addition to the available input information, the methodical approach depends on boundary conditions in the executing organization, especially the available resources and organizational structure. Even if the aim of the methodical approach is to minimize the effort required to obtain the technology strategy by providing a systematic structure, the process is still dependent on available personnel and financial and time resources. In particular, stakeholders and responsibilities are of major importance when developing a technology strategy. The result of the technology roadmapping process is significantly dependent on the experts involved and their knowledge (SCHUH 2013). In addition, the proposed methodical approach to obtain a technology strategy for metal-based AM must be synchronized with existing technology management processes. An overview of the boundary conditions and input and output for the methodical approach is depicted in Figure 4.1.

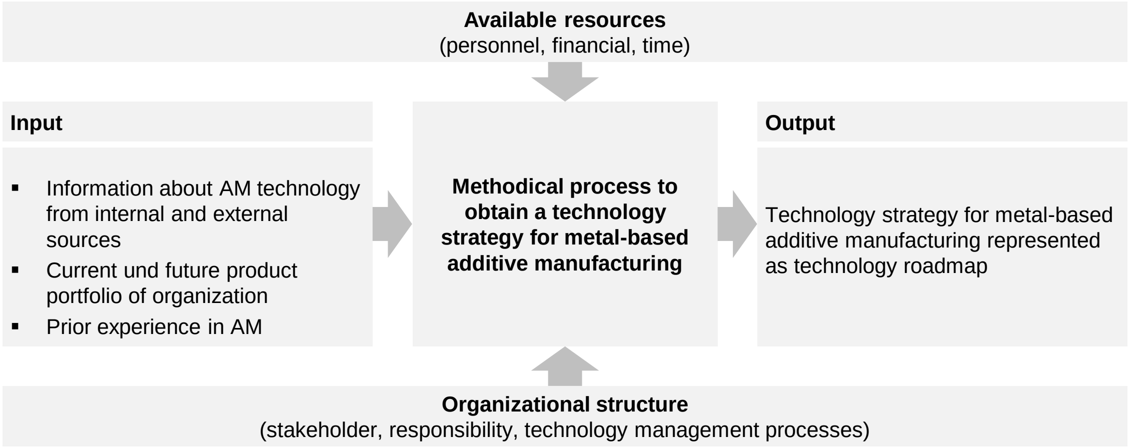


Figure 4.1: Organizational framework to obtain the technology strategy.

As stated in section 3.1, page 45, there are several hindrances for the successful implementation of AM technologies in an industrial organization. The limitations are clustered into *limited availability of technology information*, *insufficient support to develop applications*, and *restrictions from the existing organizational structure* (see Figure 3.3, page 48). The contextual requirements, identified in section 3.2, page 49, specify a methodical approach to overcoming these limitations. Based on this analysis, the methodical approach to develop a technology strategy in metal-based AM consists of three action fields to evaluate AM technologies. Finally, the outcome of each action field is assembled into an *AM Technology Roadmap*. The process is basically sequential, but contains iterative loops to integrate the dependencies among the action fields. An overview of the process is depicted in Figure 4.2.

Prior to the generation of the roadmap the motivation for the use of AM is clarified by proposing hypotheses about the AM technology potential. This hypotheses cover the utilization of the AM technology and the specific AM processes, which will be investigated in the roadmap. The hypotheses are derived from the motivation of the company to investigate metal-based AM processes, thus they express the expectations about the AM technology potential. After setting up the roadmap, the hypothesis can be approved or rejected, based on a reliable data basis and appropriate strategical decisions can be derived to exploit the AM technology potential. The hypothesis build on the typology of AM business models proposed by LUTTER-GÜNTHER ET AL. (2015A) (see section 2.3.1, page 30) and the metal-based AM processes introduced in section 2.1, page 7. Exemplary hypotheses for the AM technology potential are:

- Our product portfolio XY profits from streamline optimization and parallelized weight reduction.
- Manufacturing of preforms by DED processes for products in small lot sizes reduce the required delivery time for the preforms.
- Printing spare parts on demand by LPBF brings cost advantages and offers shorter delivery times to the customer.

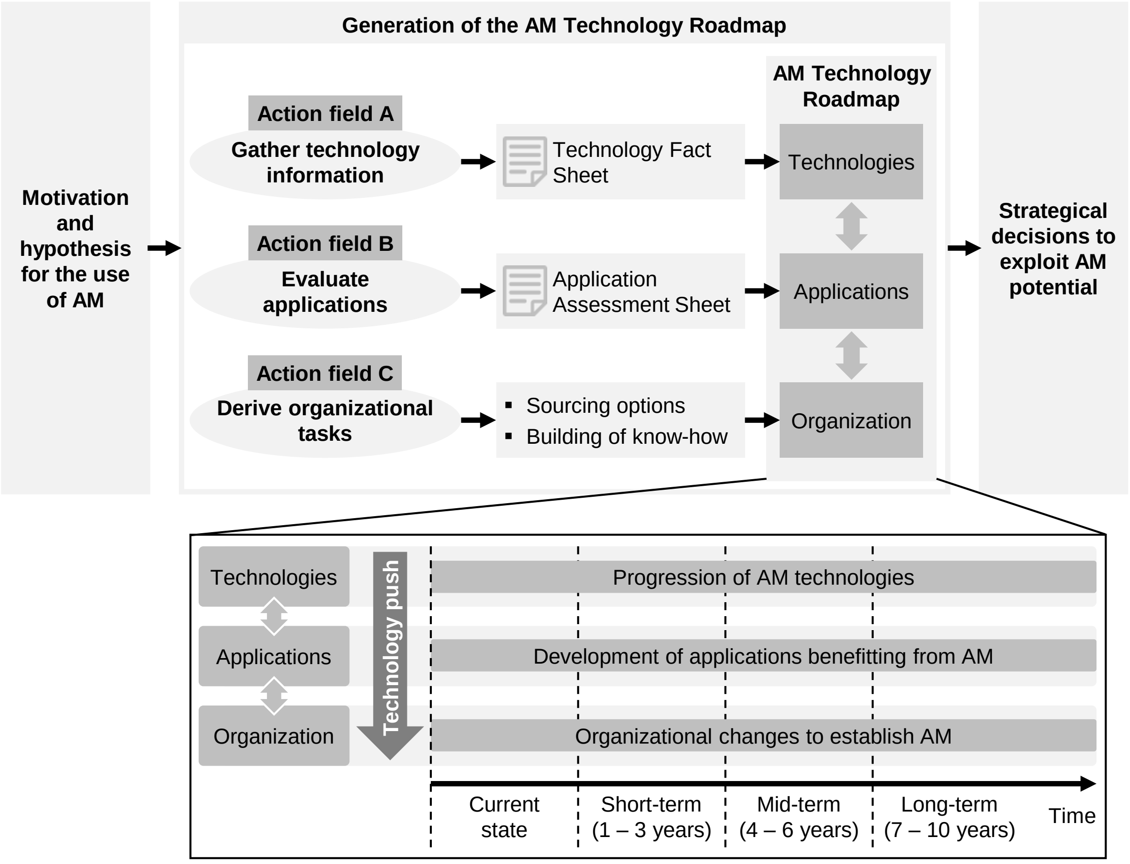


Figure 4.2: Process to obtain an AM Technology Roadmap.

Action field A, *Gather technology information*, covers the structured search for technology information. Based on GREITEMANN (2016), a method to identify information sources is developed and extended by adopting an approach for systematical search queries in formal information sources. Moreover, the information required to assess the AM technology potential is derived. This information includes an overview of available materials and detailed material properties, a reference process chain, and an analysis of available machine equipment. In addition, reference applications are collected and evaluated, and a cost indicator is obtained. Finally, the maturity of the AM technology is assessed on the basis of the concept of Manufacturing Readiness Level (MRL). All relevant information concerning AM technology performance is summarized in a *Technology Fact Sheet*.

Action field B, *Evaluate applications*, supports the identification and evaluation of applications. To identify suitable applications, a combined approach of data-based and knowledge-based part screening is introduced. The combined approach allows for identifying specific applications and also provides an overview of the AM technology potential in the product portfolio. The detailed evaluation of applications is based on the information provided in the *Technology Fact Sheet*. As a first step in the evaluation process, development goals for the application are derived on the basis of AM's inherent benefits. In a second step, a technical and economic assessment is conducted. In a last step, the maturity of the application is assessed, and a project plan is established to direct the realization phase. All evaluation steps are structured in an *Application Assessment Sheet*.

Action field C, *Derive organizational tasks,* entails the structural changes necessary to adopt additive technologies. In this action field, the sourcing of the AM technology is evaluated by analyzing an internal AM production (make scenario) and an external supply of AM parts (buy scenario). For both options, the specifications are derived, and a cost benchmark is executed. In addition, strategic aspects of the make-or-buy decision are investigated. Organizational change is also fostered by knowledge and information exchange within the organization. For that, a target group analysis is conducted. Based on the identified target groups, appropriate means of information exchange and knowledge building are proposed.

Finally, the *AM Technology Roadmap* is generated, including all relevant information from the action fields. Each action field addresses one aspect of the *AM Technology Roadmap*. The generation of the roadmap is dependent on the framework conditions of the company, and it is critical that all involved stakeholder can participate in the generation process. Derived from the action fields, the roadmap covers three planning levels. These levels are technologies, applications, and organization. The final results of each action field are depicted in the corresponding planning level in the roadmap. Moreover, the linkages between the different planning levels become evident. Based on the study of SCHUH (2013) (cf. section 2.2.2, page 22), the proposed roadmap covers a maximum 10-year time span, clustering the strategic initiatives into short-term (1 – 3 years), mid-term (4 – 6 years), and long-term perspective (7 – 10 years). Regarding the fast development of AM, a roadmap covering more than 10 years must be built on only vague technology forecasts.

When applying the proposed methodical approach to establish a technology roadmap in an organization, the action fields cannot be addressed separately because there are several dependencies among them. Hence, the generation of the roadmap is a sequential process with several iterations in which the focus is on the most promising parts and applications. Most important is the identification of applications that foster innovations within the organization that finally turn into revenue. Gathering technology information (action field A) is a mandatory process to yield the necessary technology data for the evaluation process and knowledge building, whereas the derivation of organizational tasks (action field C) is necessary to exploit the identified potential of AM.

Following the research methodology of DRM (cf. section 1.3, page 3), the presented methodical approach to obtain a technology strategy in AM is the scientific finding of the phase *Prescriptive Study,* which combines literature review and research results generated by the author. Thus, the approach to develop a technology strategy in AM was built on the prior introduced literature and is especially motivated by the lack of a strategical perspective of AM implementation. Inspired from these literature, process steps and tools to support the strategical decision taking were developed by the author and applied in different producing companies. From this application in an industrial environment, valuable feedback was provided by experts of different professions (e.g. design, production, industrial engineering, AM technology, supply chain management, human resources). Moreover, the author was responsible for the AM implementation process in an engineering company and utilized the resulting experience to improve the methodical approach. In addition, the approach of generating an AM technology strategy was discussed in the scientific community through publications and conferences. Based on these feedback and experience, the process steps and the supporting tools were continuously improved. Finally, all these information was integrated into the herein presented methodical approach to setup a *Technology Strategy for Metal-based Additive Manufacturing*.

5 Action Field A: Gather Technology Information

Action field A addresses the gathering of technology information. Thus in this action field the required data for the further evaluation process is generated, because reliable data is required when evaluating an AM technology. Consequently, corresponding data must be collected prior to the evaluation process. This requires establishing a process of data collection and storing the obtained data. To collect and structure information on technology performance, a technology fact sheet is an appropriate document (REINHART ET AL. 2012). It supports the communication of the technology's characteristics by providing formalized content in a clearly structured document (GREITEMANN 2016). To facilitate the information search process, section 5.1 provides a method to identify suitable information sources, mainly based on the approach of GREITEMANN (2016). In section 5.2, an *AM Technology Fact Sheet* is developed to summarize technology performance data for AM technologies.

5.1 Identification of Information Sources

To support the identification and exploitation of information sources, the work of GREITEMANN (2016) is instructive. That study investigated the role of information sources in the technology evaluation process. Based on this work, Table 5.1 provides an overview of information sources in general and specific examples for AM technologies. The activity of an information source was defined by GREITEMANN (2016) as the likelihood to identify continuative information sources in a given information source. Hence, the information sources are ranked by activity, because it is critical to start an information search in the most active information sources. Moreover, information sources can be classified into formal and informal ones. Whereas formal sources can be searched with a systematic approach, informal sources are based on personal contacts. The most important information source in all technology development phases is internal experts (cf. Figure 2.14, page 23).

When searching formal information sources, a systematic approach facilitates the exploitation of information sources. Table 5.3 provides a search matrix template for searching formal information sources. Synonymous search keywords are identified and linked by an or-connection, whereas different search aspects are collected and linked by an and-connection. For each combination of search terms, a query is executed and investigated according to a predefined procedure. This procedure ensures a methodically supported search process and delivers extensive search results. If underlying search parameters remain constant (e.g., search engine, time effort per search query, analyzed raw results), the systematic search approach provides reliable results.

Table 5.1: Identification of suitable information sources. List of information sources, activity and definition based on GREITEMANN *(2016).*

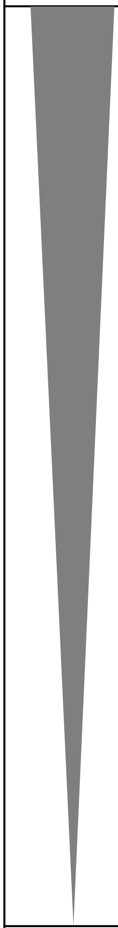
Activity	Information source	Definition	Examples for AM (excerpt)
	Internet*	Information provided by freely accessible websites, blogs and newsfeeds	▪ Internet search engines ▪ AM-related information websites
	Internal experts	Meetings and knowledge exchange with technology specialists, R&D employees	▪ Identify via companies intranet and personal network ▪ Include employees with relevant expertise from all departments
	Personal contacts	Meetings and knowledge exchange with personal contacts	▪ Personal network ▪ Social media
	External experts and business networks	Meetings and knowledge exchange with external contacts, e.g. employees from suppliers, customers or competitors	▪ Formal business networks, e.g. VDMA work group AM, Mobility goes Additive ▪ Suppliers of AM parts and raw materials ▪ Machine manufacturer ▪ Consultancies and research institutions
	Research institutions and universities	Meetings and knowledge exchange with researchers, e.g. professors, academic employees, doctoral candidates	▪ Universities ▪ Research institutions ▪ Local research centers
	Scientific publications*	Information in scientific publications, e.g. scientific journals, conferences and literature databases	▪ Google scholar ▪ Web of Science ▪ Scopus
	Technology studies*	Information in technology studies and reports provided by governmental entities, consulting companies or associations	▪ Governmental entities ▪ Consulting companies ▪ Standardization and regulation authorities ▪ Technical associations
	Commercial events	Information on latest developments of technologies published to participants of commercial events, e.g. fairs, conferences, seminars	▪ AM-related fairs ▪ Fairs, addressing AM as subdomain ▪ Scientific Conferences ▪ Industrial conferences
* Formal information sources			

Table 5.2: Systematic search structure to search formal information sources with exemplary terms for AM.

	Search aspects **→ AND-Connection**		
	Search aspect 1	**Search aspect 2**	**Search aspect 3**
Synonyms **→ OR-Connection**	Additive manufacturing	…	…
	3-D-printing		
	Generative manufacturing		
	Additive production		
	…		

5.2 *Technology Fact Sheet* for AM Technologies

The *Technology Fact Sheet* offers a structure to collect performance data about an AM technology. Thus, it offers a reliable information source for the further evaluation processes and knowledge building. In addition, the *Technology Fact Sheet* summarizes the current technology performance, because the technology information is regularly updated.

The structure of the *Technology Fact Sheet* for metal-based AM technologies is shown in Figure 5.1. In the first section, the fact sheet contains basic technology information, such as the name, functional principle, and process categorization according to ISO/ASTM 52900. In addition, the responsible contact, date, and version are documented. This information helps to keep the fact sheet up to date and maintain a clear numbering of document versions. The second section contains an overview of technology data, including the material range and properties, machine equipment, process chain, exemplary applications, cost indicators, and technology maturity. For each aspect, additional pages are attached to evaluate the information in more detail. The third section provides an outlook on technology development that is clustered into short-, mid-, and long-term perspectives. An exemplary version of a *Technology Fact Sheet* for LPBF can be found in Appendix B.

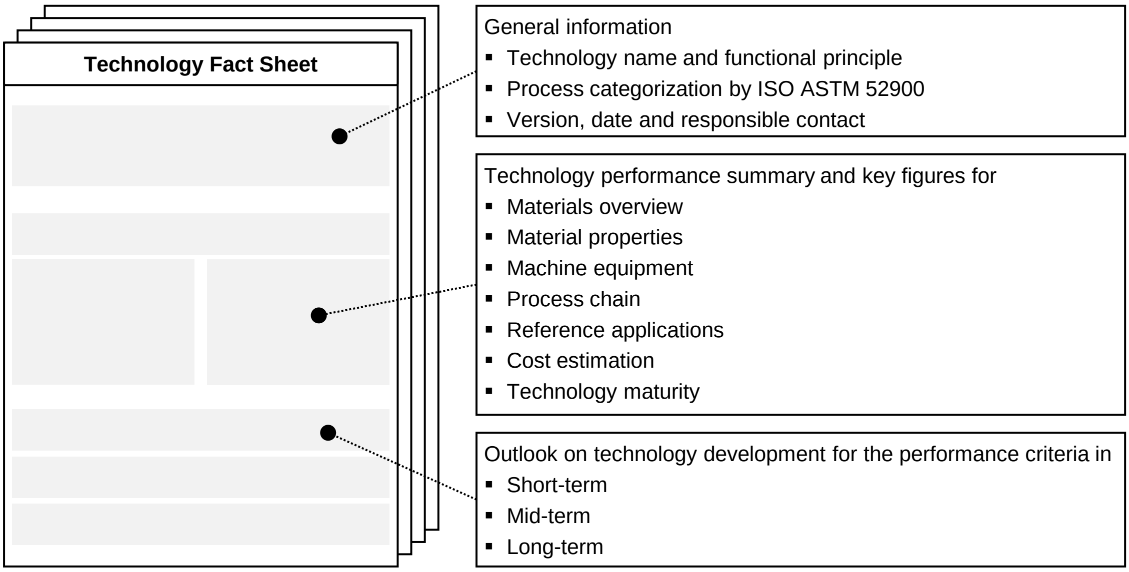


Figure 5.1: Structure of the Technology Fact Sheet.

5.2.1 Materials Overview

A key criterion when evaluating applications for AM is the availability of a material that meets the technical requirements of the application. Therefore, it is necessary to have a comprehensive overview of the available range of materials for the additive technology. The materials overview in the fact sheet offers a structured means of clustering this information, which is depicted in Table 5.3. The base structure is derived from ROOS & MAILE (2008) and categorizes metals into light (density less than 5 kg/dm³) and heavy metals (density higher than 5 kg/dm³). Furthermore, heavy metals are categorized by melting temperature into low melting (T_m < 1000 °C), high melting (1000 °C < T_m < 2000 °C), very high melting (T_m > 2000 °C), and precious metals. On the basis of correspondence to the base alloy component, materials can be categorized using this structure. Because several companies promote materials with proprietary names, the corresponding material numbers are used as leading information. Moreover, the precise alloy composition is stated. For aluminum, material numbers are standardized in DIN EN 573-1. Standardization of material numbers for steels is defined in DIN EN 10027-2. Referencing the material number facilitates further evaluative steps, especially a data-based part identification approach (cf. see 6.1.1, page 76).

Table 5.3: Structure for materials overview.

Categorization			AM material				
Density	Melting temperature	Base alloy component	Alloy composition	Material number	Material name	Market available/ Under development	Reference
Light metals (δ < 5 kg/dm³)	--	Magnesium				☐ / ☐	
		Aluminum				☐ / ☐	
		Titanium				☐ / ☐	
		…				☐ / ☐	
Heavy metals (δ > 5 kg/dm³)	Low melting (T_m < 1000 °C)	…				☐ / ☐	
	High melting (1000 °C < T_m < 2000 °C)	Copper				☐ / ☐	
		Nickel				☐ / ☐	
		Cobalt				☐ / ☐	
		Iron				☐ / ☐	
		…				☐ / ☐	
	Very high melting (T_m > 2000 °C)	Tungsten				☐ / ☐	
		…				☐ / ☐	
	Precious metals	Silver				☐ / ☐	
		Gold				☐ / ☐	
		Platinum				☐ / ☐	
		Rhodium				☐ / ☐	
		…				☐ / ☐	
☐ Checkbox blank ☒ Checkbox marked							

In addition, it is of importance to anticipate the material development for the additive technology. Which materials will be available in the future is a key information, even if the data for future upcoming materials are more difficult to access. Therefore, the material overview structure allows marking materials as *market available* or *under development*. Initially, the mark is set depending on the information source. Material data provided by service providers, system manufacturers, and material suppliers are treated as *market available*, whereas material data from scientific publications or development reviews are marked as *under development*. Caused by developments in AM manufacturing systems further materials become available. For example, advanced heating systems in LPBF machines offer the opportunity to process materials that are difficult to weld (SCHLICK 2017). Finally, the source of information is linked by a reference.

5.2.2 Material Properties

Besides the overview of available materials, the material properties of a specific material are critical for detailed technology evaluations. As depicted in Table 5.4, the material properties are split into three groups of parameters: geometric properties, static material properties, and dynamic material properties. The geometric properties include the resolution in X, Y, and Z directions and the surface roughness. The coordinate system is defined in ISO/ASTM 52900. Static material properties include tensile strength, yield strength, breaking elongation, Young's modulus, and surface hardness. For market available materials, static material properties are readily available from datasheets or can be obtained from standardized material tests, such as tensile tests (DIN EN ISO 6892-1). A detailed description of how to investigate material properties of beam-melted parts is stated in VDI 3405-2.

The determination of dynamic material properties is often cost intensive and dependent on the application purpose of the material. Therefore, it is difficult to identify universally valid information concerning dynamic material properties. The third section in Table 5.4 gives an overview of evaluative criteria for dynamic material properties, such as high and low cycle fatigue, thermomechanical fatigue, creep resistance, wear resistance, and corrosion resistance.

Additionally to the value of the material property, the deviation of this value has to be stated. Ideally, the number of investigated specimens is also included. Moreover, different conditions in which the material properties might be obtained are investigated. For each value, at least the build orientation and heat treatment condition must be specified. The reference system for the build orientation for PBF processes follows VDI 3405-2. Nevertheless, when comparing material properties of different information sources, the reference systems need to be unified. The heat treatment condition has a strong influence on material properties. In Table 5.4, “heat treated” and “as built” conditions are differentiated to generate an overview of the obtainable material properties. Due to manifold heat treatment routes and different surface treatments in post-processing, a more differentiated selector might be introduced when appropriate.

Table 5.4: Material properties of a specific AM material.

Material								
Parameter		Unit	Value	Deviation		Specification		Reference
				Min	Max	Build orientation[1]	As built / heat treated	
Geometry properties	Resolution (X-direction)[1]	µm						
	Resolution (Y-direction)[1]	µm						
	Resolution (Z-direction)[1]	µm						
	Surface roughness (Ra or Rz)	µm						
	…							
Static material properties	Tensile strength	MPa					☐ / ☐	
	Yield strength	MPa					☐ / ☐	
	Breaking elongation	%					☐ / ☐	
	Young’s modulus	MPa					☐ / ☐	
	Impact notch work	J					☐ / ☐	
	Surface hardness	HRC					☐ / ☐	
	…							
Dynamic material properties	High cycle fatigue (HCF)	Information on dynamical material behavior to be documented separately.						
	Low cycle fatigue (LCF)							
	Thermo-mechanical fatigue (TMF)							
	Creep resistance							
	Wear resistance							
	Corrosion resistance							
	…							
[1] Definition for powder bed fusion processes in VDI 3405-2; ☐ Checkbox blank; ☒ Checkbox marked								

5.2.3 Machine Equipment

For several metal AM processes the maximum part size is limited by the available size of the build chamber of the AM manufacturing system. Therefore, an overview of market-available systems is a part of the *Technology Fact Sheet*. The available systems are detailed by system provider, system name, and build chamber dimension (see Table 5.5).

Table 5.5: List of AM manufacturing systems.

System provider	System name	Build chamber		Remarks on system specifications
		Shape	Dimension (X Y Z) in mm³	
…				

To compare dimensions of build chambers of different shapes, a standardized measure has been established. It normalizes the build chamber volume $\mathrm{V}_{\mathrm{build\ chamber}}$ of an AM system to a cube of the same volume. The normalized and comparable measure is then the edge length of this cube, which is named as *corresponding cubic dimension (ccd)*. This is represented in the formula

$$ccd = \sqrt[3]{V_{build\ chamber}}. \tag{5.1}$$

To estimate a measure for the size of available AM system build volumes in the market, all gathered information are unified into a ccd value. The quantity of AM systems is then split into percentiles (see Figure 5.2). Based on the pareto principle, the commonly utilized build volume dimensions are derived. Thus, the 10th percentile and 90th percentile of the quantity of AM systems are utilized as key technology figures. Finally, this range covers 80% of all build volumes, with 10% smaller than the 10th percentile value and 10% larger than the 90th percentile value.

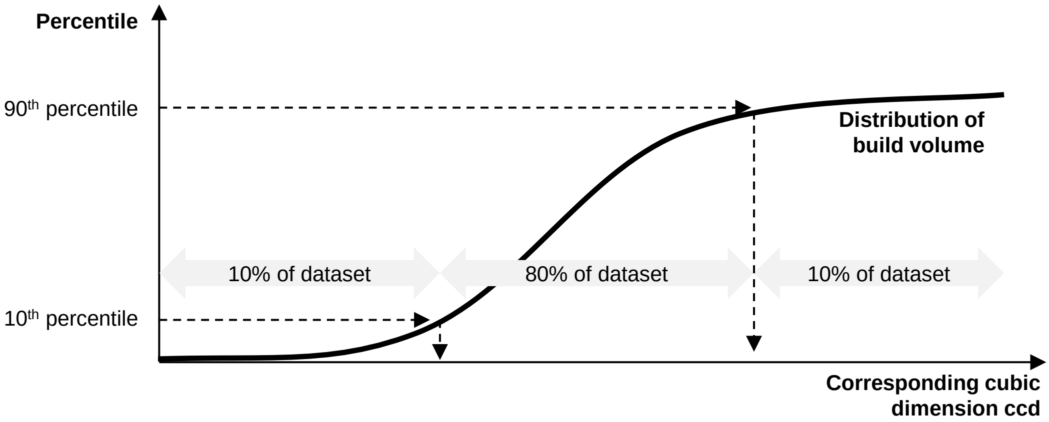


Figure 5.2: Derivation of build space volume measures.

5.2.4 Process Chain

Mostly the AM process is part of a process chain, because the AM process does not meet all requirements of a technical application. Even if the final process chain is highly depending on the specific application, there are differences in the minimal requirements for the process chain among metal-based AM processes. For example, multi-step AM processes require a process step for removing the binder material and sintering to obtain the metallic material properties. Thus, the *Technology Fact Sheet* provides an overview of the minimal required process chain for the AM process, which contains the process steps that are inherently required by the AM process. A generalized process chain of AM is defined as pre-process, in-process, and post-process steps by VDI 3405 (cf. section 2.1, page 7), which is utilized as basis in the *Technology Fact Sheet*, as depicted in Table 5.6.

According to the definition of pre-processing in VDI 3405, the pre-process is split into data creation and preparation for the AM process. The process chains of AM technologies are differentiated by the need for support structures, the dimensions to nest parts in the build space, the toolpath generation, and the references to production parameters.

The post-processing phase is split into four categories. First, parts have to be removed from the build job, and then, the material, geometric, and surface properties have to be finalized. The removal of parts depends on the AM technology. For powder-based processes, the removal of loose or coherent powder is a mandatory process step, whereas for wire-based technologies, this step does not apply. Moreover, removal of parts from a build plate is only necessary if the AM process needs a base structure to build on. The material properties are adjusted by heat treatment processes. For multi-step processes (cf. section 2.1, page 7), the removal of the binder material through washing or burning and the sintering process is necessary to generate the intended material properties of a metallic part. For single-step processes, stress-relief annealing is a commonly utilized heat treatment process. Further post-processing entails finalizing the geometry of the parts by machining. A machining process is necessary on functional surfaces like threads, fits, and tolerances that cannot be manufactured by the AM process. Moreover, the surface properties are finalized. Here, tool-bound (e.g., machining) and non-tool-bound processes (e.g., electrochemical polishing, barrel finishing) can be applied (SUCH ET AL. 2019).

Table 5.6: Minimal required process chain for AM technology.

Generalized AM process (VDI 3405)	Mandatory process steps for AM process
Pre-process	Data collection / creation □ Creation of a 3D model □ …
	AM related data preparation □ Design of auxiliary structures (e.g. supports) □ No nesting: one piece flow □ Planar nesting of parts in the build space (X- and Y-direction) □ Volume-based nesting of parts in the build space (X-, Y- and Z-direction) □ Apply material specific production parameter □ Apply part specific production parameter □ Generation of a layer-based toolpath □ Generation of a feature-based 3D toolpath □ …
In-process	Execution of build process
Post-process	Removing of parts and over material from build job □ Removing of loose powder from build job □ Removing of coherent powder from build job □ Separation of parts from build plate □ Removing of auxiliary structures (e.g. supports) □ …
	Material property adoption by heat treatment □ Burning/Washing out of auxiliary materials □ Sintering □ Stress-relief annealing □ Hot isostatic pressing (HIP) □ Hardening □ …
	Geometry finalization □ Machining of functional surfaces (e.g. fits, threads, tolerances) □ …
	Surface property finalization □ Blasting / shot peening □ Chemical process (e.g. etching) □ Electro-chemical process □ Mechanical process (e.g. flow grinding, barrel finishing, polishing) □ Coating process □ …
	☐ Checkbox blank ☒ Checkbox marked

5.2.5 Reference Applications

Exemplary applications of AM technology are of high importance to make the benefits and application purpose clear. As proposed by KUMKE ET AL. (2018), a case study collection supports the understanding of a technology application, especially for novice users. Therefore, exemplary applications of AM technology are identified and described in the *Technology Fact Sheet*. The most important exemplary applications are those comparable to the company's products. These exemplary applications are identified within the company's branch or related branches. A benchmark study on additive activities of competitors provides additional results. If no exemplary applications from the company's branch can be identified, technology demonstrators from other branches are utilized. Table 5.7 provides a template to describe exemplary use cases of an AM technology. The use case is specified by name and application purpose. Moreover, several additional categories of information are collected to provide the background of the use case. Such information is a valuable source for inspiration, but often, public information about the use cases is limited. To visualize the exemplary application, a picture is attached to the description. Universal and comparable information about the suitable part mass is derived by splitting the quantity of parts in quantiles. Based on the pareto principle, the 10th and 90th percentile define the middle 80% of all part masses (cf. Figure 5.2). This values are utilized as key figures in the *Technology Fact Sheet*.

Table 5.7: Template for exemplary applications.

Picture of application	Application name	
	Branch & Company	
	AM benefits	
	Material	
	Part dimension (bounding box)	
	Part mass	
	Cost per part	
	Application type	☐ Serial application ☐ Prototype

5.2.6 Cost Estimation

The cost of an AM process is relevant for evaluating the economic aspects of an AM technology. To facilitate the cost estimation, three different approaches can be followed: analytical cost modelling, benchmarking of supplier cost, and reviewing of cost literature (SCHNECK ET AL. 2020). First, the cost per mass or volume of an AM process can be calculated based on an analytical model. To establish the analytical model, comprehensive knowledge about the AM process is necessary to make realistic assumptions in the model. Second, the cost indicator can be derived from supplier quotes; a third option is to rely on cost data stated in the literature. A cost indicator is a rough mass- or volume-based estimation of production cost for an additive process and depends on several input variables. Therefore, it is important to state the method by which the cost indicator was obtained. As recommended by SCHNECK ET AL. (2020), validated cost information can be derived when at least two approaches of cost evaluation are followed.

In Table 5.8, a structure to collect cost information for a mass-based cost indicator is proposed. At first, the material of the cost information is specified by material number. For each information source, the amount of parts and mass per part are stated, from which the total mass is derived. Moreover, from the cost per part the total cost are derived. To obtain comparable cost information, the conditions of different information sources have to be equalized (e.g., covered process steps in cost information). Finally, the mass-based cost are derived from the total mass and total cost. In addition, the type of information source and a reference are stated.

Table 5.8: Collection of cost information.

Material number	Amount of parts	Mass per part	Total mass	Cost per part	Total cost	Mass-based cost	Type of source			Reference
	-	kg	kg	€	€	€/kg	Analytical cost model	Literature review	Supplier quotes	
							☐	☐	☐	

As key figure for the *Technology Fact Sheet* the cost range is derived from the collected information. For that, the minimum, average, and maximum mass-based cost of all collected information is calculated, which provides an overview of the cost for the AM process.

5.2.7 Technology Maturity

The concept of technology maturity describes the current development state of a particular technology. It allows an estimation of the technology's capabilities and what development efforts are needed to utilize the technology in a serial production environment. Thus, the prior collected data of the AM technology in the *Technology Fact Sheet* are summarized into a technology maturity.

The technology maturity evaluation for an AM technology is depicted in Table 5.9. It is based on the concept of Manufacturing Readiness Level (MRL), which allows a generalized statement about the manufacturing capabilities of a technology (see section 2.2, page 16). The ten MRL are summarized into the early development phase (MRL 1 – 5), the beginning of market introduction (MRL 6 – 8), and full serial production (MRL 9 – 10). To assess the MRL of the AM technology, relevant sections of the *Technology Fact Sheet* are investigated. These are materials overview, machine equipment, reference applications, and cost information. For each section, measures to estimate the technology maturity are derived, which is depicted in Table 5.9. For the assessment of the overall MRL, the correct criterion in each section is cross marked. The mark with the lowest maturity level defines the overall technology maturity of the AM technology.

Table 5.9: Assessment of AM technology maturity utilizing the Manufacturing Readiness Level (MRL) defined in DEPARTMENT OF DEFENCE *(2018).*

Section in Technology Fact Sheet	**Early development phase**	**Beginning of market introduction**	**Full serial production**
	MRL 1 – 5	**MRL 6 – 8**	**MRL 9 – 10**
Materials overview	☐ Only materials under development	☐ Market available materials, but not from service providers	☐ Material data from service providers is available
Machine equipment	☐ No AM system provider is on the market; Only principles and prototype systems are known	☐ At least one AM system provider is on the market with a serial AM system	☐ More than one AM system provider is on the market
Reference applications	☐ Reference applications in industry could not be identified	☐ Only prototypes for industrial applications are identified; no serial use documented	☐ Serial applications are identified
Cost estimation	☐ Cost information could not be obtained	☐ Cost models and literature references about cost are available	☐ At least two service providers on the market; Cost benchmarking possible
Assessment of MRL for AM technology	☐ **MRL 1 – 5**	☐ **MRL 6 – 8**	☐ **MRL 9 – 10**
			☐ Checkbox blank ☒ Checkbox marked

5.2.8 Forecast of AM Technology Development

To forecast the further development of the AM technology is an important function of the *Technology Fact Sheet* for setting up the *AM Technology Roadmap*. Thus, the outlook section in the *Technology Fact Sheet* contains the expected technology development for all prior investigated technology capabilities.

The most precise data can be obtained from the collected data. For materials, which are currently under development, the expected market entry is derived. To estimate the market entry for a material, different methods are applied. At first, the current limitations to manufacture the material are discussed with technology experts (e.g. from a technology supplier). Then the approaches and timespan to overcome these limitations are derived. Secondly, the development process of already established materials is investigated to perform a similarity analysis. Especially if comparable materials are on the market, this approach allows a well-grounded estimation of the market entry. For AM systems the development in the machine equipment are collected and analyzed. Exemplary, an improved machine equipment enables the manufacturing of further materials or reduces the production cost if the build rate is raised at same system cost. Besides the system equipment, also the market situation influences the cost, especially for external supply. Therefore cost forecasts are requested from technology suppliers. Finally, the progress in the technology maturity is estimated, if the technology is not yet used for full serial production.

Because the forecast of the technology development bears always uncertainty, it is required to ground the estimations on different sources. Thus the outlook is discussed with several technology experts. Moreover, generalized studies about the AM technology development are integrated in the forecast section.

6 Action Field B: Evaluate Applications

The identification and evaluation of suitable AM applications is the most important task when developing an *AM Technology Roadmap*. The evaluation process requires information about AM technology performance, which is provided in the *Technology Fact Sheet*. An *AM application* in the context of the presented approach is a use case for the utilization of AM technologies that leverages AM inherent benefits. Thus, an application includes parts, assembly groups, spare parts, and products, but also supportive devices like toolings, fixtures, and molds for the corresponding production processes. If an application offers technical and economic benefits through the use of AM, it is considered a *business case*. A comprehensive definition of a business case for AM applications is given by THOMPSON ET AL. (2016):

> "Competitive businesses cases can be made for Additive Manufacturing when it adds sufficient value to a product to justify higher production costs, reduces product development costs, reduces production costs, reduces costs over the entire value chain, reduces the cradle to grave costs of the product, or provides some combination of these benefits."

All decisions regarding the technology strategy build on the portfolio of applications that are suitable for AM. Therefore, an extensive screening of the product portfolio for AM applications is necessary. In section 6.1, a combined approach of data-based and knowledge-based part screening is introduced. Based on the combination of screening approaches, a holistic view of the potential of AM technology is obtained. The assessment process of a specific application is described in section 5.2, page 61. The process consists of four steps, namely the definition of development goals, the technical evaluation, the economic evaluation, and the derivation of a project plan to realize the identified AM technology potential. The assessment procedure is provided in the form of an *Application Assessment Sheet*, which is used as supporting tool during the part screening process to guide the user through the evaluation.

To start a screening for potential AM applications and invest financial and time resources into this process, requires motivation and an expected benefit for the company. This motivation is a frame condition to setup a technology strategy in AM, as discussed in chapter 4. However, this motivation and the corresponding assumption about the AM benefit can bias the outcome of the screening process. For example, if the need for AM technology is justified with a specific product by the responsible manager, the screening process may not be executed from a neutral perspective, but with a focus on this specific pre-assumed product. Hence, the screening result may favor this product, overlooking other – maybe more suitable – AM applications. Thus, it is important to execute the screening from a neutral perspective and evaluate all possible AM applications based on the same criteria.

6.1 Identification of AM Applications

To generate an overview of the AM technology potential, first, applications that benefit from AM technology must be identified. In a producing organization, there are two sources for possible applications: the established product portfolio including the underlying production processes (existing applications) and products under development in development projects of various realization phases (future applications). For a holistic view of the potential of AM technology, the established product portfolio as well as the development projects are screened for suitable AM applications. Thus, the capabilities of the AM technology need to be matched with the product portfolio. For that, three roles are required in the screening process: an AM technology expert provides the knowledge about the AM technology; an application expert has detailed know-how about the application that is evaluated for AM; and a project leader, who steers the screening process.

In literature, there are two approaches to identify AM applications: the data-based approach and the knowledge-based approach. Whereas a data-based approach allows to screen large datasets for suitable applications, the knowledge-based approach supports a detailed evaluation of a specific application and the involvement of several experts (cf. section 2.3.1, page 30). To benefit from both approaches, a combined screening process was developed to generate a holistic, but also detailed screening result. Thus, the presented approach to screen for AM applications integrates the data-based and the knowledge-based approach. An overview of the combined approach is depicted in Figure 6.1.

The combination of data-based and knowledge-based approaches yields a more detailed result than each approach on its own. The data-based screening approach allows for screening databases and therefore allows for the derivation of an overview of the AM technology potential based on the whole product portfolio. Yet, the approach is not capable of obtaining validated screening results because it is limited to formalized data queries and the already existing parts that are accessible in databases. Thus, applications identified with the data-based approach need to be validated with experts following a knowledge-based approach.

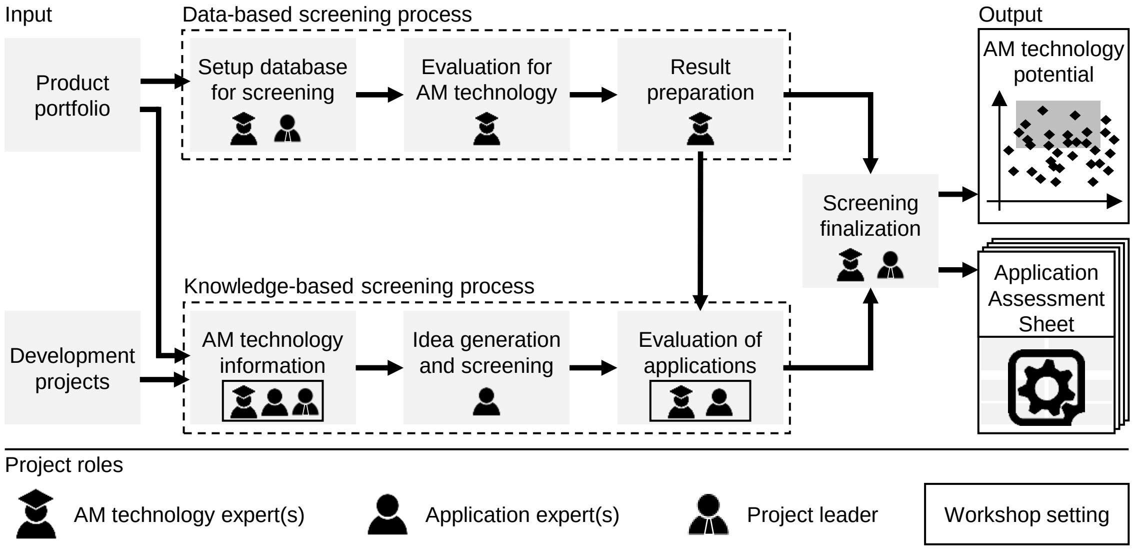


Figure 6.1: Combined data-based and knowledge-based approach to identifying AM applications.

The knowledge-based approach allows for a detailed screening of parts, including parts under development and the generation of new product ideas based on AM technology. The limitations of this approach are the knowledge and capacity of the involved experts. In most organizations, it is impossible to rate all parts in a company using a knowledge-based approach due to the required capacity. Thus, a holistic view of the potential for AM technology is difficult to obtain because only preselected applications are evaluated.

The combined approach of a data-based and knowledge-based part identification allows for a holistic view of the AM technology potential to be obtained and a detailed evaluation of specific applications. Both approaches are applied in parallel, and the results from the data-based screening are integrated into the knowledge-based screening process. Thus, the results of the data-based part screening are evaluated and validated by the responsible experts for the identified applications. As can be seen in Figure 6.1, the knowledge-based screening approach is the core process to identify AM applications. The data-based approach offers a broader overview of the AM technology potential and delivers applications for further manual evaluation, but it is not able to generate realizable results without being validated by an expert’s opinion. The following sections introduce the data-based and knowledge-based screening approaches.

6.1.1 Data-based Part Screening

The data-based screening approach for AM applications has been described in literature by only a few sources and not in detail (cf. section 2.3.1, page 30). Nevertheless, a data-driven part screening provides a valuable overview of the AM technology potential and identifies AM applications based on data-driven systematics. The data-based part screening is split into three phases, as shown in Figure 6.2.

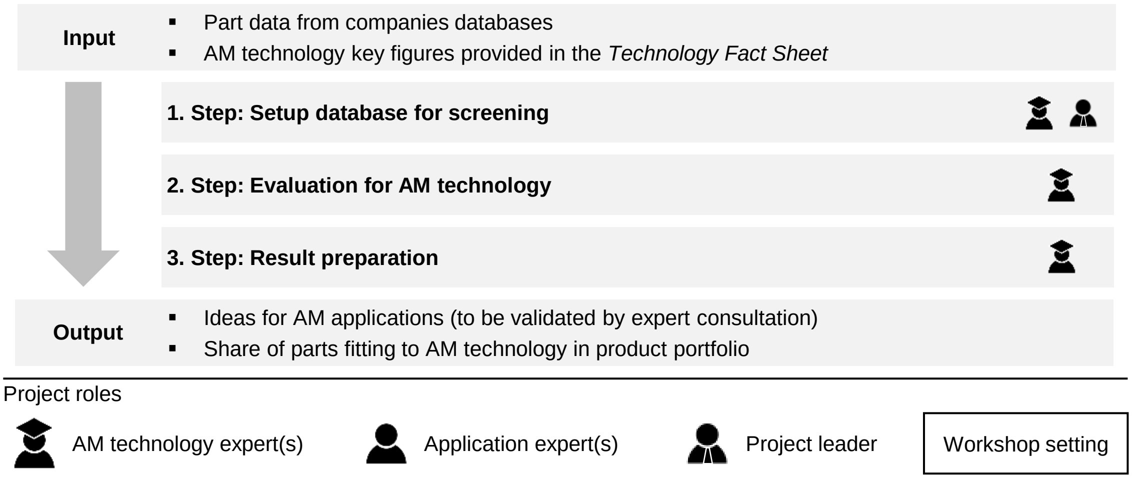


Figure 6.2: Process of data-based part screening.

The first step is to establish a database for the screening process. Depending on the purpose of the screening, data from different sources have to be merged into a unified database. Firstly, the available data sources and provided data fields must be determined. Here, background information is valuable to estimate the reliability of the data; such as the linkage of data fields to a drawing or Part Data Management (PDM) system. When unifying the data, it is important to maintain a unique identifier (e.g., a part ID) and to equal all units in the database. Moreover, some data may be provided by several data fields. For example, the *weight* information may be accessed from the drawing through the PDM system but may also be available from logistics data such as packaging. In particular, data about product cost may be available in different conditions, such as supplements for logistics, storage, and purchase. In most cases, it is appropriate to use the internal manufacturing cost for the evaluation. Finally, the obtained database is purged of obviously faulty values (e.g., weight equal to zero, negative prices). For a reliable result regarding AM technology potential, it is necessary to document all selection criteria and the remaining number of datasets carefully. The result of the second step is a unified database, with all relevant data for the AM technology evaluation.

In the second step the AM technology performance criteria, provided as key figures in the *Technology Fact Sheet,* are implemented into the database and the evaluation is executed. Based on the unified and cleaned database resulting from the first step, the evaluation criteria for the AM technology are applied. At first, part classes are excluded if they do not bear any AM applications; these include standardized elements like screws, nuts, and bolts or electrical components. The categorization of part classes is taken over from the origin dataset (e.g., PDM system). The remaining datasets are compared with the AM technology data that are based on the *Technology Fact Sheet*. Necessary evaluation criteria are the mass, cost, and material of the application, and further criteria are optionally included for a more detailed result. The three levels of the evaluation process are depicted in Figure 6.3. A first approach of the data-based screening process was published by the author *(ILLGNER ET AL. 2018)*.

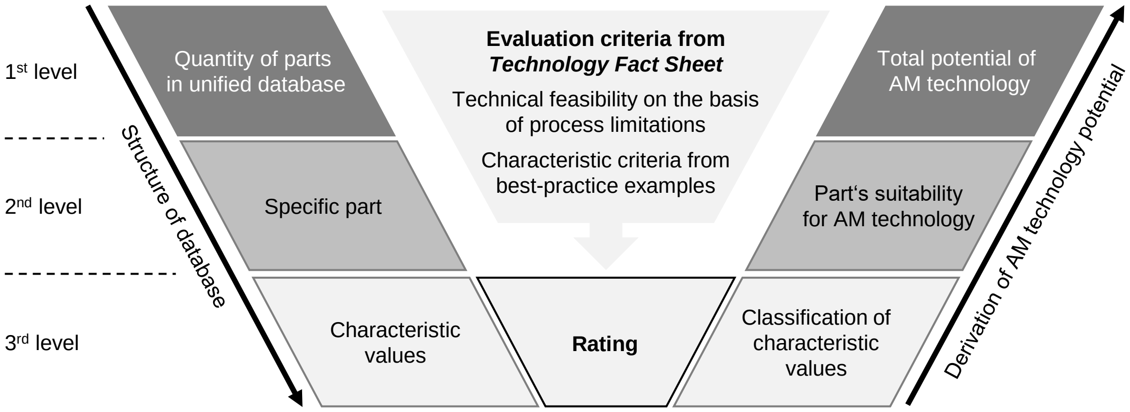


Figure 6.3: Data-based evaluation approach (based on ILLGNER ET AL. 2018).

On the first level is the quantity of all parts in the unified databases from the first step. On the second level, there are parts, marked by a unique identifier, such as a number or part ID. On the third level, characteristic values of these parts are stored, such as weight of the component or manufacturing cost. On this level, each of the characteristic values of the part is compared with the AM technology data from the *Technology Fact Sheet*. Here it is applied, if the cost structure of the AM technology meets the cost of the part or if the material is market available. On the second level, the ratings of single characteristic values are compiled to determine the part’s suitability for the AM process. On this level, the findings also show limitations for AM adoption. For example, weight and cost meet the AM criteria, but the desired material is unavailable in the AM market. On the third level, the overall potential of the AM technology is obtained. Here, the result can be seen in the context of the quantity of all parts analyzed; for example, the percentage of the product portfolio that meets the cost criteria of the AM technology.

An overview of mandatory and optional screening parameter for data-based part identification, including an explanation of each criterion, is provided in Appendix A. Further processing of the results for an AM technology is dependent on the number of identified parts. If only a few parts (less than 300) are selected as appropriate for the AM technology, a manual evaluation is performed. For a larger amount of parts, additional filtering criteria are used to further reduce the number of identified parts (e.g., total cost of a part). For AM applications, which are considered to be relevant findings by the AM expert, the first section on the front page of the *Application Assessment Sheet* is prepared for the following expert discussion (cf. section 6.2).

The third step covers the preparation of the screening results. The screening results are visualized in a chart, providing a graphical overview of the product portfolio. Figure 6.4 shows the schematic chart of the data-based part screening result. Each part or product in the product portfolio contains a specific value for each evaluation criterion, which is depicted as data point. In the exemplary result visualization in Figure 6.4, two rating criteria are depicted. Thus, a specific part, identifiable by its part ID, can be represented as a point in the 2D diagram. Moreover, the AM technology potential is visualized as an area in the diagram, defined by the key figures from the *Technology Fact Sheet*. For more complex evaluations, based on several rating criteria, the visualization is extended by additional dimensions or multiple 2D diagrams are set up. Based on this visualization, the amount of suitable parts for the AM technology in the context of the product portfolio becomes obvious.

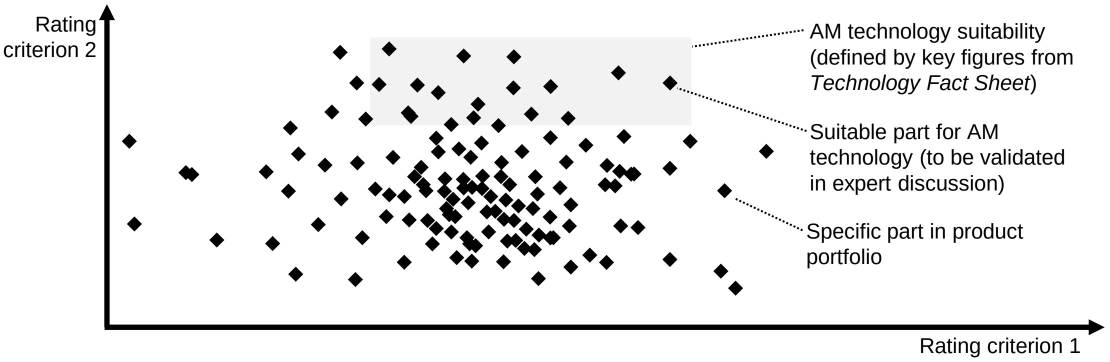


Figure 6.4: Schematic result of a data-based part screening.

6.1.2 Knowledge-based Part Screening

The knowledge-based part screening approach is based on workshops, as proposed in the concept of LINDEMANN ET AL. (2014) (see section 2.3.1.1, page 34). It follows three steps, which cover the *AM technology information*, the *idea generation* *and screening*, and the *evaluation of applications*. The process is depicted in Figure 6.5.

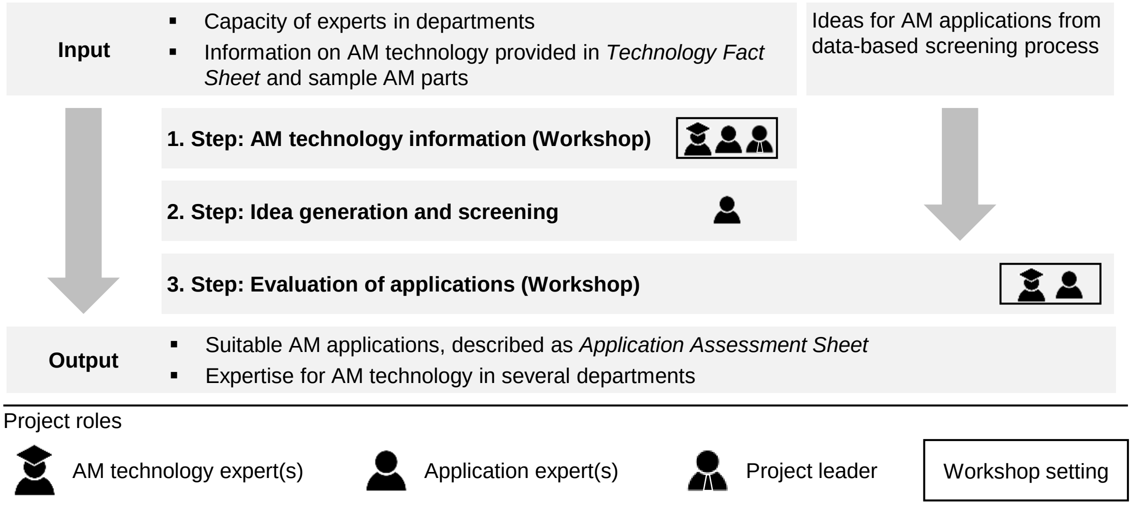


Figure 6.5: Process of knowledge-based part screening.

The first step is a workshop setting with the expert from different departments to introduce the AM technology and screening process. Depending on the number of involved experts, it may also be appropriate to hold a workshop series. It is beneficial to hold the workshops as in-person events; however, video conferences are appropriate when experts at distributed locations will take part. The goal of the workshop is to establish know-how concerning AM technologies and thus to enable the experts to contribute to the part screening process. To establish a knowledge base, the *Technology Fact Sheet* is a valuable tool because it summarizes the technology potential. According to KUMKE ET AL. (2018), physical models (e.g., demonstrator parts, samples) are the most important tool to visualize an AM technology. In particular, novices to AM technologies rate them as useful for the learning process. Thus, the first expert workshop achieves three major results:

1. Introduction of theoretical information about AM technology potential provided by *Technology Fact Sheets.*
2. Practical information through discussion of physical models and demonstrator parts; introduction of tools for the screening process (e.g., *Application Assessment Sheet*, cost estimation tools, and checklists).
3. Foster motivation for AM and the screening project among the involved experts by explaining relevance, project motivation, goals, and schedule.

The second step is the idea generation and screening process, which is executed by the application experts. After building up knowledge on AM technology in the first step, they seek for appropriate parts and applications in their area of responsibility. Each application idea is documented in the first section of an *Application Assessment Sheet* (see section 6.2, page 82). The goal of the screening process step is to generate manifold ideas for the application of the AM technology across the organization.

The third step is a workshop setting to discuss the ideas of the application experts in the screening process and the findings from the data-based screening approach. The goal of this process step is to evaluate the ideas for the application of AM technology. For that, the evaluation process, which is formalized in the *Application Assessment Sheet*, is executed until the suitability of the AM technology for the proposed application can be approved or rejected. In this context, information requirements arise from insufficient AM technology information (e.g., availability of a specific material) or missing information about the application (e.g., financial background information). If there is an information requirement about the AM technology, the *Technology Fact Sheet* is updated by the AM technology expert with the required information. Furthermore, the application expert provides additional information about the application, if required for the evaluation process. Due to occurring information needs, the evaluation of applications can require several iteration loops to finalize the evaluation process. Finally, each identified application from the knowledge-based and data-based screening approach is documented in form of an *Application Assessment Sheet.*

6.1.3 Screening Finalization

Finally, the overall result for the part screening process is generated, which entails the clustering and ranking of the AM applications. Moreover the relevance of the AM technology for the investigated product portfolio is summarized. The process of screening finalization is depicted in Figure 6.6.

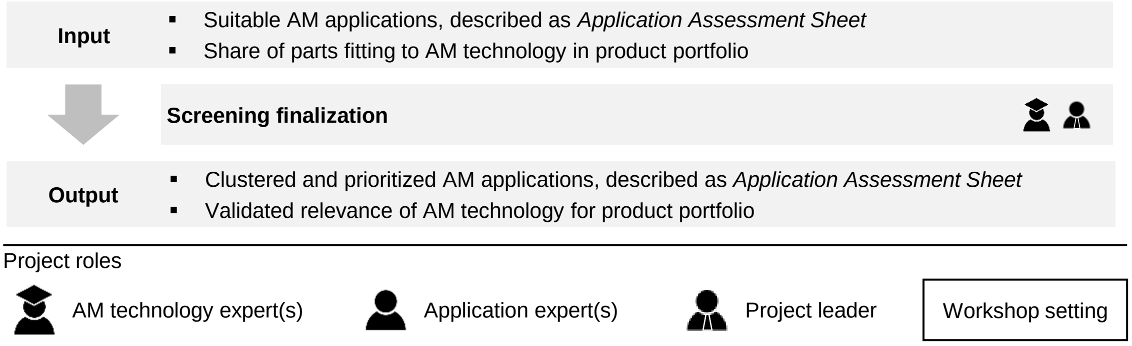


Figure 6.6: Process of screening finalization.

In a first step the identified AM applications are clustered by AM technology and material (e.g., all AM applications utilizing LPBF for a Ni-base material). Moreover, introducing additional criteria for clustering supports a detailed result in reference to the origin hypothesis about the AM utilization in the company (see chapter 4). Additional criteria can be the conventional manufacturing process (e.g., all machined applications which are suitable for AM) or the applications functionality (e.g., all hydraulic components that are suitable for AM).

After the clustering, which provides an overview of the suitable AM applications, a ranking must be obtained to prioritize the applications and focus the development in AM technology. For that, the numerical criteria from the *Application Assessment Sheet* are utilized. Based on the *AM Suitability Index (AMI)*, a measure for the technical fit of AM technology, and the *cost factor (cf)*, which expresses the economic feasibility, the AM applications are ranked and prioritized.

An exemplary result for the combined part screening process is visualized in Figure 6.7. In the combination of the results from data-based screening and the detailed evaluation of applications in the knowledge-based screening process, the overall relevance of the AM technology for the product portfolio is obtained. In the exemplary result, the identified applications are clustered by their functionality. By comparing the number of suitable AM applications to the total number of parts in the database, the relevance of the AM technology for production is calculated. In the exemplary visualization, the AM technology is relevant for 4.2% of the analyzed product portfolio.

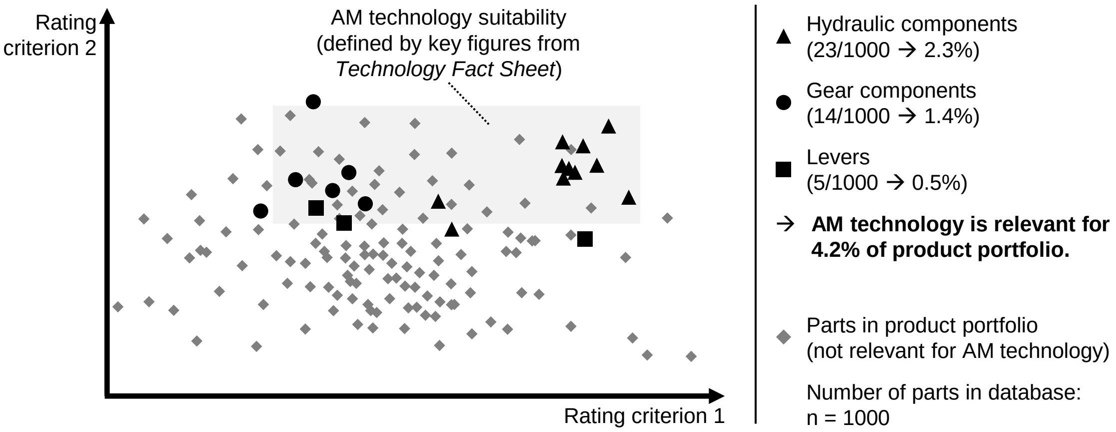


Figure 6.7: Exemplary final result of part screening process.

6.2 *Application Assessment Sheet* for the Evaluation Process

In the previous section the combined part screening process is introduced from an organizational perspective. Within this process, the evaluation of specific applications is important, covering the matching of AM technology capabilities and application requirements. For that, the evaluation process of a specific application is discussed in the following section. The evaluation process is provided in form of the *Application Assessment Sheet*, which is depicted in Figure 6.8. In the first section of the *Application Assessment Sheet*, general information about the application is collected. In the next section the application assessment is executed, which consists of three substeps: the definition of development goals, the technical evaluation, and the economic evaluation. Finally, the realization phase of the application is planned.

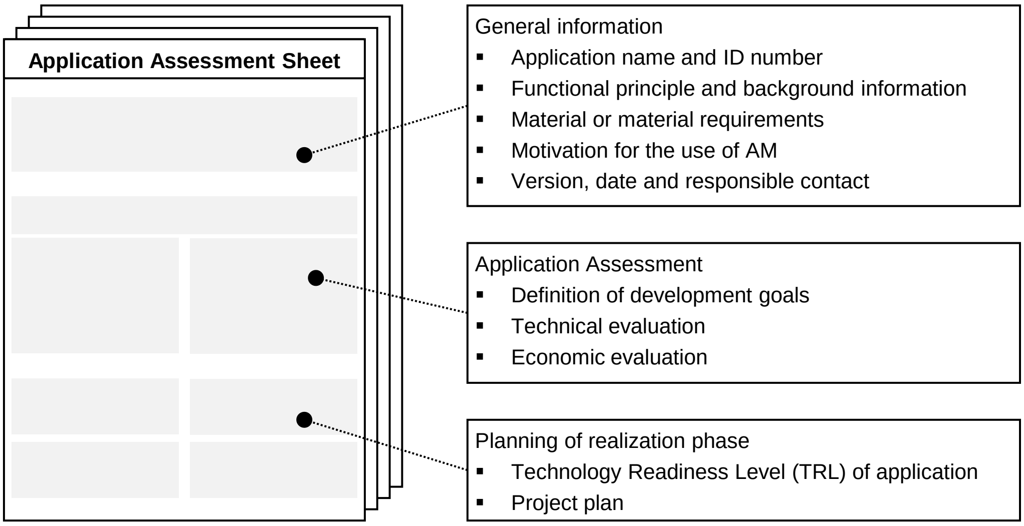


Figure 6.8: Structure of the Application Assessment Sheet.

In the first section, background information about the application is collected. These are the basic functional principles and a sketch, drawing, or image of the application. Moreover, information on dimension, mass, cost or target cost, quantity per year, number of variants, and lead time is stated. In addition, material requirements and the motivation for the use of AM are obtained.

In the second section, the evaluation of the application in the context of the AM technology is executed. The evaluation consists of three parts. An overview of the evaluation methods and results is provided in Figure 6.9. At first quantified development goals for the application are derived on the basis of an *AM Benefit Matrix*. The *AM Benefit Matrix* is introduced in section 6.2.1. Based on the development goals, a technical and economic evaluation is executed. It is derived from the evaluation approach in VDI 2225-3, which provides a guideline to assess technical and economic aspects in a design process. The approach of VDI 2225-3 supports the identification of design solutions, that are technically feasible, but also economic. Moreover, it allows for a straightforward visualization of both aspects.

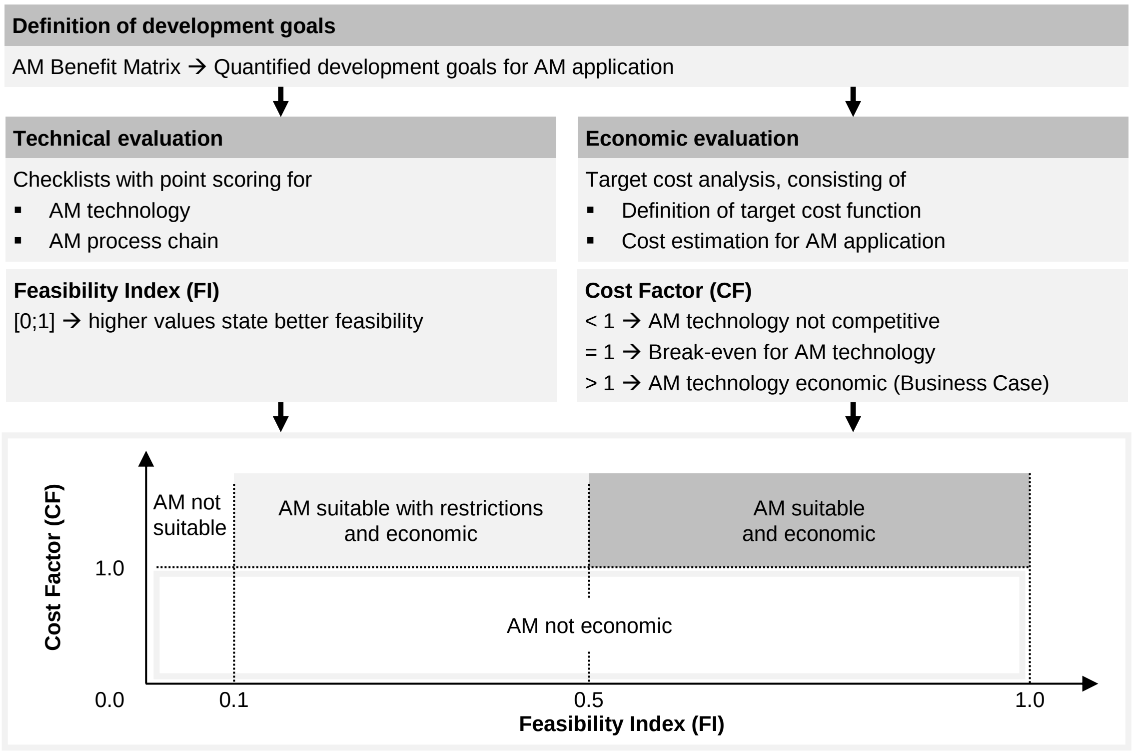


Figure 6.9: Economic and technical evaluations for AM applications.

The technical evaluation is based on checklists in combination with a point-score. In the context of the requirements for the application, the feasibility for AM technology is assessed on the basis of the *Technology Fact Sheet*. Finally, the *Feasibility Index (FI)* is obtained, which ranges from 0 to 1, whereas higher values state a better technical feasibility. Based on the *Feasibility Index* an AM application is rated as *not suitable*, *suitable with restrictions* or *suitable* for the AM technology. The technical evaluation is discussed in detail in section 6.2.2.

The economic evaluation uses a target cost analysis to estimate, if the AM technology is a business case. In a first step, the target cost are defined as a function which correlates the fulfillment of the quantified development goals and the target cost. In a second step, the cost of the additive manufacturing process for the AM application are estimated. Finally, the *Cost Factor (CF)* is derived as ratio of AM cost and target cost. If the *Cost Factor* is lower than one, AM is not economic, whereas if it exceeds one, AM is economic. At the break-even point for the AM technology the *Cost Factor* equals one. The economic assessment is presented in section 6.2.3. In conclusion of the technical and economic assessment, the result is visualized in a chart using the *Feasibility Index* and *Cost Factor*, which is depicted in Figure 6.9.

In the third section of the *Application Assessment Sheet*, the further proceeding to realize the application is prepared. For that, a Technology Readiness Level (TRL) is obtained for the application. Furthermore, a project plan is derived, providing information about the schedule, resources, and investment needed for the realization phase.

6.2.1 Definition of Development Goals

The first step in the evaluation of an application is to derive quantified development goals by analyzing the benefits of AM technology. A quantified development goal is required for the economic analysis, which states if the AM technology is a business case. For this purpose, generalized AM benefits are investigated on the basis of literature references (GEBHARDT 2013, SCHRÖER ET AL. 2019, GIBSON ET AL. 2015, PFÄHLER ET AL. 2019, KUMKE ET AL. 2018, LUTTER-GÜNTHER ET AL. 2015A, THOMPSON ET AL. 2016) and research approaches of the author (SCHNECK ET AL. 2019, HAAS 2019, GOLLNAU 2018, JEGEL 2019, KNEIßL 2020). In total, more than 100 AM benefits were identified and analyzed. To cluster the AM benefits, the model of *enablers and objectives* is adapted from SCHNECK ET AL. (2019). The enablers are split into *AM technology inherent properties* and *technical possibilities*. Moreover, the implementation levels of SCHNECK ET AL. (2019) are adapted, clustering the enablers and objectives into *product* and *product lifecycle* categories. The *AM Benefit Matrix* is presented in Table 6.1. Due to the manifold benefits of AM and their different concretization levels, a clustering of AM benefits may not be complete. Moreover, the benefits vary between different AM processes. Nevertheless, the matrix represents a systematic scheme to cluster AM advantages and identify the most common AM advantages.

The inherent properties of AM technology are directly linked to the AM process. The geometric shape is defined by a digital description of the shape as a toolpath of the energy source. Thus, the generated geometry is a monolithic structure. Moreover, this allows for freeform surfaces and undercuts. In some AM processes, gaps between solidified volumes are manufacturable. Regarding the material properties, AM offers the opportunity for AM-tailored materials. Even if the material range is currently limited to conventional available materials, new materials utilizing the AM process for entirely new material properties (e.g., metallic glasses) are under development and will be available in the near future (Schleifenbaum et al. 2019). In addition to AM-tailored materials, AM also offers the possibility of graded or discrete material combinations within one part (Anstaett et al. 2016, Ott 2012). Moreover, local material properties can be adjusted by varying production parameters. With local parameter variation, different surface textures can also be manufactured.

Table 6.1: AM Benefit Matrix.

		Enabler		Objective
		AM technology inherent properties	Technical possibilities	AM benefit utilization
Product	Geometry	☐ Monolithic design ☐ Freeform surfaces ☐ Undercuts ☐ Gaps between volumes	☐ Complexly shaped structures and cavities, e.g. cooling channels ☐ Mesoscopic structures (regular, irregular, graded), e.g. thin walls, lattices, honeycombs, foams ☐ Movable objects , e.g. joints, limb objects, nets ☐ Bionic and simulation-driven designs, e.g. topology optimization	Optimized functionality in… ☐ Mechanics: Lightweight design, static and dynamic structural strength, damping ☐ Thermodynamics: Insulation, Energy absorption, heat transfer, energy conversion and transport ☐ Fluid dynamics: Streamline optimization, Pressure losses ☐ Lifetime: Wear resistance, reliability ☐ Aesthetics / Optical appearance / Ergonomics ☐ Individualization / Customization
	Material	☐ Unique AM material properties ☐ Material combination (graded and discrete) ☐ Local adjustment of material properties ☐ Local adjustment of surface textures	☐ Porous structures ☐ Surface textures ☐ Material properties optimization	
Product life cycle	Manufacturing process	☐ Building on existing structures / conventional parts ☐ Integration of components within AM process	☐ Less interfaces in assembly, e.g. fewer but more complex parts ☐ Less production or assembly steps ☐ Material efficiency ☐ Reduced machining volumes ☐ No invest in tools if part geometry changes ☐ Product identification by hidden marks or component integration ☐ Tools and manufacturing aids by AM	Improvements in… ☐ Development phase → Time to product / to market, digitalization of product, enables continuous innovation ☐ Production process → Flexibility, lead time, manufacturing cost ☐ Logistics → Decentralized production ☐ Use phase → Operating cost, resource consumption, emissions ☐ Services → Repair, maintenance, protection against plagiarism ☐ Recycling
	Digital process chain	☐ Each produced part can be individual ☐ Manufacturing directly from digital part representation ☐ Transmit and provide digital data	☐ Reproduction from 3-d-scanning ☐ Customer as designer ☐ Decentralized production ☐ Production-on-demand / digital warehouse ☐ Trade barrier bypassing	
				☐ Checkbox blank ☒ Checkbox marked

The inherent geometric and material properties of AM technology lead to technical possibilities. Geometric possibilities are complexly shaped structures and cavities, such as cooling channels. This allows for the manufacture of bionic-inspired and simulation-driven designs. Moreover, mesoscopic structures such as thin walls, lattices, or honeycombs can be manufactured. These structures can be regular, irregular, and/or graded. For example, BINDER ET AL. (2017) presented an investigation of complexly shaped honeycomb structures manufactured by LPBF. Some AM technologies allow for the production of movable objects like joints or nets. The material properties can be upgraded by AM (e.g., improved material properties in comparison to a prior design). Moreover the requirements for the material can be lowered by design optimization (e.g., improved cooling behavior). In addition, porous structures and surface textures are producible (cf. KLAHN (2015) for gas-permeable structures produced by LPBF).

Finally, the objective of using AM on the *product* is to improve the product. Optimized functionality can be achieved in mechanical behavior, thermodynamic behavior, fluid dynamic behavior, product lifetime or reliability, aesthetics, optical appearance, and ergonomics as well as through individualization or customization.

In the *product life cycle*, the AM inherent properties are split into the *manufacturing process* and the *digital process chain*. For the manufacturing process, inherent properties of AM entail the possibility of building on existing structures or conventional parts and integrating components in the AM process (BINDER ET AL. 2018). Technical possibilities for the manufacturing process are fewer interfaces in an assembly, fewer production or assembly steps, and material efficiency or reduced machining volumes. In addition, investment costs for tools are not necessary, and products can be tagged by hidden marks or integrated sensors or chips. Also, tools and manufacturing aids can be produced by AM. The benefits of the digital process chain are that each part can be individualized due to tool-less manufacturing from a digital representation. Moreover, digital information can be generated automatically (e.g., parts with a unique serial number) and can be transmitted much faster and cheaper than a hardware part. The possibilities resultant from the digital benefits include reproduction from a 3D scan and the customer as designer. Additionally, the digital model of the part can be used for decentralized production, production-on-demand, or digital warehouses. Finally, this can lead to improvements along the life cycle of the product, starting with the development phase and continuing with the production process, distribution and logistics, the use phase, service aspects, and recycling.

To evaluate an application, the enablers and objectives in the *AM Benefit Matrix* are assessed with respect to whether they provide a benefit to the application. A leading question clarifies if an enabler or objective applies to the application:

Can the application be improved/optimized in [objective] by [enabler]?

It is important that not all enabler and objectives are applicable to each application. In particular, SCHNECK ET AL. (2019) investigated the use of AM benefits in industrial applications, revealing that the most frequent objectives for the use of AM are improved part performance or a simplified manufacturing process. In the presented study, production-on-demand or decentralized production approaches are less frequently used in industrial applications.

To obtain the quantified development goal, the enabler-objective combinations are discussed with the responsible application expert, who finally decides about the development goal for the application. If the application expert is not able to prioritize the enabler-objective combinations, supportive ranking process like pairwise comparison or weighted point scoring are applied. The quantification expresses an ambitious but realistic development goal for the application. For example, when the prioritized objective is a lightweight design, the quantified development goal states: *Through the use of AM, the application's mass can be reduced by 25%.*

6.2.2 Technical Evaluation

The technical evaluation identifies the feasibility of the application with the AM technology. The feasibility is expressed by the *Feasibility Index*, which is obtained from checklists and a point scoring system. The required background information on the AM technology is provided in the *Technology Fact Sheet*, describing and quantifying the current state of technology performance (see section 5.2, page 61). For applications, which are identified by a data-based screening process, some of the rating criteria are already used to identify the application. The technical evaluation consists of two parts: At first the suitability of the AM technology itself is investigated based on six criteria. Secondly, implications in the AM process chain are derived on the basis of five criteria. The checklists provide a standardized approach for the evaluation. In the checklists, three suitability level for the rating are exemplified by statements and linked to a point score. They cover the levels of *suitable*, *suitable with restrictions*, and *not suitable/major hindrances*. For each criterion the suitable statement is crosschecked. The technical evaluation of the AM technology covers six rating criteria and is depicted in Table 6.2.

Table 6.2: Technical evaluation of the AM technology.

Technical evaluation of AM technology	AM suitability		
	AM suitable (2 points)	AM suitable with restrictions (1 points)	AM not suitable (0 points)
Dimension	☐ Application fits build volume of available AM systems (up to 90th percentile)	☐ Application fits build volume of available AM systems (exceeds 90th percentile) ☐ Fit of application in build chamber is expected after redesign for AM: Expected dimension after redesign: ____________________	☐ Application exceeds available build spaces
Similarity analysis	☐ Serial parts with comparable dimensions are known	☐ Demonstrator parts with comparable dimensions are known	☐ Parts of the intended dimensions are unknown
Mass	☐ Application matches the established mass range (10th to 90th percentile)	☐ Application matches the established mass range (out of 10th to 90th percentile) ☐ Match of established mass range is expected after redesign. Expected mass: ____________________	☐ Application exceeds the established mass range
Material availability	☐ Material is market available	☐ Material is under development ☐ Another available AM material suits the material requirements. Alternative AM material choice: ____________________	☐ Material non-processable or unknown in AM technology
Material properties	☐ Required material properties are known or easy to access (e.g. tensile strength, surface hardness)	☐ Required material properties must be investigated for the application (e.g. fatigue behavior, wear resistance)	☐ AM material insufficient for required material properties
MRL level of AM technology	☐ MRL 9 – 10	☐ MRL 6 – 8	☐ MRL 1 – 5
Minimum point score in all criteria (m_1)			
Sum of points (s_1)			
			☐ Checkbox blank ☒ Checkbox marked

First, the criterion *dimension* is evaluated. This criterion is linked to the section *machine equipment* in the *Technology Fact Sheet*, summarizing the available build chamber dimension of AM systems. The application is suitable to AM if it fits into the available build dimensions. If the application's dimension requires a large but available build chamber size, which exceeds the 90th percentile, it is rated as suitable with restrictions because specialized AM systems are required to manufacture the application. If the application exceeds the available build chamber dimensions, it is rated as not suitable. If it is expected that the application will match the available build chamber sizes after a redesign process, it is rated as suitable with restrictions. In addition to the availability of appropriate machine equipment, the dimensions of the application are compared to the *Reference applications* in the *Technology Fact Sheet*. For that, it is evaluated whether applications of comparable dimensions are known as serial applications, demonstrator parts, or unknown for in AM technology. In addition to the dimensions, the mass of the application is evaluated, which is linked to the *Part mass derivation* in the *Technology Fact Sheet.* The best suitability for AM is given for a match of the 10th to 90th percentile of the mass deviation. If the application's mass is below the 10th or above the 90th percentile, the AM suitability is evaluated as with restrictions because very small and very large parts cause additional efforts in setting up the AM manufacturing process. If the application exceeds the described mass distribution, it is rated as not suitable.

The evaluation criteria *material availability* and *material properties* are linked to the *materials overview* and the *material properties* sections in the *Technology Fact Sheet*. If the intended material for the application is stated in the materials overview as market available and the relevant material properties are known, the adoption of AM technology is facilitated. In the case of an available material with unknown material properties, the material behavior has to be investigated. Furthermore, the intended material for the application can be listed as under development, which limits the availability of the material. In addition, if the desired material is not available in the AM technology, another AM material can match the required material properties of the application. If the material is not known for the AM technology and no alternative AM material can be identified, the application is rated as not suitable for the AM technology. The technology maturity is assessed through the MRL. A MRL level of 9 – 10 indicates that a serial production environment is established. For MRL levels 6 – 8, the concept of the AM technology is approved, and the technology is in the development phase. For an MRL level of 1 – 5, only concepts or prototype systems of the AM technology exist. Thus, in this state of technology development, it is difficult to develop specific applications. After the assessment of all six criteria, the minimum point score for a single criterion (m_1) and the sum of all points (s_1) are obtained from the checklist.

The process chain of an AM technology is assessed based on five rating criteria. As in the previous checklist, the evaluation is based on three levels of suitability and given statements, which are cross marked. The technical evaluation approach for the AM process chain is provided in Table 6.3.

Table 6.3: Technical evaluation of the AM process chain.

Technical evaluation of AM process chain	AM process chain suitability		
	AM process chain suitable (2 points)	AM process chain suitable with restrictions (1 points)	AM process chain cause major hindrances (0 points)
Pre-processing: 3D-Model	☐ 3D-model is available and printable with AM technology	☐ 3D-model is available but must be optimized for AM technology ☐ Generation of a 3D model is already planned (e.g. in a development project)	☐ 3D-model is not available; The model must be created (e.g. based on available drawings or hardware parts) and optimized for AM
Post-processing: Manual efforts; Removing of support	☐ Parts need little or no manual work to remove support ☐ Processing steps are automated	☐ Parts need manual work to remove supports; Good accessibility of supported facets	☐ Extensive manual work is necessary; Accessibility of surfaces with support is limited
Post-processing: Finalize material properties	☐ Material properties in as-build condition are sufficient ☐ Basic heat treatment is sufficient (e.g. stress-relief annealing); Material properties after heat treatment are available from multiple independent sources (e.g. material data sheets)	☐ Adoption of material properties by heat treatment necessary; Material properties after heat treatment process are available from few suppliers and/or described in scientific sources (e.g. hardening of AM materials)	☐ Unclear if necessary material properties can be obtained by heat treatment; The required process is not fully described in literature; Heat treatment process must be customized for the application
Post-processing: Finalize geometry	☐ Resolution and accuracy of AM process are sufficient for final part	☐ Few easy accessible facets need to be machined (e.g. threads, fits, tolerances); clamping position is clear and standardized fixtures are appropriate	☐ Machining of AM part is complex (e.g. multiple undercuts need to be machined, fragile load-optimized structure); specialized clamping features or aids are necessary
Post-processing Finalize surface properties	☐ Surface roughness in as-build condition sufficient ☐ Slight reworking of surface necessary (e.g. blasting process) ☐ Surface specifications do only apply to surface facets that are machined	☐ Surface specifications require separate process steps; Surface specifications are met by batch-wise working processes (e.g. trowalization, barrel finishing)	☐ Demanding surface specifications and high geometrical tolerances apply to the same surface facets; Surfaces are complexly shaped and require freeform finishing processes (e.g. electro-chemical processes, manual polishing)
Sum of points (s_2)			
			☐ Checkbox blank ☒ Checkbox marked

The process chain assessment is based on the process steps of pre- and post-processing as defined in VDI 3405. As input to the evaluation, the *Reference process chain* in the *Technology Fact Sheet* is used.

The first criterion to evaluate the AM process chain is the availability of a 3D model for the application because all AM technologies require a digital 3D representation of the geometry for manufacturing. If a 3D model is available, which is already usable in the AM technology, the suitability is given. When a 3D model is available but needs optimization for AM or the generation of a 3D model is planned, the suitability is restricted, because a printable design of the application has to be developed. A major hindrance in the process chain occurs if no 3D model is available and the model must be created from a hardware part or drawings.

The evaluation of the post-processing chain focuses on the finalization of the technical requirements of the application, based on four criteria. One important criterion is the amount of manual work in post-processing. The best suitability is given for applications that need only little to no manual work. For LPBF, this is true when parts can be removed from the build plate by bending. Moreover, the best suitability is also given when removal and separation process steps are automated. If the application requires manual efforts for removal of supports, the suitability is restricted and if it is expected that removal requires extensive manual work, this is rated as a major hindrance in the process chain.

The final material properties are obtained by heat treatment processes. If the required material properties can be reached by standard heat treatment processes (e.g., stress-relief annealing) or if the as-built condition of the material is sufficient, the suitability is given. For standard heat treatment processes, multiple information sources are available (e.g., material data sheets), allowing for comparison of the material properties after heat treatment as stated in the *Technology Fact Sheet*. If the adoption of material properties by more specialized heat treatment processes is necessary (e.g., hardening, nitriding), the suitability is restricted. When it is unclear if the intended material properties can be attained due to missing information sources, the heat treatment is rated as a hindrance.

The geometric tolerance of the AM process defines which tolerances are met in the as-built condition. If the resolution of the AM process is sufficient for the geometric requirements of the application, it is rated as suitable. In most cases, a machining process is necessary to manufacture features like threads, fits, and tolerances. In this case, the restrictions of the machining process must be regarded in the AM design of the application (e.g., machining forces in a topology optimization, accessibility of the facets to be machined). Thus, if a machining process is required, the suitability is restricted. If the machining of the AM application is complex, which can be caused by multiple undercuts or a fragile structure, the machining is a hindrance in the AM process chain.

The fourth rating criteria in the process chain evaluation investigates the surface properties of the application. If the surface roughness of the AM process is sufficient, or commonly used processes, such as blasting for PBF parts, can provide the final surface properties, it is rated as suitable. Furthermore, if surface specifications only apply to facets that need to be machined, the process chain is also rated as suitable. In some cases, the surface requirements of the application demand for specific surface finishing processes. If surface and geometric requirements apply to different facets and are met by batch-wise working processes (e.g., barrel finishing), the suitability is rated as restricted. The most demanding requirements for the surface finalization are highly geometric tolerances and demanding surface properties applying to the same facets of a complex shape. For example, these requirements occur on LPBF-manufactured vane structures of turbomachines (SUCH ET AL. 2019). Finally, the sum of all points for the AM process chain (s_2) is derived from the checklist.

Based on the evaluation of the AM technology and the corresponding process chain, the *Feasibility Index (FI)* is derived. The definition of the FI is given in Formula (6.1):

$$\mathit{Feasibility\ Index}\ (FI) = \frac{m_1 * (s_1 + s_2)}{\mathit{Maximum\ point\ score}} = \frac{m_1 * (s_1 + s_2)}{44} \tag{6.1}$$

The maximum point score is obtained for $m_1 = 2$, $s_1 = 12$ and $s_2 = 10$, which results in 44. This normalizing limits the FI to a value range between 0 and 1. The feasibility of the AM technology has a prioritized weight in the calculation. Using the minimum point score m_1 as multiplier, results in FI = 0, if at least one criterion in the AM technology evaluation is rated as *not suitable*. Moreover, the calculation approach of FI allows to differentiate into three levels of technical feasibility, which are depicted in Figure 6.10. The feasibility level is defined by the point score of the AM technology, whereas the feasibility of the AM process chain enhances or decreases the resulting FI value.

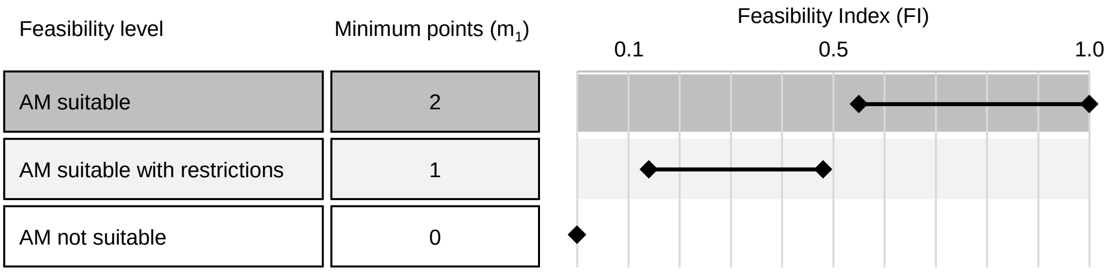


Figure 6.10: Result range of the Feasibility Index (FI) and corresponding feasibility level.

6.2.3 Economic Evaluation

The economic evaluation indicates whether the AM application is a business case, which provides an economic benefit (cf. THOMPSON ET AL. 2016). In the economic evaluation, there are two sources for uncertainty, which must be considered. One the one hand, the cost of the additively manufactured application need to be obtained, and on the other hand, the additional value of improvements, defined by the development goal, must be estimated. Moreover, it is uncertain if the development goal can be realized to full extend. Thus the approach for the economic evaluation consists of three steps: At first, a target cost function is setup that indicates the permissible target cost over the fulfillment of the development goal. Secondly, the cost of the AM application are estimated from the mass-based cost information in the *Technology Fact Sheet*. In a third step, the *Cost Factor* is obtained as ratio of the target cost and the estimated cost of the AM application for different fulfillment degrees of the development goal. A schematic result of the economic evaluation is depicted in Figure 6.11.

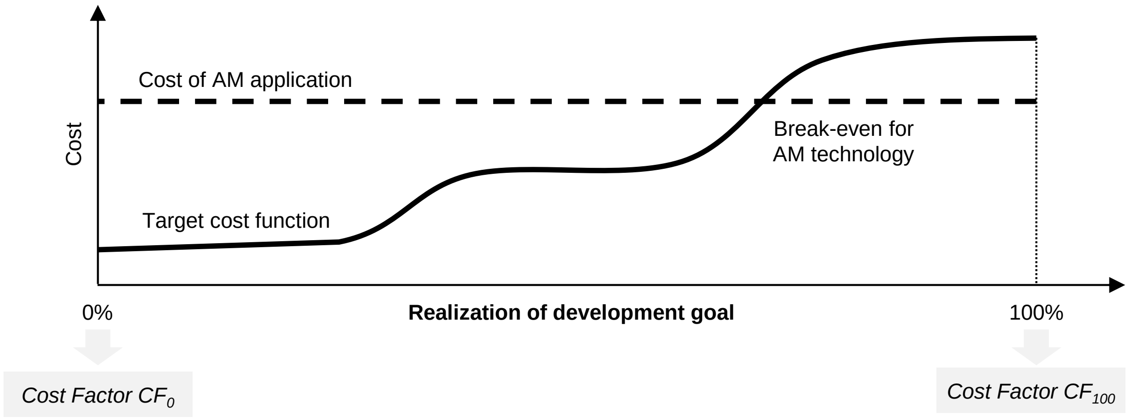


Figure 6.11: Approach of the economic evaluation.

In the first step, the target cost function is setup. To ensure comparability with the AM application, the boundary conditions of the function are defined, covering three aspects:

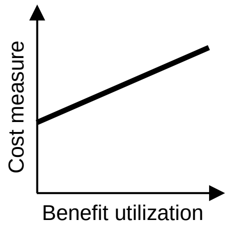
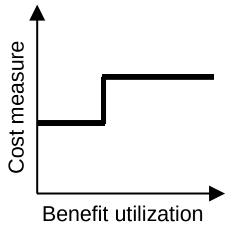
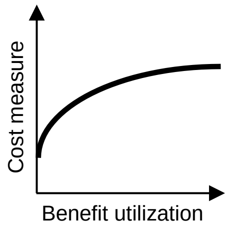
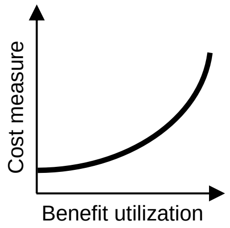
- Scope of application (e.g., component, assembly group, product, service)
- Finalization state (e.g., usable product, ready for installation, raw part)
- Measure of cost (e.g., manufacturing cost, sales price)

The scope of the application defines which parts to integrate into the evaluation. For example, if an AM part can integrate functions of adjoining parts, the evaluation must be based on the whole assembly group to cover the effect of functional integration. The second aspect defines the finalization state of the application and the process chain covered by the evaluation. Here, it is determined whether the cost evaluation is based on a usable product, an application ready for installation, or a raw part. For example, when the reference is an externally bought part, which is bought as installation ready, the evaluation of the AM application must meet the same finalization state to maintain comparability. The third aspect is to define the boundary conditions to set up a measure for the cost. The measure for cost must be available for the AM application and the target cost. In most cases, manufacturing costs are an appropriate choice, but the economic evaluation can also build on other cost measures. The composition of the cost are investigated to identify shares of fixed costs (e.g., overhead cost, cost levies). For example, if there is a cost levy for externally bought parts to cover the supply chain expenses, this levy must be included when calculating the cost of an externally bought AM part.

After the definition of the boundary conditions, which ensure the comparability of the AM solution with the target cost, a linkage between improvements and cost measures is derived. The quantified development goals describe the improvements. Because the development goals describe an aspirational functionality of a future component, it is uncertain to what extent the goal can be realized. Thus, the linkage of improvement and cost measures is described as a function over development goal fulfillment. Because the development goal is quantified, the gradual fulfillment of the development goal can be used as basis for the cost linkage. An overview of functions to link cost and benefits is given in Table 6.4. The function description is derived from DEPPE (2019). The target cost function can consist of a combination of the depicted basic functions, either in conjunction of the functions or in sequence. If an AM application utilizes more than one development goal, the target cost function is set up for each development goal separately. By deriving weights for the development goals (e.g., with a pairwise comparison), a target cost function is derived based on all development goals. Exemplary, the linkage between cost and mass reduction in the aerospace industry is linear, allowing for cost hikes of €500–1000 for each kg of reduced mass (SCHMIDT 2016).

In the second step, the cost of the AM application are setup. Based on the prior definitions, the cost of the additively manufactured application is derived by cost data provided in the *Technology Fact Sheet*. For that, a parametric, mass-based evaluation approach is followed, which allows to estimate the cost of the AM application. To obtain the cost of the AM application, the mass of the application is multiplied by the cost indicator from the *Technology Fact Sheet*. Moreover, the cost of the AM process chain is evaluated based on the process chain information in the *Technology Fact Sheet* and the aspects provided in the technical evaluation of the AM application. The cost of a serial process chain is estimated by analyzing the cost of a conventional reference process chain and estimating the changes required for AM adoption.

Table 6.4: Overview of target cost functions to link cost and AM benefits.

	**Linear function** Description: The linkage of benefit and cost is linear. Each incremental benefit utilization allows to raise the cost. Example: Lightweight design in aerospace industry allows to raise production cost at 500 – 1000 € per kg reduced mass.
	**Jump function** Description: The linkage of benefit and cost is discrete. A specific level of benefit utilization is required to effect the cost. Example: Lightweight design of a gear. When reaching a specific level of mass reduction a smaller and cheaper power unit can be used. The saved cost from the smaller power unit add up to the cost for the lightweight gear.
	**Logarithmic function** Description: The linkage of benefit and cost is degressiv. Whereas an improvement has a strong influence on the cost in the beginning, the impact reduces for further improvements. Example: Improvement of wear behavior. Because wear is a non-linear process, a small improvement in wear resistance can cause significant cost advantages.
	**Exponential function** Description: The linkage of benefit and cost is exponential. Whereas a slight improvement has only little impact on the cost, further benefit utilization allows increasing cost. Example: Individualized products. For a product with more degrees of individualization higher cost can be realized.

As third step in the economic evaluation, the *Cost Factor* is obtained. Based on the economic assessment in VDI 2225-3 and Bohnacker (2018), the *Cost Factor (CF)* is defined as the ratio of target cost and the cost for the AM solution, expressed as

$$Cost\ Factor\ (CF) = \frac{cost_{Target}}{cost_{AM}}. \tag{6.2}$$

Based on the definition in formula 6.2, it is obvious that the *Cost Factor* is 1 (CF = 1) if the cost of the AM solution and the target cost are equal. If the AM solution is more expensive than the target cost, the *Cost Factor* is lower than 1 (CF < 1). In contrast, when the AM solution has lower cost than the target cost, the *Cost Factor* exceeds 1 (CF > 1).

Because it is uncertain to what extent the development goals can be utilized, the *Cost Factor* is derived for two degrees of development goal realization: First, it is assumed that the development goal cannot be realized (0% realization). Hence, the AM application does not provide any benefit for the defined development goal. For this, the *Cost Factor* CF_0 is derived, using the estimated cost of the AM solution and the reference cost. Second, the full realization of the development goal is assumed (100% realization). Thus, the AM solution provides a significant benefit in the context of the development goal. For this case, the *Cost Factor* CF_{100} is derived, using the cost of the AM solution and the target cost at 100% realization of the development goal.

Regarding these two cases for the fulfillment of the development goal in combination with the definition of the *Cost Factor*, three options for the result of the economic evaluation occur, which are depicted in Figure 6.12. In the first case, the *Cost Factor* is lower than 1 even at full realization of the development goals. Thus, the application of AM is uneconomic. In the second case, the AM solution is more expensive than the target cost when the development goals are not realized. But for fully realized development goals, the AM solution becomes economic. Thus, there is a break-even point defining the degree of realization necessary for economic exploitation of the AM application. At the break-even point, the *Cost Factor* is equal to 1. In the third case, AM offers an economic advantage compared to the target cost, even if no benefits of AM are utilized. In this case, the AM technology is an economic choice, regardless of the fulfillment of the development goal.

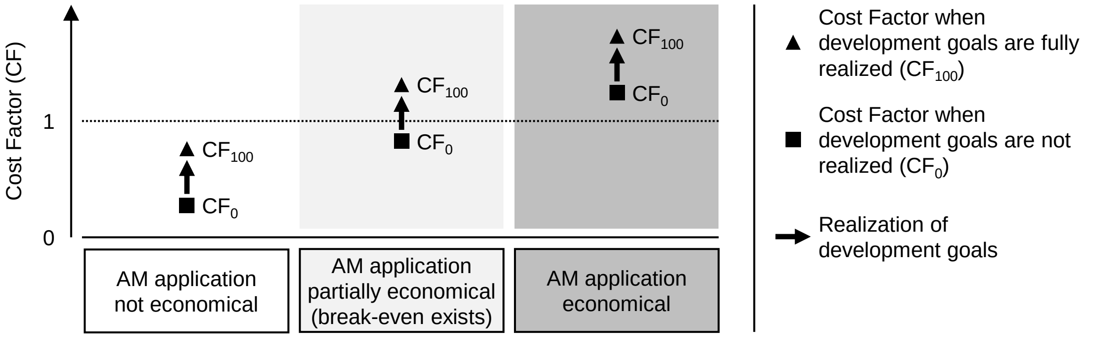


Figure 6.12: Schematic result of economic evaluation.

6.2.4 Planning of Realization Phase

Based on the prior evaluation steps of deriving development goals and the technical and economical evaluation, the realization of the AM application is planned. For that, a Technology Readiness Level (TRL) scale for the AM application is set up and a project plan for the realization phase is generated. Based on the descriptions of each TRL level in DIN ISO 16290, an adaption for AM technologies is derived, providing a generalized maturity level for the application, as depicted in Table 6.5. For a specific AM application, the terms of the standard have to be defined according to the organization and application purposes. The terms to be concretized cover analytical models, supporting laboratory tests, laboratory environment, critical functions, relevant environment, required tests and qualifications, and final environment. It has to be stressed that the TRL is a nonlinear ordinal scale that does not allow for forecasting timelines and realization effort on the basis of the actual or prior TRL.

Table 6.5: Technology Readiness Level (TRL) for AM applications.

Technology readiness level TRL (DIN ISO 16290)		Adaption to AM application	Terms to be defined for specific AM application
1	Basic principles observed and reported	☐ Idea for AM application proposed (e.g. 1st section of Application Assessment Sheet)	
2	Technology concept and/or application formulated	☐ Idea for AM application refined ☐ Development goal and AM benefits analyzed ☐ Suitable AM process identified ☐ First draft of AM design	
3	Analytical and experimental critical function and/or characteristic proof-of-concept	☐ Development goals quantified ☐ Conceptualization of the AM application ☐ Suitability of AM technology approved by a non-functional manufacturing prototype ☐ Estimation of the performance by analytical models and supporting laboratory tests	Analytical models: Supporting laboratory test:
4	Component functional verification in laboratory environment	☐ Development goals quantified ☐ Conceptualization of the AM application ☐ Plan for functional testing established ☐ Functional prototype tested in a laboratory environment	Laboratory environment:
5	Component critical function verification in a relevant environment	☐ Definition of performance requirements ☐ Identification and analysis of critical functions ☐ Verification of the functional prototype in a relevant environment for the target application	Critical functions: Relevant environment:
6	Model demonstrating the critical functions of the element in a relevant environment	☐ Functional prototype demonstrating the critical functions in a relevant environment	
7	Model demonstrating the element performance for the operational environment	☐ Use of the AM application in the final environment as beta version	Final environment:
8	Actual system completed and accepted for flight (flight qualified)	☐ AM application has completed all required tests and qualifications ☐ AM application is ready for market introduction	Required test and qualifications:
9	Actual system “flight proven” through successful mission operations	☐ AM application successful established in the market delivering the intended performance	
			☐ Checkbox blank ☒ Checkbox marked

The final step in the planning of the realization phase is setting up a project plan, which is based on the assessment of the TRL of the AM application. The project planning is based on DIN 69901-1. The project plan breaks down the development of the AM application to work packages and milestones. For each work package, the responsibility, personnel resources and financial resources are stated. The forecast of required resources is a complex task that is supported by methodical approaches provided in DIN 69901-3. The definition of TRL for the AM application supports the project planning by providing a guideline with steps to be executed. The final milestone of the project plan is the market entry of the serial AM component (corresponds to reaching TRL 9) and the start of serial production. Figure 6.13 visualizes a draft project plan for the realization phase of the AM application.

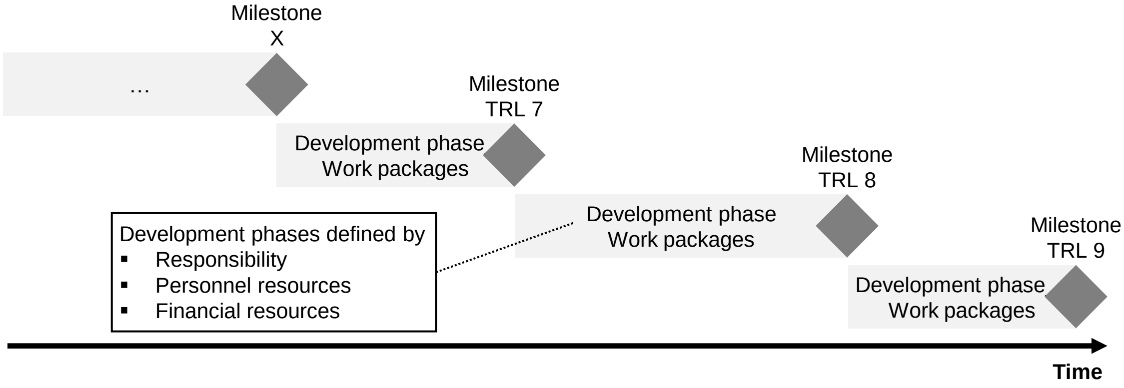


Figure 6.13: Project plan for the realization phase of an AM application.

7 Action Field C: Derive Organizational Tasks

Besides the gathering of technology information (Action field A, chapter 5) and the evaluation of applications (Action field B, chapter 6), it is necessary to foster the shift towards AM technologies within the organization. To develop the *AM Technology Roadmap*, two tasks are important to the organization. First, the sourcing of AM technologies must be evaluated to ensure the supply of additively manufactured parts. In this context, two options are available: the establishment of a company's own production facility (make) and the development of a supply chain for AM (buy). Also, a combined make-buy strategy can be appropriate to reduce the risk of machine capacity utilization (FELDMANN & PUMPE 2016). Regarding the *AM Technology Roadmap*, both options are evaluated to prepare a well-justified make-buy decision. Second, the building and exchange of knowledge within the organization must be organized. When deriving the *AM Technology Roadmap*, it is therefore necessary to structure the build-up and exchange of know-how. The building of knowledge within an organization is a key factor for successful adoption of any new technology (HACKEL ET AL. 2015). Thus, organizational learning is an important task to be addressed in the *AM Technology Roadmap*.

7.1 Sourcing of AM Technology

For the sourcing of an AM technology, there are two possibilities: purchase of one or more AM systems (make) or the establishment of an external supply chain (buy). A make-buy decision is based on several inputs, which have to be evaluated. Prior to an investment in an AM production facility, the production task and product portfolio have to be investigated (MÖHRLE 2018). To facilitate the evaluation for an AM technology, the derivation of the make-buy decision is structured in a three step process depicted in Figure 7.1.

The sourcing decision process starts with the clustered AM applications from the part screening process (see section 6.1.3, page 80). To prepare a sourcing decision, the AM applications are clustered by AM technology and material. Hence, this *sourcing cluster* summarizes applications of similar production requirements. Based on the project plan in the *Application Assessment Sheet*, the production volume over time for each application is derived and summarized to obtain the annual production volume. Based on the sourcing cluster, the two sourcing options of make and buy are evaluated. Based on the available infrastructure in the organization, the appropriate scenario for making or buying is selected in the current state analysis. In the cost benchmark, the costs of the make and buy options are derived for a best-case and a worst-case scenario. The average scenario is calculated as the mean value of best- and worst-case estimation. Moreover, strategic aspects of the make-buy decision are evaluated before the realization phase of the make-buy strategy for the sourcing cluster is prepared.

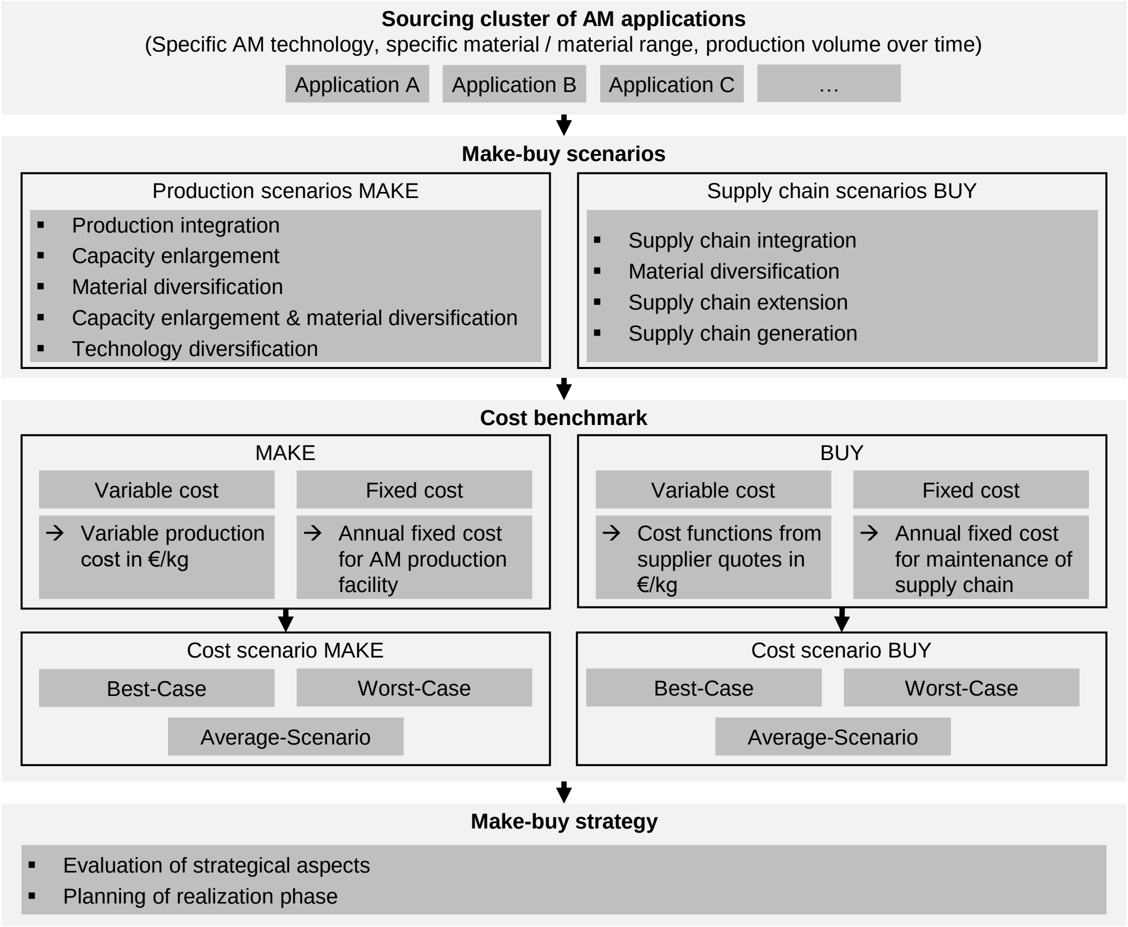


Figure 7.1: Sourcing process for AM technologies.

7.1.1 Make-Buy Scenarios

As a first step to obtain a make-buy strategy, a current state analysis investigates which scenario applies in the case of make-or-buy, based on the already existing infrastructure in the organization for AM technologies. Five scenarios are defined for the make option, and four scenarios apply to the buy option, summarized in Table 7.1. In the make scenario of *production integration*, all necessary structures are already established in the organization. Thus, AM system capacity and the intended material are internally available. The second make scenario, *capacity enlargement*, describes, if AM technology and material are available but the production capacity is insufficient for the production task. Hence, production capacity must be enlarged by an additional AM system. In the third scenario, *material diversification*, machine capacity on an AM system is available, but an additional material needs to be introduced. However for LPBF, material changes on a single AM system are limited by aspects of cross-contamination (Horn et al. 2019). The fourth make scenario, *capacity enlargement and material diversification*, is to purchase a new AM system to process an additional material. In this case, production volumes cannot be split between different AM systems, and thus, flexibility is reduced, and each system must be fully utilized by a specified range of products. The fifth make scenario, *technology implementation*, is to set up a new AM technology in the organization without any prior experience in the AM technology.

Table 7.1: Current state analysis based on make and buy scenarios.

		Inhouse availability			Scenario description
		AM technology	AM system capacity	Material	
MAKE scenario	Production integration	✓	✓	✓	Integrate applications in existing AM production
	Capacity enlargement	✓	✕	✓	Invest in a new AM system for an established material
	Material diversification	✓	✓	✕	Add a new material on established production systems
	Capacity enlargement and material diversification	✓	✕	✕	Invest in a new AM system to process a new material
	Technology implementation	✕	✕	✕	Setup of an AM production area and/or invest in new AM technology

		Established business relationship	Technology supplier qualified	Material qualified	Scenario description
BUY scenario	Supply chain integration	✓	✓	✓	Integration of applications in existing and qualified supply chain
	Material diversification	✓	✓	✕	Qualification of an additional material from an existing technology supplier
	Supply chain extension	✓	✕	✕	Qualification of an existing business partner for AM technology and material
	Supply chain generation	✕	✕	✕	Qualification of a new supplier and material

For the external supply, four buy scenarios are defined. The scenario of *supply chain integration* describes the possibility to integrate the production task in an existing supply chain. In this scenario, a qualified supplier exists, which already delivers products of the required material. In the *material diversification* scenario, a qualified supplier exists, but the material to be sourced is new to the organization and needs to be qualified. If an existing business partner, for instance, a supplier in another technology field, is available as a supplier for the AM technology, the scenario of *supply chain extension* applies. In this case, the organization benefits from established framework agreements and contacts with the supplier, but the AM technology and material must be qualified. The fourth scenario for the buy option is *supply chain generation*, which incorporates the establishment of a supply chain with completely new suppliers for the AM technology.

7.1.2 Cost Benchmark

For the cost benchmarking, a cost model is set up, which compares the identified make- and buy-scenarios based on a best-case and worst-case estimation. The cost benchmark compares the internal manufacturing cost (make) to an external supply of AM parts (buy). The cost benchmark is based on an analysis of production and supply cost. According to German Commercial Code (HGB) § 255, the production cost is split into material cost, manufacturing cost, and special production cost. Moreover, the production cost is categorized by reliance on production volume in fixed and variable costs.

The cost structure of the make scenario regards fixed and variable costs. Table 7.2 provides an overview of the cost structure for the make option. The fixed cost for the make scenario is split into two categories. There are one-time investments to set up or improve the AM production facility. These costs cover the AM production systems, necessary peripheral systems, qualification processes, and infrastructure. Then, there are fixed costs that cover all costs on an annual basis. These costs add up from the maintenance of AM systems, maintenance of infrastructure and peripheral systems, fixed labor costs, and space requirements. A detailed description of each cost category is provided in Table 7.2. Based on a depreciation time, the one-time investments are broken down to an annual cost share. Here, different depreciation models can apply. Exemplary, a linear depreciation rate can be assumed over the lifetime of the AM production system,

The variable costs in the make scenario cover all costs that depend on the production volume. They split into raw materials, consumables, working time, and disposal. A list of exemplary cost positions is presented in Table 7.2. Whereas the cost for raw materials can directly be obtained in €/kg, the cost for consumables, working time, and disposal must be estimated based on the annual output volume of the AM production system. For example, electric energy, shield gas, and compressed air consumption depend on the system runtime and the operation mode of the system. Measured consumption for different types of LPBF systems are stated in LUTTER-GÜNTHER ET AL. (2018) and GEBBE ET AL. (2015). In addition to the consumption of the AM production system, the unit price for consumables is a necessary input value. Moreover, the ratio of the different operation modes (preheating, build, cool down) in the AM system is derived from a reference build job representing the applications on the sourcing cluster. Finally, the summarized costs for the AM production system are calculated on an annual basis.

Table 7.2: Cost structure of the make scenario.

Fixed costs		
One-time invests	AM production systems	▪ One or more AM systems
	Infrastructure and peripheral systems	▪ Raw material processing: storage, supply, reprocessing ▪ Processing of consumables: inert gases, compressed air, electric energy ▪ Digital process chain and licenses: Build job generation, material processing parameters, additional AM system features ▪ Post-processing: Removing of supporting structures, removing of auxiliary materials, heat treatment, sintering ▪ Environment, health & safety: Housing, climate control, air filtration ▪ Construction work: Setup or extension of AM production facility
	Qualification process	▪ Material and first sample qualification processes
Annual costs	Maintenance of AM systems	▪ Annual cost for AM system maintenance or maintenance contract with AM system supplier
	Maintenance of infrastructure and peripheral systems	▪ Annual cost for maintenance of infrastructure and peripheral systems or maintenance contracts with system suppliers
	Fixed labor cost	▪ Salaries of employees in AM production
	Space requirement	▪ Annual rent for the space covered by the AM production facility
Variable costs		
	Raw materials	▪ Cost of raw materials ▪ Factor of material losses
	Consumables	▪ Inert gases / shielding gases ▪ Compressed air ▪ Electric energy ▪ Coolant / thermal energy
	Working time	▪ Wages of employees in AM production
	Disposal of waste materials	▪ Disposal of unusable, processed materials (e.g. contaminated metallic powders)
Output		
	Production hours	▪ Productive hours of the AM production system
	Build rate	▪ AM production system build rate based on productive hours

For the cost evaluation of the make scenario, the most important input factors are investment in the AM systems, depreciation time, and build rate of the AM system (SCHNECK ET AL. 2020). To model the output of an AM production, the build rate, which is a measure for produced mass over time, must cover the system output in a production environment. Build rates, which are published in supplier datasheets, are mostly theoretical or exposure build rates. Neither cover the influence of the production portfolio on the system output, and thus, these build rates are higher than the process and system build rate, which are realized in a production environment. The dependency of build rates for LPBF is visualized in Figure 7.2.

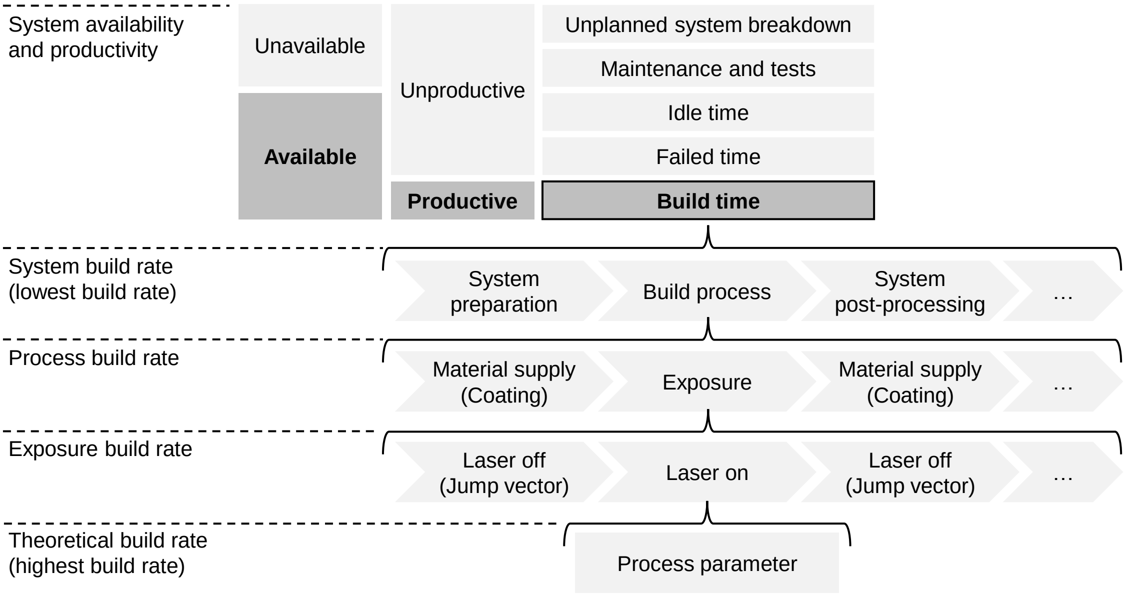


Figure 7.2: Definition of build rates (exemplary for a LBPF production system).

For the input and output factors of the make option, listed in Table 7.2, best-case and worst-case estimations are obtained and compared. Then, an average scenario is calculated as mean value of the best- and worst-case estimation. Finally, the estimations are visualized by depicting the total cost per year over the production volume, which results in a staircase function. The share of variable cost leads to a slight increase of total cost per year for increasing production volume, whereas the maximum production capacity of the AM system causes a stepwise increase due to additional fixed cost. A schematic result for the cost of the make-option is given in Figure 7.3.

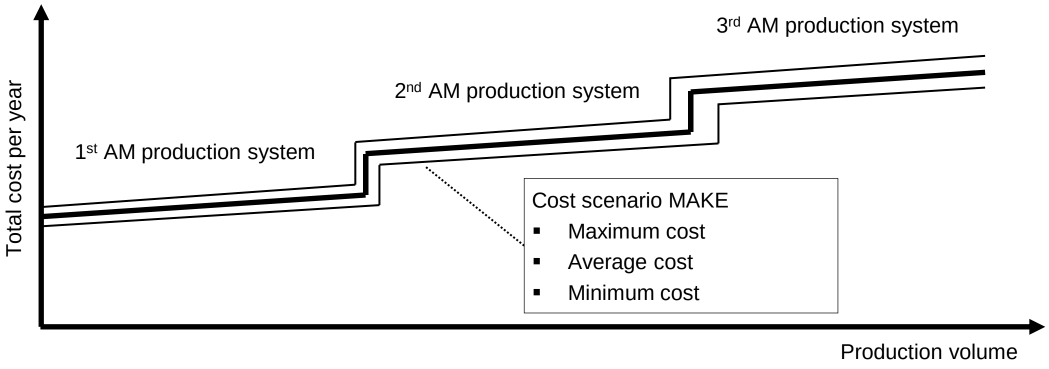


Figure 7.3: Schematic result for the cost estimation of the make-option.

The buy scenario is based on the evaluation of the cost for an external supply with AM parts. As in the make scenario, the costs are split into fixed costs and variable costs, as listed in Table 7.3. To set up and maintain a supply chain requires prior investment before parts can be purchased from a supplier. Thus, fixed costs of the supply chain must be evaluated. The fixed costs cover the supplier selection and qualification, a first sample process, and the material qualification process. The variable costs in the supply chain depend on the order volume of parts. Further details on fixed and variable costs are summarized in Table 7.3. For the economic evaluation of the buy scenario, the fixed costs are calculated as an annual levy for the supply chain, corresponding to the depreciation rate in the make scenario. Therefore, a time span to derive the annual levy is assumed.

Table 7.3: Cost structure of the buy scenario.

Fixed costs		
	Supplier selection and qualification	▪ Capacity of buyer / supply chain manager ▪ Travelling expenses ▪ Cost for supply chain consulting (internal, external) and literature (e.g. benchmark reports, market data) ▪ Contract negotiation ▪ Investment in specialized equipment at the supplier
	First sample qualification process	▪ Ordering and testing of samples ▪ Development of specialized quality measures for AM parts
	Material qualification process	▪ Approval of material properties, if material information provided by supplier is not sufficient (e.g. fatigue properties, wear resistance,…) ▪ Development of a numerical material model
Variable costs		
	Order volume	▪ Cost per part based on supplier quotes (e.g. fixed scale prices) ▪ Internal levy for logistics, purchase, administration
Output		
	Delivered volume	▪ Amount of products delivered by the supplier

To obtain the variable costs in the buy scenario, an analysis of supplier quotes is executed. Hence, in a first step, supplier quotes for the applications of the sourcing cluster are requested. To maintain the comparability with the make scenario, the requested delivery conditions of the parts are defined in an invitation to tender. The request includes the geometries of parts with all necessary information to manufacture the production task (e.g., drawings, material properties), the process steps to be carried out by the supplier, and stepwise order volumes. Because this is sensitive information, a nondisclosure agreement with the supplier is negotiated prior to the request. In addition, the request can be based on dummy geometries that allow cost calculation for the supplier but do not reveal the final design of a component. This is also useful if a finalized design for AM is not yet available. In general, all definitions and specifications apply to the requested parts instead of the AM process. Part-based requirements support a better understanding of the manufacturing task, and thus, they allow for higher supplier flexibility. For example, the request for a specific surface roughness might generate an offer for an AM part in combination with a specific post-processing, whereas the request for a layer thickness may be rejected due to the availability of an appropriate manufacturing parameter set.

The obtained data from the supplier request are analyzed to obtain a calculation metric for the buy scenario. Therefore, all obtained quotes are converted into mass-based costs by dividing the offered price by the order volume. Then the lowest and highest mass-based costs are selected, and a proximity function is derived. As a result, a best-case estimation and a worst-case estimation for the variable cost in the buy scenario are obtained. The average scenario is calculated as mean value of best- and worst-case. Finally, the fixed cost on an annual basis and the variable cost for the external supply are summarized. A schematic result for the cost of the buy-option is given in Figure 7.4.

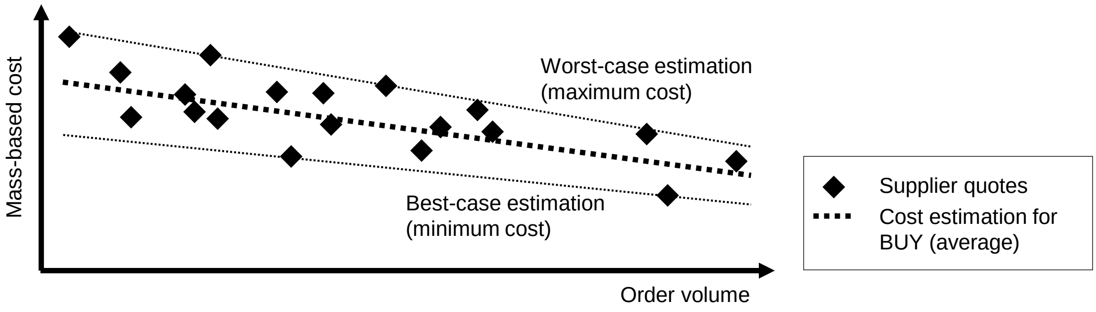


Figure 7.4: Schematic result for the cost estimation of the buy-option.

To draw an economic comparison of the make and the buy scenarios, both cost structures are overlaid and compared to the required production volume of the sourcing cluster. From this comparison, the favorable economic supply scenario can be derived. A schematic result of the cost benchmark analysis is depicted in Figure 7.5.

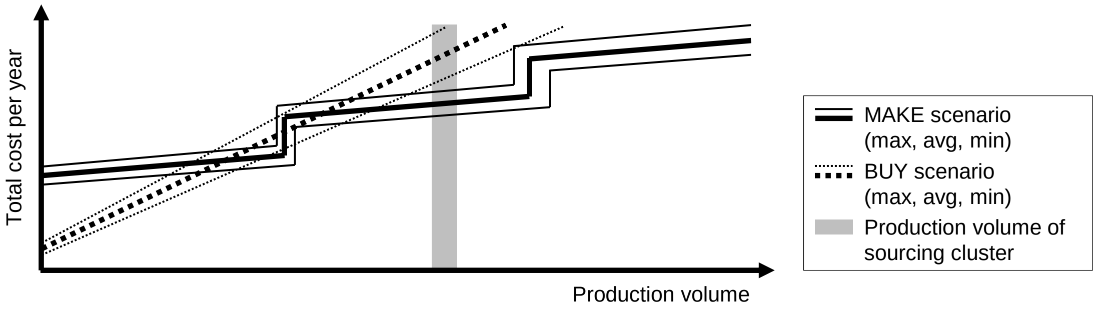


Figure 7.5: Schematic result of cost benchmark.

7.1.3 Make-Buy Strategy

Besides the current state analysis and the cost benchmark, strategic aspects are part of the make-buy evaluation process. The strategic aspects include the composition of the AM applications, the production volume, the AM market development, and the strategic alignment of the organization. The evaluation of strategic aspects for the make-buy decision covers 10 points that are listed in Table 7.4. These points serve as a guideline to choose a preferred sourcing strategy. Nevertheless, the introduction of additional decision criteria and an appropriate weighting are subjected to the applying organization.

Table 7.4: Strategic aspects of the make-buy decision.

	Make scenario	Rating	**Buy scenario**
Current state analysis			
Production and supply scenario	☐ Production integration ☐ Capacity enlargement ☐ Material diversification ☐ Capacity enlargement and material diversification ☐ Technology implementation		☐ Supply chain integration ☐ Material diversification ☐ Supply chain extension ☐ Supply chain generation
Cost benchmark			
Annual production volume	Average cost for make scenario:	☐ ☐ ☐ ☐ ☐	Average cost for buy scenario:
Strategic aspects			
Technology portfolio	▪ Homogeneous portfolio of AM technologies among the intended applications	☐ ☐ ☐ ☐ ☐	▪ Heterogeneous portfolio of AM technologies among the intended applications
Material portfolio	▪ Homogeneous portfolio of materials among the intended applications ▪ Materials belong to the same material group and can be processed on a single AM system	☐ ☐ ☐ ☐ ☐	▪ Heterogeneous portfolio of materials among the intended applications ▪ Processing of materials need multiple AM systems (material changes not feasible)
Production volume / Risk of AM system utilization	▪ Annual production volume needs several AM systems ▪ Constant production volume available (base load) ▪ Outlook for production volume indicates comparable applications / development tasks clear and scheduled	☐ ☐ ☐ ☐ ☐	▪ Annual production volume is significantly less than annual machine capacity ▪ High volatility in production volume ▪ Outlook for production volume is uncertain, high risks in the development projects
AM process know-how	▪ Comprehensive know-how necessary to fully utilize AM potential in the product (process optimization, process parameters)	☐ ☐ ☐ ☐ ☐	▪ Established and market available know-how sufficient to exploit AM potential
AM market development	▪ Current state of AM systems sufficient to exploit AM benefits for applications	☐ ☐ ☐ ☐ ☐	▪ Applications require newest AM technology on the market (e.g. type of energy source, heating)
Supplier availability / Sourcing risk	▪ No or very few supplier on the market → Risk of single-sourcing with high dependency from supplier	☐ ☐ ☐ ☐ ☐	▪ Several suppliers on the market for AM technology and material → Multi-sourcing strategy applicable (benchmarking, price negotiations)

Continued on next page

Relevance of AM applications	▪ AM applications cover core functions of the product	☐ ☐ ☐ ☐ ☐	▪ AM applications do not cover core functions of the product
Strategic framework	▪ Technology strategy of technological leadership ▪ Constant invest in new technologies	☐ ☐ ☐ ☐ ☐	▪ Technology strategy of cost leadership ▪ As little capital lock-up as possible
Production depth	▪ High production depth in the organization	☐ ☐ ☐ ☐ ☐	▪ Low production depth in the organization
Confidentiality	▪ Necessity to keep design and/or process data strictly internal ▪ Insecure process chain with supplier	☐ ☐ ☐ ☐ ☐	▪ Long and trustable relationship to supplier, comprehensive supplier contracts → Low risk for outsourcing
Summary	**Make scenario in favor**	☐ ☐ ☐ ☐ ☐	**Buy scenario in favor**

The strategic aspects include the overall portfolio of AM technologies and materials among the analyzed applications. In addition, for the production volume, the total volume and the volatility of the demand are important. An internal AM production requires a constant production load to utilize the AM system capacity. For the estimation of the production volume, development projects are included, which generate future demand for production capacity.

The aspects for the supply chain evaluation are derived from a supply portfolio method, clustering the supply parts by risk in the supply chain and financial impact for the organization into a Kraljic matrix (KRALJIC 1983, MANNKE 2011). This categorization defines four types of supply parts. The strategic parts are characterized by a high risk in the supply chain (e.g., very few suppliers are available) and a high financial impact for the organization. For a supply situation with several suppliers on the market, the buy strategy is based on benchmarking and price negotiations. By contrast, for strategic parts, the market is dominated by the supplier, resulting in high dependency for the buying organization. In this case, an external supply must rely on long-term strategic partnerships. To avoid these situation in a producing organization, strategic parts are particularly appropriate for internal production.

Besides the strategic aspects of the supply chain, the AM market development needs to be investigated because fast progression of technology can necessitate reinvestments in AM systems before full depreciation (GEBHARDT 2013). In addition, the overall technology strategy of the organization is considered. For an organization that focuses on technology leadership and high production depth, the make option is a more preferable choice because the organization is used to introduce and develop new production technologies. Also, confidentiality aspects influence the make-buy decision because some applications or development parts require a strictly internal production process. Finally, the current state analysis, the economic evaluation, and the strategic aspects are balanced, and a preferred sourcing strategy for the sourcing cluster is selected.

After deciding about the preferred sourcing strategy, the execution phase for the supply decision is prepared. Generalized process steps to realize a make-buy strategy are depicted in Figure 7.6. The process steps for the buy strategy are based on ZÄH (2013). A project plan provides an overview of the time scale to set up or extend the internal AM production system or to select and qualify a supplier. Moreover, the necessary invests and required employee capacity are stated. As part of the *AM Technology Roadmap*, the project plan summarizes the schedule to execute the make-buy strategy and defines important milestones in the roadmap. For an internal AM production, the milestone is the start of production, whereas for an external supply, the milestone is the start of delivery. Both milestones define the realization of the first AM-manufactured serial products.

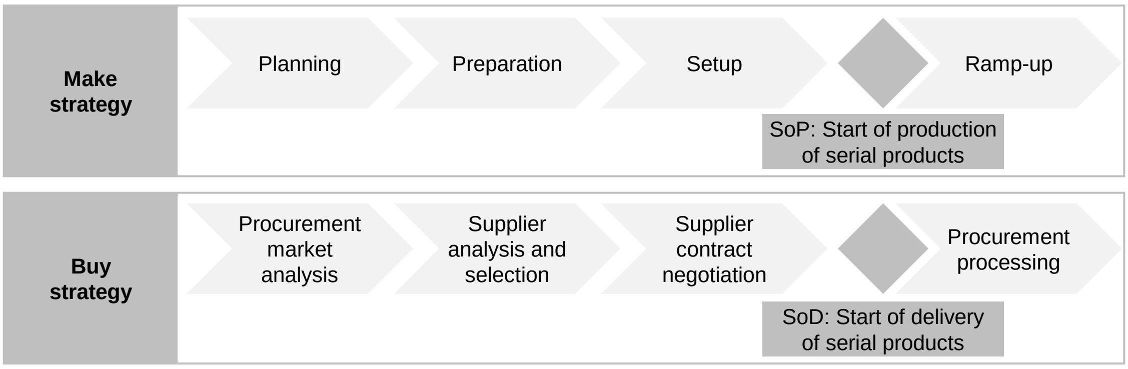


Figure 7.6: Project plan for the make and buy options.

7.2 Building of Knowledge and Information Exchange

The availability of knowledge on AM technologies is a limiting factor for the successful implementation within an organization (see Figure 3.3, page 48). Hence, internal generation of know-how and measures for knowledge exchange must be addressed when developing an *AM Technology Roadmap*. Following SEIDEL & SCHÄTZ (2019), there are two reasons for providing continuing education in AM to employees through part-time trainings: a strong demand for experts in AM, which cannot only be covered by graduates from universities and other educational institutions, and the rapid and manifold progress in AM technologies, which requires a continuous process to keep knowledge up to date.

The task of knowledge and information exchange is part of knowledge management in an organization. Although there is no precise definition of knowledge in the context of organizational learning, it is common sense that knowledge exists and that it can be managed (FREY-LUXEMBURGER 2014). The *Munich Model of*

Knowledge Management proposes four areas of interest for knowledge management: generation of knowledge, representation of knowledge, communication of knowledge, and application of knowledge (REINMANN-ROTHMEIER 2001).

The requirements for building and exchanging knowledge cover the analysis of the necessary knowledge within the organization to execute the development of the AM applications and thus utilize the AM technology potential. An overview of the requirements is depicted in Figure 7.7. As a first step, the target groups within the organization are identified. The target groups are derived from the clustered AM applications by identifying the required knowledge to execute the development projects. Moreover, appropriate structures to disseminate technology information and to build knowledge need to be established, which ensures the exchange of already available knowledge. Especially in larger organizations with manifold products and many sites, this structure must be a network of knowledge sharing to keep involved employees informed about the progress in AM and to avoid costly parallel developments.

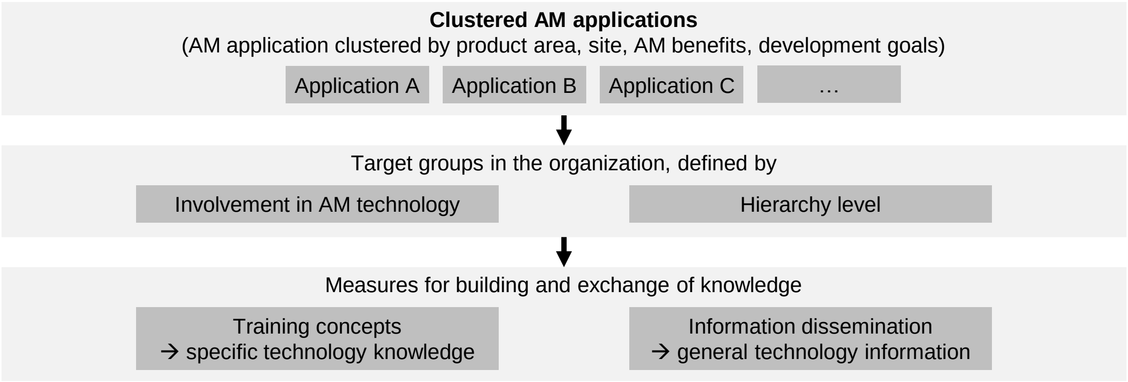
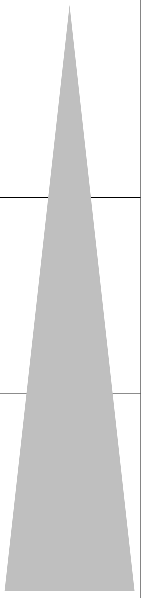


Figure 7.7: Knowledge and information requirements.

7.2.1 Target Groups in the Organization

The target groups consist of people working in the organization with different involvement in the AM technology. They can be categorized into three groups: experts, involved employees, and interested employees (SCHNECK 2018), which is characterized in detail in Table 7.5. The experts in AM technology work with AM on a daily basis (*AM experts*). Thus, they have mostly specialized skills concerning the design, the production process, or materials engineering. There are only a few AM experts within an organization. Several more employees are typically involved in AM technologies on a part time basis (*Involved employees*). These are employees from different departments or serving various functions in the organization and they need specific know-how on AM technology to execute their function in the context of AM. For example, consider an engineer of machined parts who must decide if a part is machined or additively built in future. Thus, this employee can build on prior knowledge but needs additional information about AM. A third target group covers employees who are not yet involved in AM technology but are interested (*Interested employees*). This target group is important for disseminating information to foster an innovative mindset and generate new ideas for AM technology applications. Often employees are first interested in AM technology, and become involved, when they start their first AM project. The described target groups are found across different departments and functional units of the organization, as presented in Table 7.5. The involvement of specific departments and function groups in the organization in AM technology depends on the identified applications, the necessary development steps, and the sourcing strategy. Nevertheless, mostly, the implementation of AM technologies is a decentralized initiative, coordinated by R&D staff (MÜLLER & KAREVSKA 2016).

Table 7.5: Target groups for building up knowledge in an organization.

Target groups for AM technology			
Target group	Definition	Methods for knowledge building and communication	Number of employees
AM experts	▪ Work with AM technology on a daily basis ▪ AM is main part of the job description ▪ Have specialized skills of AM technology (e.g. AM process, design, production, materials)	▪ Conferences ▪ Specialized trainings (external) ▪ Expert and standardization bodies on national and international level (e.g. ISO, DIN, VDI) ▪ Inter-company technology networks	
Involved employees / Specific functions	▪ Employees from different functions and departments of the company, which are involved in AM projects ▪ Know-how about AM is needed as background to execute the job's function for projects in AM	▪ Trainings (internal by AM experts) ▪ Technology network (internal) ▪ Idea and design competitions ▪ Specific internal platforms of target groups (e.g. management conference, CAD user meeting)	
Interested employees / Everyone	▪ All employees of the organization, which are interested in AM.	▪ Internal publications (e.g. Intranet, company's print media) ▪ Internal communication platforms (e.g. strategy day, technology day, staff meeting) ▪ Exhibition of AM technology ▪ Introductory presentations	
Involved departments and functions (exemplary)			
Development	Sourcing	Sales and distribution	Supporting functions
☐ Design	☐ Production	☐ New product sales	☐ IT
☐ Simulation (FEM,…)	☐ Buying	☐ Spare parts sales	☐ Human resources
☐ Materials	☐ Supply chain mgmt	☐ Services	☐ Marketing
☐ Testing	☐ Quality	☐ Logistics	☐ Legal

The building of knowledge and the dissemination of information depends on the target group that receives the information. Depending on the target group, the content of information and the communication channel are defined. For the implementation of additive technologies, the target groups in the organization can additionally be clustered by hierarchy level (DIETRICH ET AL. 2019). A holistic view of target groups, considering the involvement in AM technology and the hierarchy level is depicted in Figure 7.8.

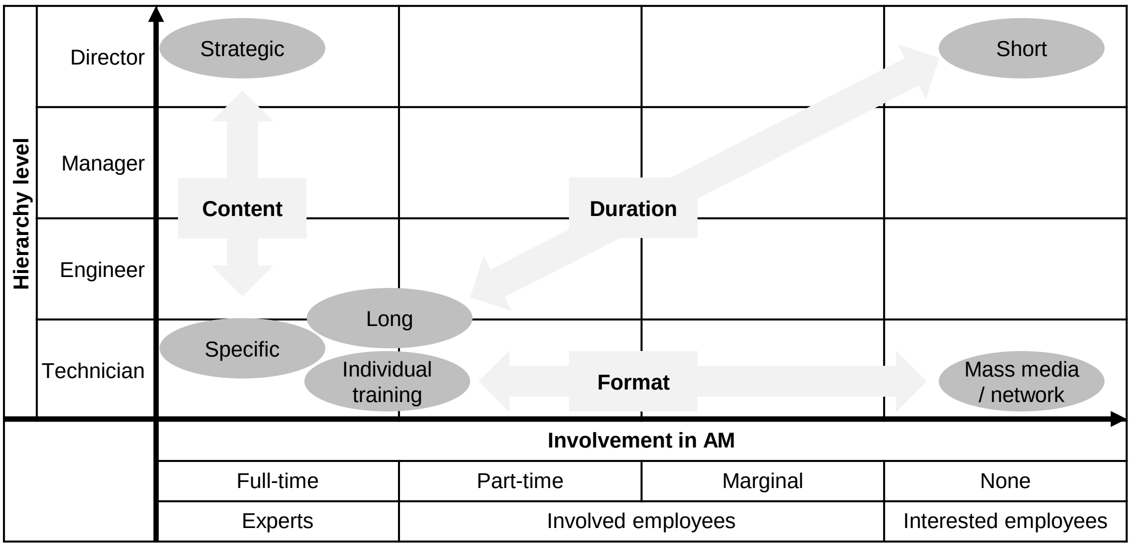


Figure 7.8: Specification of target groups in an organization.

Based on this clustering, the specifications for information exchange are the content, duration, and format of information. The information content varies depending on the hierarchy level. Whereas employees on the technician level require very specific information (e.g., specific machine, software, and work instructions), the management and director level focus on strategic aspects of the technology (e.g., market data, technology maturity, make-buy decision). The format of information exchange depends on the involvement in the AM technology. Employees who are interested but not involved in the AM technology are informed by mass media (e.g., the organization's intranet, technology days, internal newspaper). Employees that are involved in AM technology on a full-time or part-time basis require training customized to their information requirements. Finally, the available time to inform staff about AM technologies depends on hierarchy level as well as involvement in the AM technology. Whereas a technician (e.g., machine operator) may spend several days in a training on a specific AM system, a less-involved manager requires a brief and comprehensive status update.

7.2.2 Development of AM Training Concept

An appropriate means of building knowledge is providing trainings for employees (Frey-Luxemburger 2014). Following Hentrey et al. (2019), trainings are an established method of personnel development. In trainings, employees are taught new knowledge, new skills, and practices. Therefore, trainings are appropriate to deepen knowledge and to foster the application of know-how. As recommended by Hentrey et al. (2019), the framework of a training is 8–12 employees and a duration of 1–3 days. Moreover, several training methods have to be utilized (e.g., presentation, discussion, exercise) to improve learning success.

To facilitate the understanding of AM, a problem-based learning approach has been recommended by Seidel & Schätz (2019) and Kirchheim et al. (2018). The problem-based learning concept places the learner in an active role to self-develop knowledge supported by the trainer. The objectives for a training are categorized into cognitive (knowledge), affective (motivation and inspiration), and motoric (practical skills) objectives. Improved learning success when utilizing different learning methods for the application of AM was proved by Keaveney & Dowling (2018) for a student laboratory environment.

There are four major steps to develop a training or training program according to Hentrey et al. (2019):

1. Concept phase: definition of project goals, stakeholder, target group, frame conditions, learning goals.
2. Design of learner experience: derive emotions and thoughts based on the target group; design learning concept.
3. Communication: planning of roll-out; deriving key messages.
4. Quality check and pilot phase.

Conceptualizing a training for AM follows the generalized steps of training design. The project goal of a training in AM is to provide knowledge about AM technologies and to empower the participants to handle AM technologies in their daily business. In addition, the stakeholders for the training project are identified, and the responsibility for the trainings are clarified. Then, the target groups for the training (see section 7.2.1) are derived, based on the leading question: *Who must know which aspects of AM technology to fully utilize the AM technology potential within our organization?* In this step, the evaluated AM applications are analyzed to identify knowledge requirements and obtain an overview of the involved departments and functions. Thus, the lack of knowledge hindering AM implementation is identified. Moreover, the target group is concretized by the function in the organization, the number of employees to be trained, the prior knowledge in AM, and the knowledge level to be achieved in the training. Besides the target group, the framework conditions for setting up the training are defined, especially the budget, capacity, and schedule. Finally, precise learning goals for the training are formulated. Based on the target group and learning goals, it is decided whether a trainer is internally available or external expertise must be requested.

8 Derivation of the *AM Technology Roadmap*

The *AM Technology Roadmap* is based on the prior collected information about AM technologies in action field A (chapter 5), the evaluated applications in action field B (chapter 6), and the organizational tasks derived in action field C (chapter 7). In accordance with the roadmap definition of SCHUH (2013), stating constitutional elements as timeline, planning levels, planning objects, and their connections, the *AM Technology Roadmap* visualizes the generated data from all three action fields. A schematic *AM Technology Roadmap* is depicted in Figure 8.1.

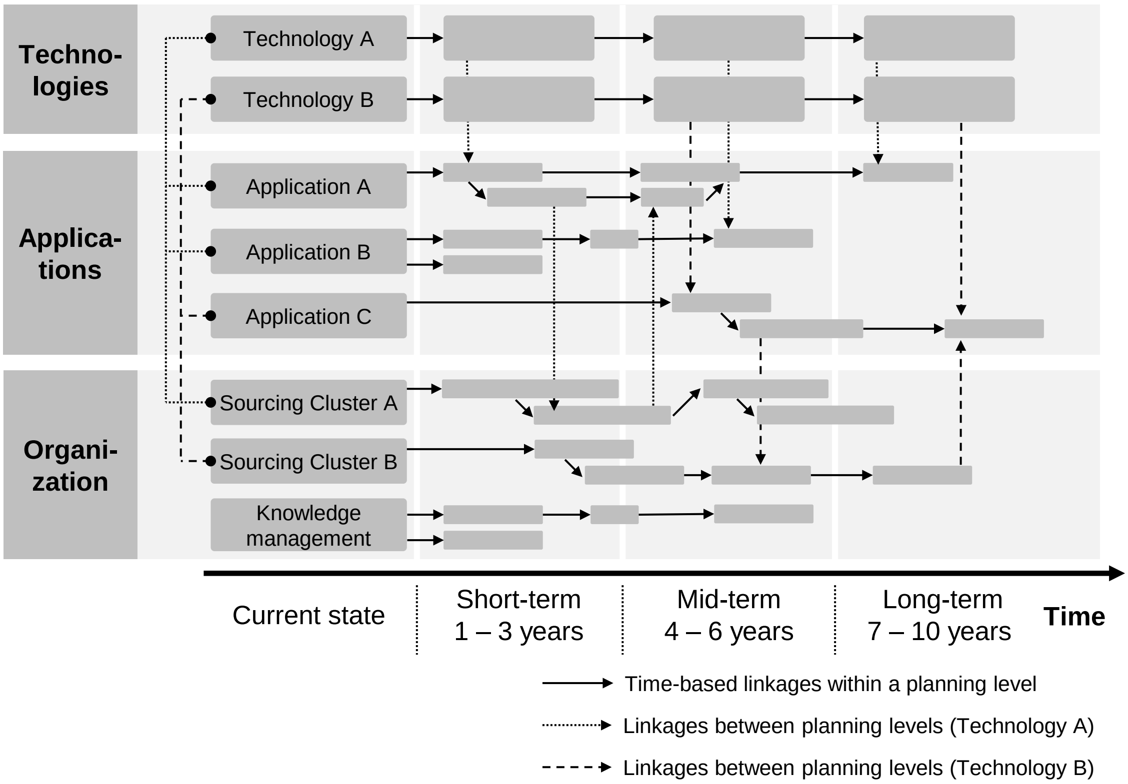


Figure 8.1: Schematic AM Technology Roadmap.

Each action field addresses a planning level in the roadmap. Thus, there are three planning levels covering AM technologies, applications, and organization. The obtained results in each action field are planning objects, covering a specific time span on the timeline in the roadmap.

For AM technologies, the outlook on further technology development is derived from the *Technology Fact Sheet*. The outlook on technology development includes materials, which will become market available, technical aspects of the technology to develop (e.g., reliability), and economic aspects (e.g., cost of the process, changes in the AM technology ecosystem). For AM applications, the planning objects are derived from the *Application Assessment Sheet* containing the project plan for the next development steps. Moreover, the maturity of the application, stated as TRL, can be utilized to visualize the development of the application in the roadmap. The third planning level covers organizational tasks necessary to develop the applications and exploit the AM technology potential in the organization. This planning level addresses the sourcing strategy for the AM technology and knowledge management tasks. The sourcing strategy states the preferred make- or buy-scenario and resulting activities for its realization (see section 7.1, page 99). In the roadmap, the tasks to realize the preferred sourcing strategy are depicted. The knowledge management includes setting up structures for building and exchanging knowledge. In the roadmap, the measures for knowledge management are integrated.

The planning objects are clustered into short-, mid-, and long-term realization potential. Despite there being explicit definitions for the short-, mid-, and long-term outlook in Figure 8.1, the specific values depend on the organizations planning processes. Ideally, the *AM Technology Roadmap* is integrated into the technology management process of the organization, and the planning horizon is taken over from superordinate processes. Nevertheless, most technology roadmaps cover a planning horizon between 6 and 10 years (SCHUH 2013). To show the dependency of the planning objects, the time-based connections among the planning objects are derived. In addition, connections between the planning levels are visualized, showing the dependency of a specific AM technology, the applications utilizing this technology, and the organizational tasks to exploit the technology's potential.

After preparing the *AM Technology Roadmap*, the draft is discussed with all involved stakeholders. Based on the *AM Technology Roadmap*, the motivation and hypotheses for the utilization AM technologies within the organization are revised. With the comprehensive collection of information, visualized as roadmap, the hypothesis can be approved, rejected or found as partially applicable. Moreover, the *AM Technology Roadmap* contains detailed plans on how to utilize the AM technology potential in the organization. Hence, strategical decisions (e.g. investment in an AM production system, qualification of specialized materials) can be taken on the basis of the *AM Technology Roadmap*. In the end, a finalized version of the *AM Technology Roadmap* is released. However, due to the developing AM technologies and changes in the organization, the *AM Technology Roadmap* must be continuously updated.

9 Application and Evaluation

In chapters 4 to 8, a method to prepare an *AM Technology Roadmap* was introduced. The application and evaluation of the method is split into two parts. The first part, section 9.1 to 9.4, presents the exemplary application of the method to obtain an *AM Technology Roadmap* in an industrial company from the power engineering sector. A potential in AM technology was expected for LPBF of Ni-base materials (hypothesis). Therefore, a *Technology Fact Sheet* for LPBF with a focus on Ni-base alloys is created. Based on this, the combined data- and knowledge-based identification approach is applied. The detailed evaluation of an AM application, which is based on the *Application Assessment Sheet* is demonstrated for the exemplary AM application *injection component*. Finally, the setting up of the *AM Technology Roadmap* is demonstrated for the further development steps of the component.

The second part, section 9.5, evaluates the method in the context of its application in different production companies. Therefore, the method is applied in whole or in part in six industrial companies. On this basis, the cross-case implications of the method are discussed and compared to the requirements (cf. chapter 3). Finally, economic aspects of the method are evaluated.

9.1 Action Field A: Gather Technology Information

In the following section, the approaches to generate technology information are applied. At first, the approach of a web-based information search is presented, which allows to identify AM applications in different domains. Secondly, a *Technology Fact Sheet* for LPBF with a focus on Ni-base materials is developed.

9.1.1 Identification of Information Sources

Based on the approach to identifying information sources (cf. section 5.1, page 59), a study to obtain industrial applications for metal-based AM is carried out. The goal of the search request is to identify industrial applications in metal-based AM as exemplary applications in the *Technology Fact Sheet*. Table 9.1 shows an exemplary result for the systematic search approach, based on JEGEL (2019). It can be seen that most applications in the web search were found by the term *Additive Manufacturing*, whereas *3D printing* was less relevant when identifying metal-based AM applications. Considering the domains, the search term of *Additive*

Manufacturing and *Medical* identified 19 relevant applications in metal-based AM.

Table 9.1: Result of a systematic search for applications of metal-based AM in different domains, based on JEGEL (2019).

X = Number of identified applications for metal-based AM		**Search term for AM**			**Sum for domain**
		“Additive manufacturing”	“Generative Engineering”	“3D Printing”	
Domain	Automotive	12	10	2	24
	Tooling	14	8	2	24
	Medical	19	6	4	29
	Aerospace	10	5	0	15
	Lifestyle	9	1	2	12
	Industry	0	4	0	4
Sum for AM search term		64	34	10	108

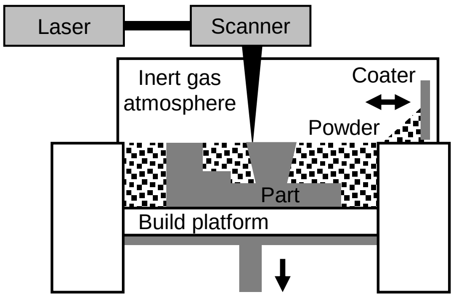
> 10 Use Cases identified | 5 – 10 Use Cases identified | < 5 Use Cases identified

9.1.2 *Technology Fact Sheet* for LPBF

The *Technology Fact Sheet* summarizes the relevant technology information needed for the identification and evaluation of AM applications. Moreover, it is a valuable information source for engineering support and knowledge building in AM. The structure of the *Technology Fact Sheet* was introduced in chapter 5 and an overview is depicted in Figure 5.1, page 61. The exemplary *Technology Fact Sheet* focuses on LPBF and Ni-base alloys. The full version of the *Technology Fact Sheet* including all data sources and references is attached in Appendix B.

The summary of the *Technology Fact Sheet* is shown in Figure 9.1. It provides comprehensive information about the technologies functional principle, process category, and process chain, based on the definitions of ISO/ASTM 52900. In addition, the functional principle is provided as a sketch to visualize the process. In the lower part of Figure 9.1, the technology’s key figures are summarized. The key figures cover the relevant information from the *Technology Fact Sheet* and provide a materials overview, specific material properties, machine equipment, reference applications, costs, and technology maturity.

Laser-based Powder Bed Fusion



Process category	Powder Bed Fusion
Process chain	Single step

Layer wise generation of a part by using a laser beam to melt metallic powder locally in an inert gas atmosphere. The process consists of applying a powder layer, solidifying with the laser beam and lowering of the build platform.

Materials overview	**Material properties**	**Machine equipment**	**Reference applications**	**Cost**	**Technology maturity**
Market availability	Available for	Corresponding cubic dimension ccd	Part mass	Cost indicator for 2.4668	Manufacturing Readiness Level MRL
Total: 49 Ni-alloys: 8	2.4668	93 – 404 mm	47 – 1229 g	1074 €/kg (441 – 4036 €/kg)	9 - 10

Figure 9.1: Summary of key figures in the Technology Fact Sheet for LPBF.

To obtain the materials overview, the offered materials of 20 AM system manufacturer and contract manufacturer were investigated. 49 market available alloys were identified, as shown in Figure 9.2. To offer a more detailed view of the available alloys, market availability is classified into *market entry phase* with three available suppliers or less and *established in market*, divided into classes of 4 to 9 suppliers and 10 or more suppliers, representing 50% of the investigated number of suppliers. It can be seen that from the total of 49 alloys, 35 are in the market entry phase, whereas only 14 are established in the market. Finally, only five alloys are available from 10 suppliers or more. These alloys are AlSi10Mg (3.2381), 1.2709, 316L (1.4404), In718 (2.4668), and In625 (2.4865). For Ni-based alloys, the state of *under development* was also investigated. For 11 alloys, which are not market available, scientific sources were identified, stating that the mentioned alloy is processed by LPBF. Nevertheless, several publications noted hindrances (e.g., cracks, pores) that must be overcome before these Ni-based alloys become market available and can be utilized for serial parts. Most of the available Ni-based alloys are in the market entry phase and offered by less than three suppliers. Only three alloys (Alloy HX/Hastelloy X, In625, In718) are established in the market and offered by more than three suppliers.

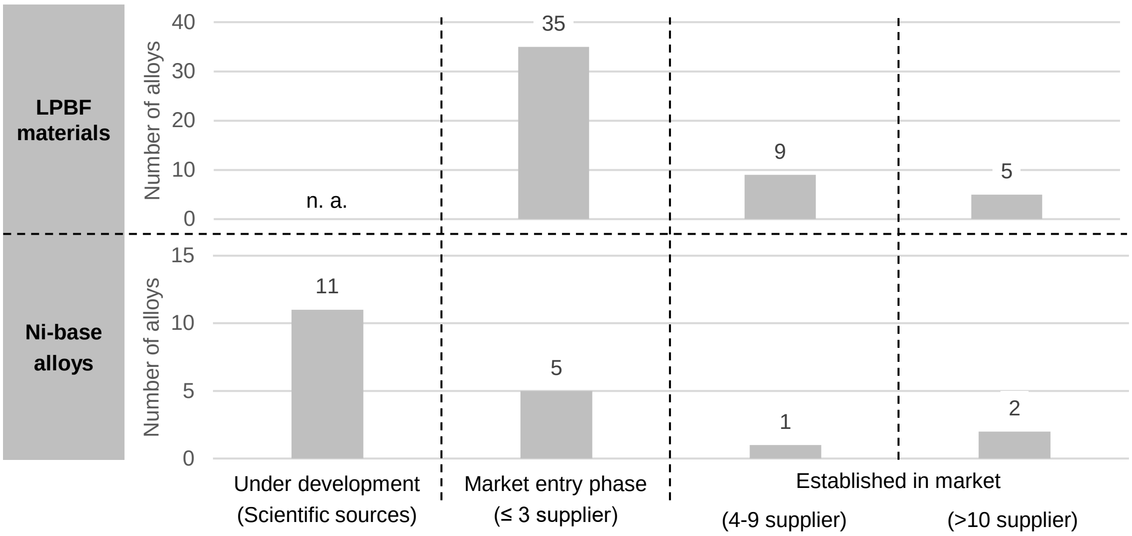


Figure 9.2: Overview of available materials and Ni-based alloys for LPBF. (Excerpt)

For In718, the material properties were investigated in more detail. 21 material datasheets for In718 were compared in a study. As benchmark, the material properties stated in VDI 3405-2.2 were used. In the study, the average of all available values is depicted as well as the range of minimal and maximal values for a specific material property. In Figure 9.3, the material benchmark is shown for the tensile and yield strength, covering vertical and horizontal build orientations and *as built* and *heat treated* conditions.

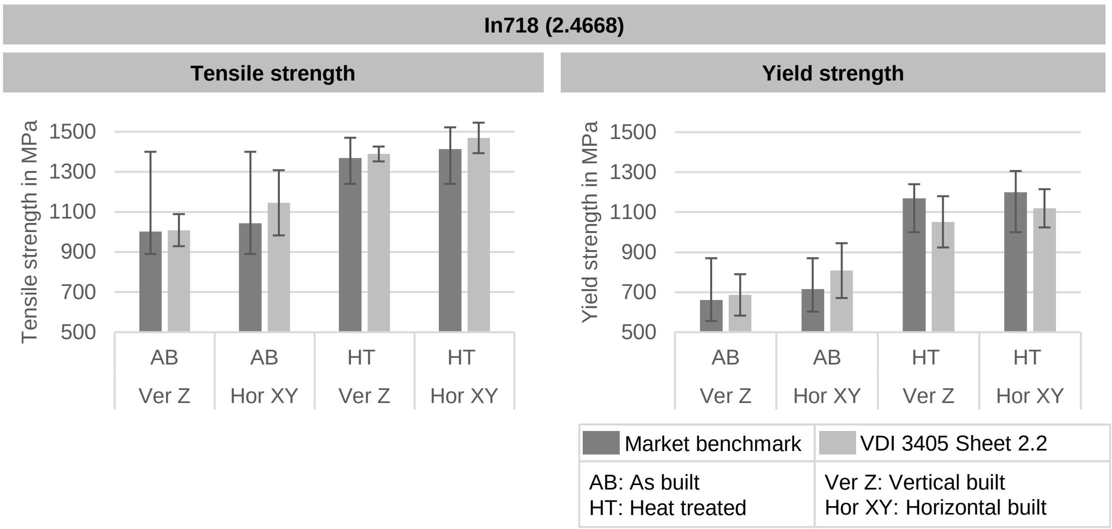


Figure 9.3: Static material properties of In718. (Excerpt)

For the machine equipment, the available build volume and dimension are the important information. Therefore, the build volume of available AM systems was investigated, as described in section 5.2.3, page 64. The build volume was calculated as *corresponding cubic dimension* (ccd) and the 10th and 90th percentiles derived from the total quantity, as shown in Figure 9.4a. Based on this evaluation method, the available build dimension are represented by a cubic build volume, ranging from 93 mm to 404 mm edge length.

The reference applications were derived from two sources. MÖHRLE (2018) conducted a study, which investigated the volume of 253 additively manufactured parts in a research laboratory. Moreover, JEGEL (2019) developed a catalogue of 214 published use cases for LPBF. Because MÖHRLE (2018) stated only classified values of the part volume without a material reference, the volumetric data were converted into mass considering the density for Al-based alloys of 2.68 g/cm³, and Fe-based alloys of 7.8 g/cm³. In the use case catalogue of JEGEL (2019), the mass of the parts was stated for 17 use cases. Based on the further information in the use case catalogue, such as description, picture, and material, the mass for another 113 parts was estimated. Finally, the results of all data sources were compared, and the range for AM part masses was derived, see Figure 9.4b. The 10th percentile of all parts was 47 g, whereas the 90th percentile was 1229 g. This indicates, that 80% of all LPBF manufactured parts have a weight between 47 g and 1229 g.

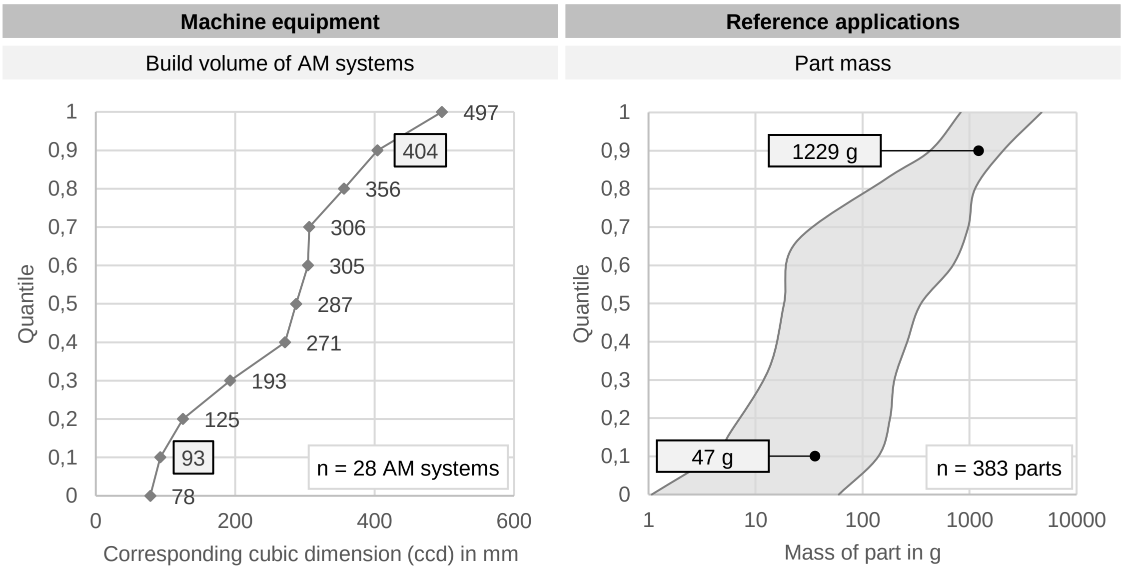


Figure 9.4: a.) Left side: Build volume of LPBF systems. (Excerpt)
b.) Right side: Part mass of LPBF parts. (Excerpt)

The cost for In718 were investigated by a cost benchmark study. Therefore, supplier quotes for AM applications were requested and compared. Based on these offerings the average mass-based cost factor was derived. The result of the cost benchmark study is depicted in Figure 9.5. Based on 36 supplier quotes, including indicative quotes for higher order volumes, a cost factor of €1074/kg was derived, and the total cost range reaches from €441/kg up to €4036/kg. It can be seen that the cost are dependent on the order volume. For order volumes lower than 1 kg, five out of six quotes indicate a cost over €1000/kg. By contrast, for order volumes over 100 kg, all quotes were lower than €1000/kg. The mass-based cost indicator is an input to the economic evaluation of an AM application and the make-buy evaluation.

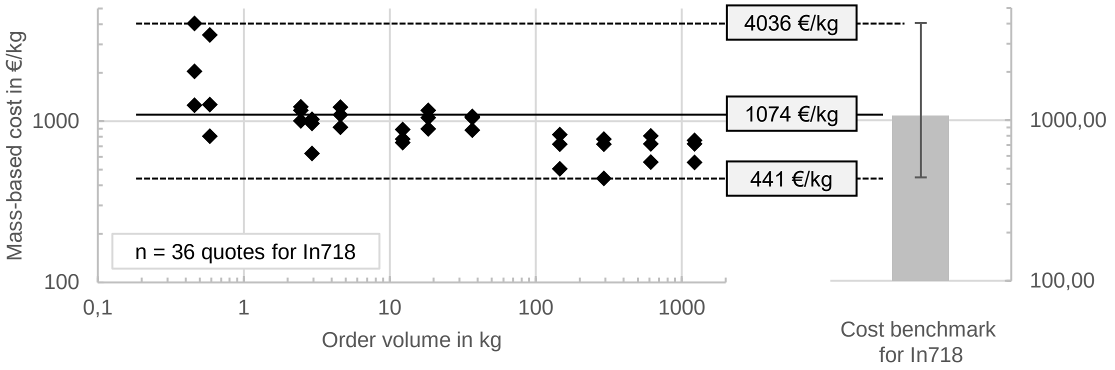


Figure 9.5: Cost benchmark for In718. (Excerpt)

The MRL is derived according to the criteria listed in Table 5.9, page 70. For LPBF, all criteria of *full serial production* are true, and thus, the corresponding MRL ranking is 9 – 10.

The forecast of the expected LPBF technology development is concluded from the provided information in the prior sections of the *Technology Fact Sheet* and literature sources. It is clustered into market, AM system, material, and cost aspects. The market development is stated in WOHLERS ET AL. (2019). An outlook for materials and AM systems development is provided in SCHLEIFENBAUM ET AL. (2019). Moreover, reports and technology roadmaps are integrated in the outlook section (e.g., MUNSCH ET AL. 2019C, SCOTT ET AL. 2016, ZWECK ET AL. 2015, NIST 2013, BEYER ET AL. 2012). The future available materials are investigated on the basis of the *materials overview* section. It is expected, that in a short-term perspective, the focus in the LPBF market remains on the five most utilized materials. On a mid-term perspective, additional materials will become fully established in the market (available from more than 10 supplier), but these are materials, which are already on the market today. On a long-term perspective, AM-tailored materials will become available, which offer unique material properties. Moreover, the material properties are adjusted to local requirements within the part. LPBF is capable to produce multi-material parts (SCHNECK ET AL. 2021).

9.2 Action Field B: Evaluate Applications

In action field B, applications for AM are identified and evaluated. Thus, the application of the data- and knowledge-based part screening approach in a power engineering company is described in section 9.2.1. In section 9.2.2, the evaluation process of an AM application is described using the example of an *injection component* for large-bore engines. The evaluation process is based on the *Application Assessment Sheet*, presented in section 6.2, page 82. For this use case from industry, commercially sensitive data has been redacted and economic values have been changed. Nevertheless, the applicability of the generated approach can be validated on the basis of this use case.

9.2.1 Data- and Knowledge-based Part Identification

The combined data-and knowledge-based approach to identify suitable applications for an AM technology was introduced in section 6.1, page 74. The identification process was conducted in a producing company in the power engineering sector. An overview of the identification process and result is provided in Figure 9.6.

The data for the data-based screening approach were extracted from the internal SAP database. Based on the list of parameters for the screening process, provided in Appendix A, the available data fields were analyzed. Depending on the infrastructure and confidentiality, the filtering of the data sets can be executed in an excerpt from the database (e.g., in Windows Excel or Access) or directly within the internal database. The extracted raw data were cleaned from faulty datasets. Finally, the dataset contained all data that were relevant for the screening process, each data point representing a specific part, assembly, or product. For a first screening result, the evaluation of LPBF was focused on the mandatory screening criteria. Because plain material data were not accessible through the database, the screening focused on the criteria *mass of part* and *mass-based cost*. Using the key figures from the *Technology Fact Sheet* as input values for the screening criteria, 114 parts were identified to meet both criteria fully. In addition, there are 212 parts, which are more expensive than the average cost of AM-manufactured In718, but which only meet the wider criteria for the mass of LPBF. Moreover, 283 parts meet the common mass of a LPBF part, but cost are between the average and the minimum cost of LPBF. A third group of parts, 295, meet the wider range in both criteria. Following this prioritization, the parts are investigated in more detail by the AM expert analyzing the description and drawing of the parts. Here, also incorrect matches were identified, e.g. for some assembly groups the mass field had a default value of 1 g or 1 kg, which did not correspond to the mass in the drawing (see accumulations as vertical lines in Figure 9.6). Thus the real mass and mass-based cost did not match the AM criteria, but due to the default value in the database the part was identified. If the identification criteria were approved, the part was discussed with the Application expert in a workshop setting.

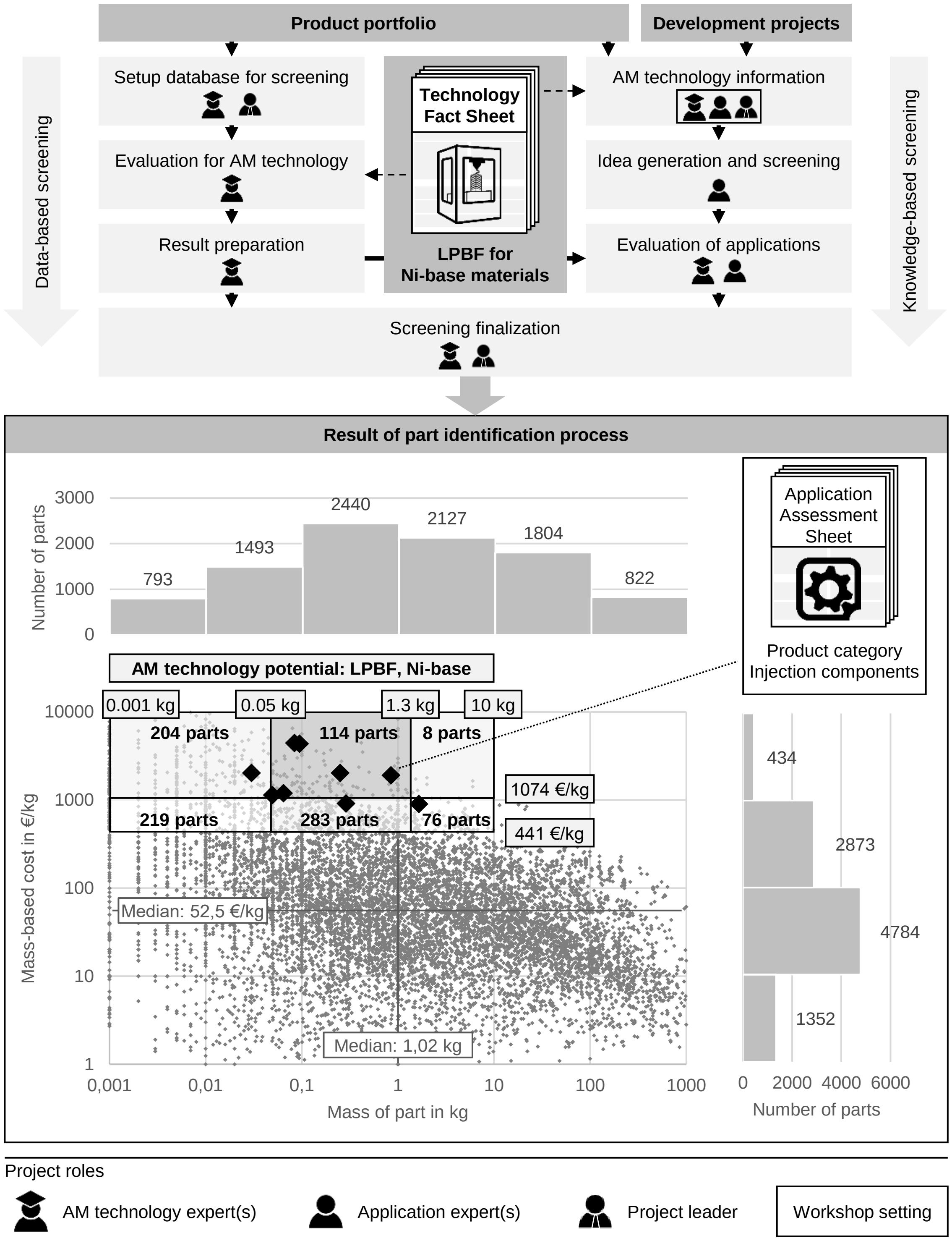


Figure 9.6: Exemplary result of the combined part-screening approach.

The knowledge-based part screening steps were integrated in a training concept for AM, which is described in more detail in section 9.3.2. Within a two days training, the steps for part screening were applied. At first, comprehensive *AM technology information* was provided, using the *Technology Fact Sheet,* but also giving an overview of AM activities in the company and fostering motivation by presenting demonstrator parts, which highlight AM benefits. The *idea generation and screening* process was executed as individual work and in small working groups. Finally, all generated ideas were collected and evaluated using the *Applications Assessment Sheet*, including the findings of the data-based screening process. After getting a first overview of all ideas, the parts were clustered by product section, to hold the *evaluation workshops* in small groups only with the involved Application experts from the specific product section. In the workshops, extensive time for discussions about the identified parts and the AM technology was required. In most cases, the evaluation required more than one workshop, due to occurring information requirements. As result of the knowledge-based part screening process, the suitable AM applications of the involved product sections were obtained.

In a final step of the screening process, all findings were categorized using the evaluation criteria obtained in the *Application Assessment Sheet* (e.g. Feasibility Index and Cost Factor). On this basis, a prioritized list of all AM applications in the company, covering technical and economic aspects was generated. Moreover, the suitable AM applications were set in the context of the product portfolio, as depicted in Figure 9.6 for the product section of injection components.

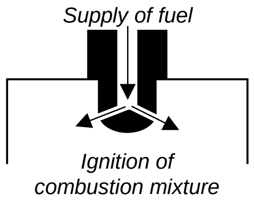
In conclusion, the combined part screening approach, consisting of three steps of data-based and three steps of knowledge-based screening, allows for the identification of AM applications and a holistic overview of the technology potential in the product portfolio.

9.2.2 Application Assessment of Injection Component

The assessment of a specific application in the context of an AM technology is presented in section 6.2, page 82. The assessment process is provided in the form of an *Application Assessment Sheet*. The assessment process is exemplified with an injection component for large-bore engines. The complete *Application Assessment Sheet* for the injection component is provided in Appendix C, and a summarized version is depicted in Figure 9.7.

Application Assessment Sheet: Injection component

1. General information



Functional principle / sketch / description

Supply of a specific mass of fuel with a predefined pressure in the burning chamber. Requirements for the component arise from chemical, abrasive and temperature load. The component is a wear part, which lifetime is critical to the overall function of the engine.

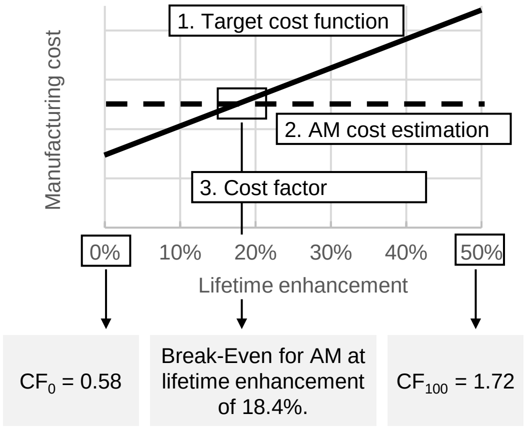
2. Technology Assessment

Development goal: *50% extended lifetime of component through advanced cooling design*

Technical evaluation

AM Technology	***2***	***1***	***0***
Dimension	☒	☐	☐
Similarity analysis	☒	☐	☐
Mass of application	☒	☐	☐
Material availability	☐	☒	☐
Material properties	☐	☒	☐
MRL level of AM technology	☒	☐	☐
AM process chain			
Pre-process: 3D-Model	☐	☒	☐
Post-Process: Manual efforts	☐	☒	☐
Post-Process: Finalize material properties	☒	☐	☐
Post-Process: Finalize geometry	☐	☒	☐
Post-Process: Finalize surface properties	☒	☐	☐
→ Feasibility Index (FI)	***0.386***		

Economic evaluation

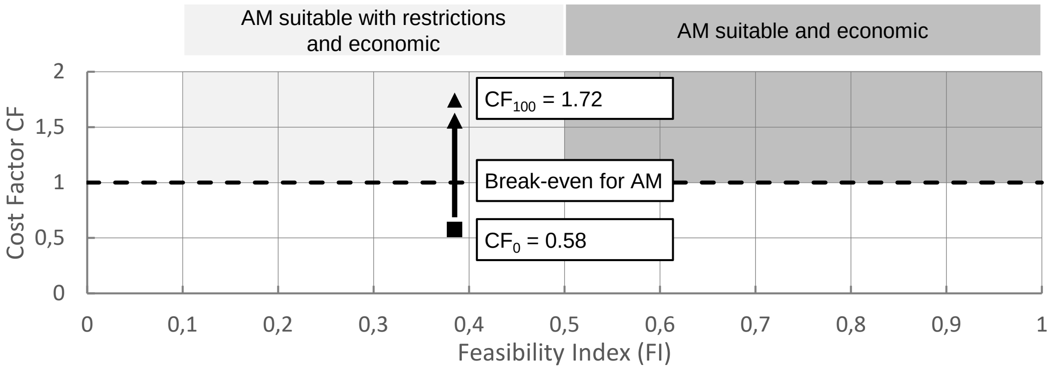


CF_0 = 0.58

Break-Even for AM at lifetime enhancement of 18.4%.

CF_{100} = 1.72

Result of technical and economical evaluation



3. Planning of realization phase

Technology Readiness Level (TRL) of AM application: 3

Project plan

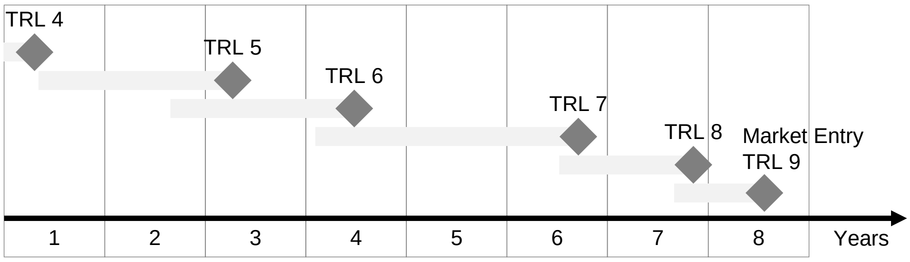


Figure 9.7: Summarized Application Assessment Sheet of injection component.

The injection component is a core part for the overall function of the engine. The basic function of the component is to inject a specific amount of fuel into the burning chamber of the engine. This injection is precisely defined as a pressure and time dependency. In addition, this behavior has to be reliable over several million opening cycles. Moreover, the component must resist thermal loads from the burning process and corrosive and abrasive wear from the fuel. The injection component is a wear part, thus the main limitation of the component is lifetime.

In the technology assessment, the first step was to define quantified development goals based on the AM benefits, as provided in Table 6.1, page 85. For the injection component, the objective for the utilization of AM was the enhancement of the component lifetime, which is a benefit in the use phase of the product. Advantages for the component were expected from improved thermodynamic behavior. Finally, the development goal for the component was to extend the lifetime by 50% compared with the current solution by an improved cooling behavior.

The technical evaluation of the injection component was based on the checklists and scoring system, provided in section 6.2.2, page 87. In the first checklist, the AM technology of LPBF was assessed, and in the second checklists, the corresponding process chain was evaluated. Based on the information provided in the *Technology Fact Sheet*, the dimensions and mass of the component were determined to be *suitable* for LPBF. Moreover, comparable parts, such as those in the tooling branch, are available. Because the currently utilized material of the component is not available in LPBF, the material aspect was assessed as *with restrictions*. It was assumed that In718 provides comparable material properties. In the process chain, the generation of an AM-suitable 3D model, the manual effort of support structures, and the machining of the component were identified as restrictions. Finally, the injection component was rated with a *Feasibility Index* of FI = 0.386. In conclusion, the injection component was evaluated to be suitable for LPBF with restrictions, due to the material availability and limitations in the AM process chain.

The economic evaluation was based on the setting up of a target cost function, the estimation of AM cost, and the derivation of Cost Factors, as described in section 6.2.3, page 93. The target cost function was derived from the cost of the conventional manufactured component at the state, if no AM benefits are utilized. Because the lifetime of the part is critical to the overall function of the engine, a lifetime extension is directly linked to a cost benefit, thus allowing for higher production costs. Hence, the target cost function was linear. The cost of the AM-manufactured injection component were estimated from the cost indicator in the *Technology Fact Sheet*. Due to the production volume of the component, it was assumed, that the AM cost were between 441 €/kg and 1074 €/kg for order volumes above 100 kg. Considering the weight of the component of 0.35 kg, the cost of the AM raw part are calculated to be €154 to €376. Moreover, the cost for the AM assembly group were estimated by a comparison with the conventional assembly (e.g. additional parts, assembly cost). Finally, comparable cost for the assembly group, including the AM manufactured component were obtained.

In the third step, the *Cost Factor* was generated. The Cost Factor, as a ratio of target cost and the AM cost, was $CF_0 = 0.58$ if no lifetime advantage is generated and $CF_{100} = 1.72$ when the lifetime is extended by 50%. Furthermore, the break-even point for the LPBF-manufactured component was calculated to be at a lifetime extension of 18.4%. Thus, from an economic perspective, the lifetime must be extended by at least 18.4% through the advantages of LPBF to be a business case.

The last step in the application assessment was the planning of the realization phase. For that, a TRL scale for the injection component was defined using the criteria in Table 6.5, page 97. Based on the application-specific definitions, the current development state of the injection component was assessed as TRL 3. Finally, a project plan was setup, describing the work packages and milestones to structure the development project utilizing the application-specific TRL definitions. Hence, the market entry of an AM-manufactured component (TRL 9) is estimates to be in 8 years.

In conclusion, the evaluation process of an AM component, provided as *Application Assessment Sheet*, has proved applicability. By considering various technical and economic parameter, a comprehensive evaluation of an application is executed. Moreover, the numerical *Feasibility Index* and *Cost Factor* are appropriate to prioritize applications on a comparable basis. Thus, they allow to focus the resources on the most promising AM applications.

9.3 Action Field C: Derive Organizational Tasks

In action field C, chapter 7, organizational tasks to foster the shift towards AM are derived. This is focused on two tasks for the organization: supply of AM parts by an internal AM production (make) or external supply (buy) and the building and exchange of know-how within the organization. The make-buy strategy is setup for the exemplary AM application *injection component*. The measures for knowledge building and information exchange are evaluated by applying them in the power engineering company.

9.3.1 Sourcing Strategy for Injection Component

The derivation of a sourcing strategy is split into three steps and is based on a cluster of AM applications that share comparable requirements for the AM production (e.g., same AM technology and material). As a first step, the applicable make and buy scenario are defined in the context of the organization. Secondly, a cost benchmark compares the economic aspects of make and buy. At third, strategical aspects are investigated, before a preferred make-buy strategy is selected. In the following, the setup of a make-buy strategy was demonstrated with the exemplary AM application *injection component*. The evaluation documents, including the make-buy cost model, are stated in Appendix D.

The scenarios of make and buy are defined in section 7.1.1, page 100. Because AM has not been established as production process in the power engineering company, the suitable make scenario was *technology implementation*. In the buy scenario, there were existing business partner that offer AM parts, thus the suitable buy scenario was *supply chain extension*.

For the cost benchmark, a calculation model for the make and buy scenario was established (see Appendix D). The cost model was based on the input parameter for make, stated in Table 7.2, page 103, and buy, stated in Table 7.3, page 105. For each scenario the cost were calculated as best case, worst case, and average case, which was the mean value of best and worst case. The case-dependent approach allowed for the use of estimated input values, resulting in a cost range for the AM parts as best-case/worst-case estimation. For precise input values, the calculated cost range for the AM parts was narrow, whereas rough estimations were suitable to generate a first estimation.

As stated by SCHNECK ET AL. (2020), the most influencing cost parameter in a make scenario are investment in the AM systems, depreciation time, and build rate of the AM system. For the make scenario a mid-size LPBF production system was assumed with invest cost of T€707. The depreciation time was assumed to be 7 years. The exposure build rate was stated by the AM system manufacturer as ~26 cm³/h per laser source. In combination with the production task, the system build rate was calculated by estimating the utilization of the second laser source, the share of auxiliary time, and the share of coating time. Thus, the AM production system allowed for building 177 g/h up to 291 g/h. Assuming a two shift operation system, the productive time per year was 3750 hours, which resulted in an annual production volume of 665 kg up to 1091 kg. The resulting total annual cost over production volume (stair case function) are depicted in Figure 9.8.

The cost of an external supply of parts is analyzed on the basis of reference quotes. These are stated in the *Technology Fact Sheet* in the cost section. To obtain the best-case and worst-case estimations for the external costs, the supplier quotes were evaluated by mass-based cost over production volume. In this evaluation, a maximum cost function (worst-case scenario) and a minimum cost function (best-case scenario) have been derived. For that, the quotes were categorized by order volume in four groups (1 – 10 kg, 10 – 100 kg, 100 – 1000 kg, >1000 kg). In each category, the two maximum and minimum quotes were selected. Finally, an approximated power function was setup for the maximum and minimum mass-based cost. The resulting functions are depicted in Figure 9.8.

In the next step, the make and buy cost structure were overlaid and compared to the required production volume. The annual production volume of the *injection component* was calculated from the part mass (0.35 kg) and the annual demand for the component (5000 parts), it was determined that the annual volume is approximately 1750 kg for a serial AM production, which was expected to be realized in 8 years (see project plan in Figure 9.7). Based on the developed scenarios for make and buy and the production volume of 1750 kg, the cost per part were derived from the scenarios. For the internal production, the part-based costs were estimated to be in the range of €295 to €447 per part. By contrast, the external supply was estimated to cost €461 to €735 per part. For the annual production volume of 1750 kg, two AM production systems were fully utilized. Thus the make scenario was the more economic choice, as shown in the cost charts in Figure 9.8.

To obtain the final make-buy strategy for the injection component, the strategical aspects were investigated on the basis of the checklist provided in section 7.1.3, page 107. The checklist for the production task injection component is provided in Appendix D. The aspects that accounted for an internal production are the economic evaluation, a homogeneous technology and material portfolio and a constant production load which utilizes two LPBF systems to full capacity. Moreover, the current state of LPBF systems was sufficient to exploit the potential of the application and the power engineering company had a high production depth, which facilitates the implementation of a new production technology. The strongest argument for an external supply was the availability of several suppliers in the market, which allows for benchmarking and price negotiations. In addition, the established know-how in LPBF was sufficient to exploit the applications. Thus, a dual sourcing strategy can be applied.

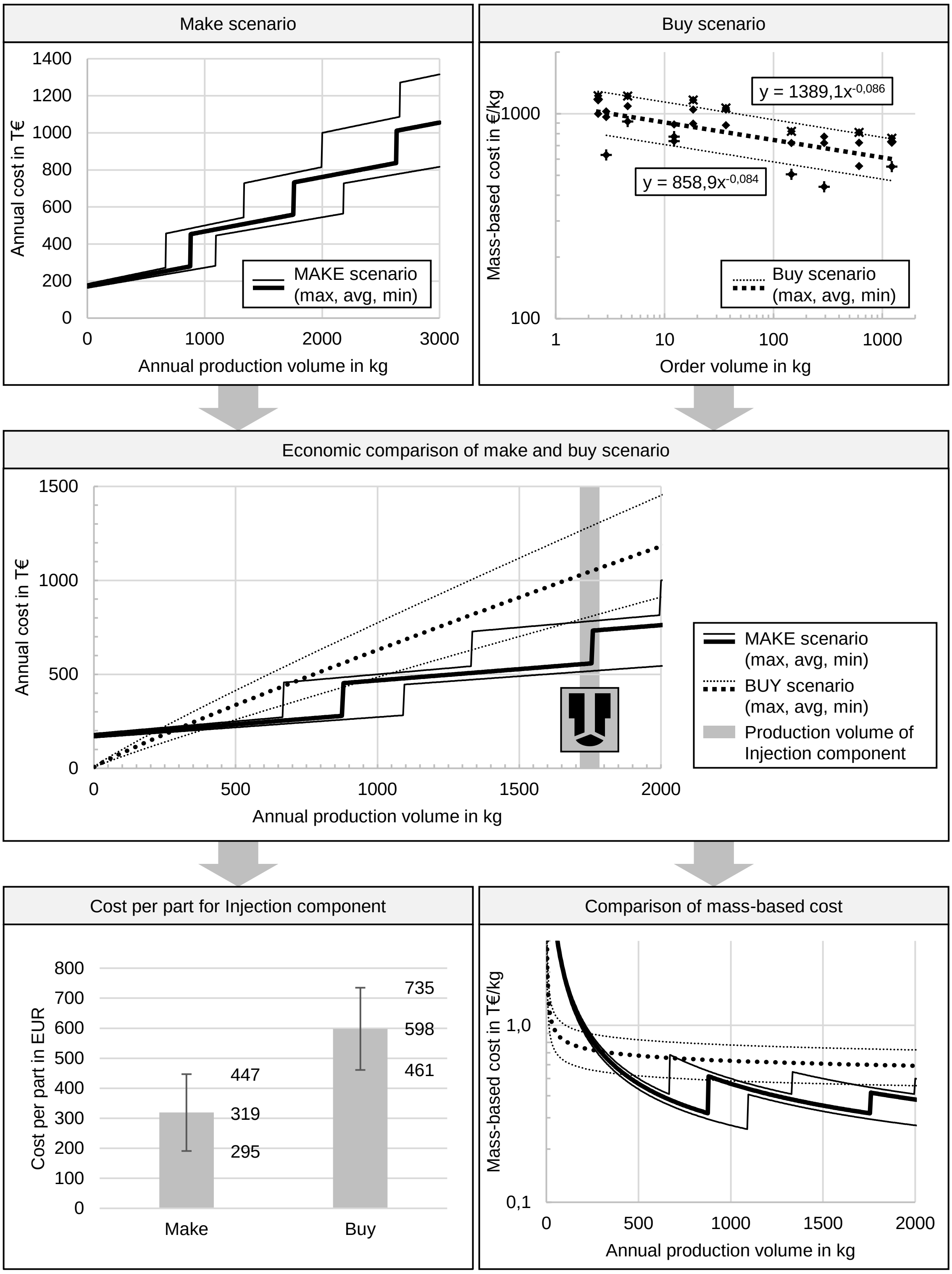


Figure 9.8: Economic comparison of make and buy scenarios.

As a result, an internal manufacturing was preferred for the AM application *injection component.* However, the make scenario did only apply for a full serial production, which was expected to be realized in 8 years, as evaluated in the application assessment (see Figure 9.7). Thus, an external supply for prototyping purposes was required within the next years, before an internal production is ramped-up to produce the serial AM injection component.

Regarding the AM application *injection component*, the make-buy analysis delivered valuable results to obtain a sourcing strategy. The cost model for the economic analysis allowed to adapt several input parameters of the make scenario to the requirements of the power engineering company. For the cost of an external supply, the cost calculation derived the cost range as function on the basis of supplier quotes, which provided well-grounded cost information. Moreover, strategical decision taking was supported by a checklist, considering the application, AM market, and company requirements. Hence, the approach to setup a sourcing strategy was successfully demonstrated for the injection component.

9.3.2 AM Network and Training Program

The building and exchange of knowledge is based on the analysis of the clustered AM applications and the target groups in the organization. Then the appropriate measures to build and disseminate technology know-how are defined. The measures for knowledge building and dissemination are applied in the power engineering company.

Based on the clustered AM applications as outcome of the screening process and the definition of target groups in section 7.2.1, page 110, the required know-how and measures for knowledge exchange were derived. From the target groups for AM technology, see Table 7.5, page 111, the relevant target groups in the power engineering company were identified. These were three target groups:

1. Employees, which are responsible for an AM application, that was identified as business case in the screening process.
2. Managers, who are responsible for a department, in which an AM business cases was identified.
3. Employees, which are interested in AM, but do not have a specific function in the context of AM (e.g., employees, who contributed an idea in the screening process, which was no business case).

Thus, measures for building and exchanging knowledge for these three target groups were developed. For the involved employees and managers a training program was setup, consisting of a *Comprehensive Basics Training* (2 days) and an *Awareness Management Training* (3 hours). The content of each training was tailored to the requirements of the target group. For interested employees, an *AM Network* was established as an open platform with regular meetings, which were open to attend for everyone. Moreover, the internal communication channels were used to publish information about AM technology implementation. The established measures are depicted in the context of the target groups in Figure 9.9.

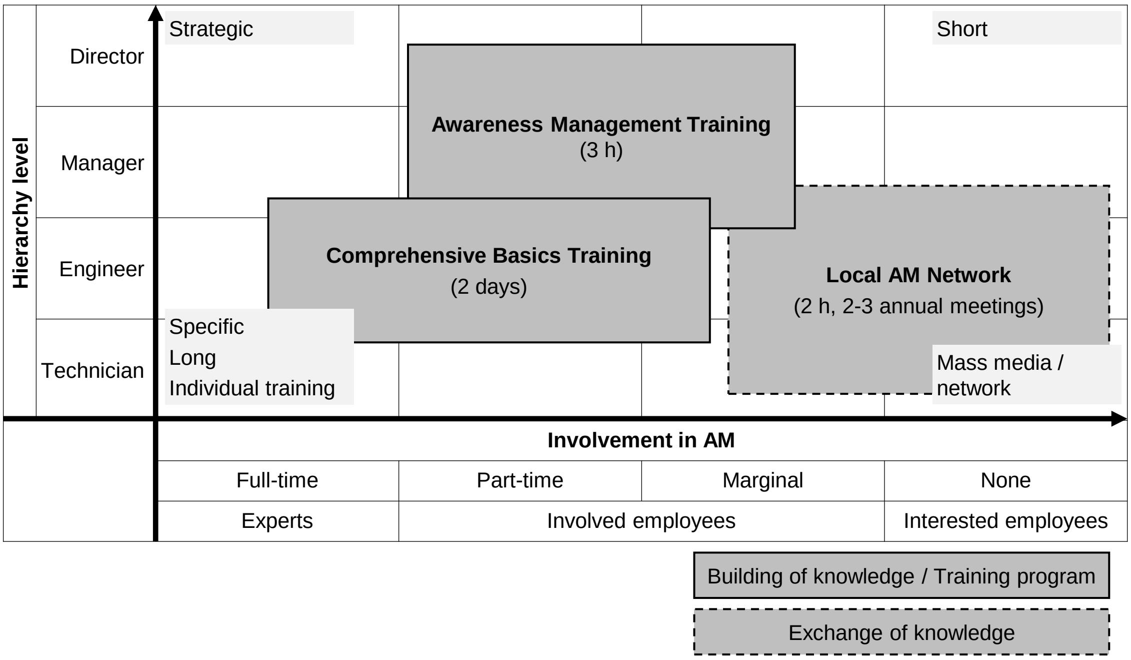


Figure 9.9: Established methods for building and exchanging knowledge.

The development of a training for AM followed a four-step process, as described in section 7.2.2, page 113. First, the concept of the training was defined, and then, the training materials were developed (design phase) and the training was delivered. Finally, a pilot run was executed and evaluated to check whether the participants had acquired the intended learning content. When setting up the trainings, it was important to empathize with the target groups and understand their expectations for the trainings. The objectives of a basic training in AM were identified in SEIDEL & SCHÄTZ (2019). Moreover, the schedule for a 2-day basic training in AM was presented, including different didactic methods to improve learning success among the participants of the training (SEIDEL & SCHÄTZ 2019). The provided training content of SEIDEL & SCHÄTZ (2019) was used as the nucleus for the developed trainings.

The *Awareness Management Training* addressed involved managers who wanted to have a comprehensive overview of the current state of AM technology and technology implementation. The learning goal of the management training was to establish the necessary know-how to make decisions about AM; in particular, to foster the implementation of AM technologies that were identified as relevant for their area of responsibility. The management training consisted of summarized technology information and a concluding workshop to discuss chances, risks, and ideas. The training agenda is provided in Figure 9.10. Due to availability constraints of the target group of middle and higher management positions, the training duration was set to 3 hours. The final workshop format allowed for a guided discussion of further technology implementation and also provided valuable feedback to the AM experts about the expectations in AM technology.

A more detailed technology information was provided in the 2-day *Comprehensive Basics Training*. The target group was engineers, who were involved in AM technology on a part-time basis and therefore needing a comprehensive background in AM technology. The training followed the problem-based learning approach by providing several workshop parts. The workshop parts focused on the identification of AM applications as part of the screening process, which is introduced in section 6.1.2, page 78. Hence, the participants discussed the learning content based on their own ideas or applications for the use of AM technology. This concept also fostered the transfer of the generated knowledge into practice. The agenda of the training started with an introduction to AM and an explanation of the most common metal-based AM processes. Then, the design of AM parts was introduced and trained on an exemplary part in a workshop setting. After discussing AM applications from different industrial domains, the participants collected their ideas for AM. On the second day, the focus was set on LPBF. The physical principle of the process, the material range, and the typical process chain were introduced. Then, the design and part identification workshop was completed by evaluating the generated ideas. The training agenda is provided in Figure 9.10.

For each training, a pilot run was executed in which comprehensive feedback from participants was requested. Based on this feedback, the content and methodical approach of the trainings was reworked to meet the expectations of the target group. In conclusion, the training program was evaluated as *very good* (see Figure 9.10), which demonstrates the suitability of trainings as appropriate measure to build and disseminate AM technology information.

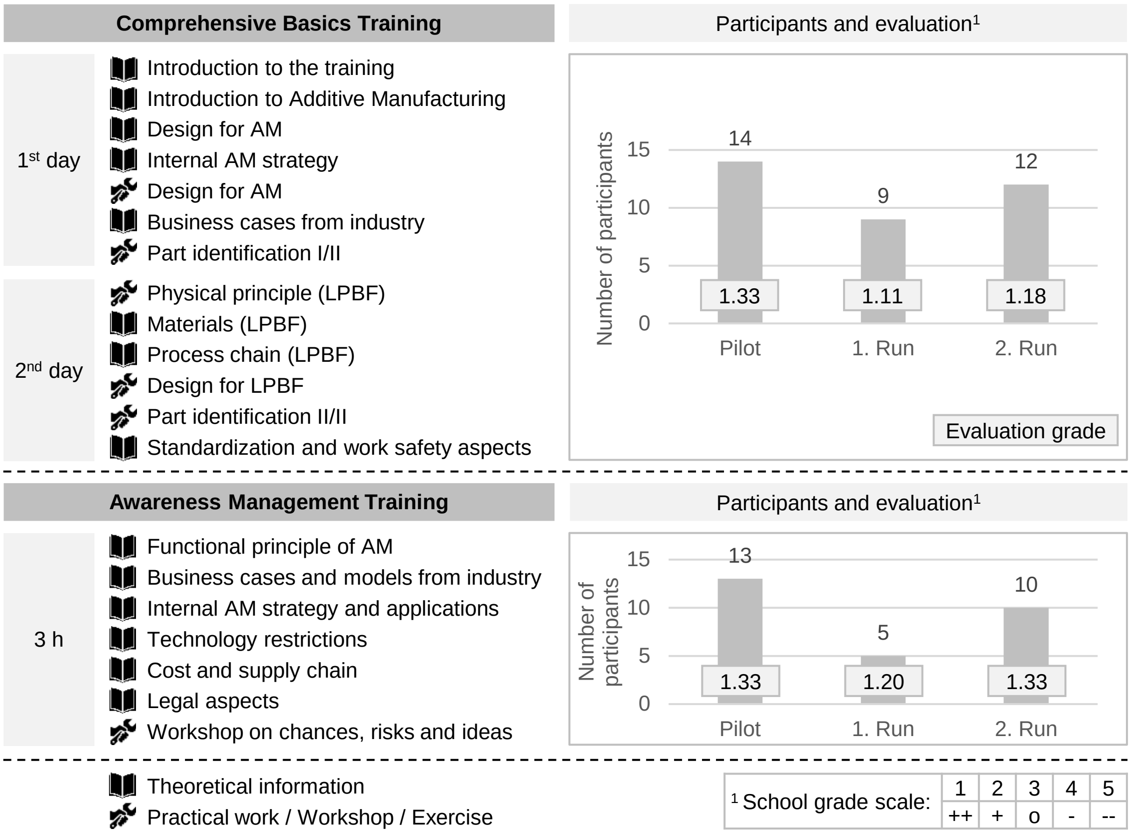


Figure 9.10: Agenda, participants and evaluation of exemplary training program.

9.4 Derivation of the *AM Technology Roadmap*

As final result the *AM Technology Roadmap* is obtained for the power engineering company. To evaluate the setup of the roadmap, the aspects considering the previously introduced AM application *injection component* are presented in detail. The excerpt of the *AM Technology Roadmap* for the application *injection component* is depicted in Figure 9.11.

Because the complete methodical approach to obtain the technology roadmap was based on the goal to match the potential of an AM technology with appropriate applications, it follows the technology push principle. Therefore, the first step in building the *AM Technology Roadmap* was to set up the planning level of *AM technology*. In the exemplary roadmap for the injection component, LPBF was the focus. Based on the information in the *Technology Fact Sheet*, the planning objects for the roadmap were derived. In the roadmap, the focus was set on current and future materials for high-temperature (HT) application. The materials overview showed that additional HT materials would be available in near future, as visualized in Figure 9.2, page 120. Moreover, it was expected that in a mid- to long-term horizon prices for these new HT materials would decrease. A decreasing price trend over time for the established Ni-base alloy In718 was stated in LANGEFELD ET AL. (2019).

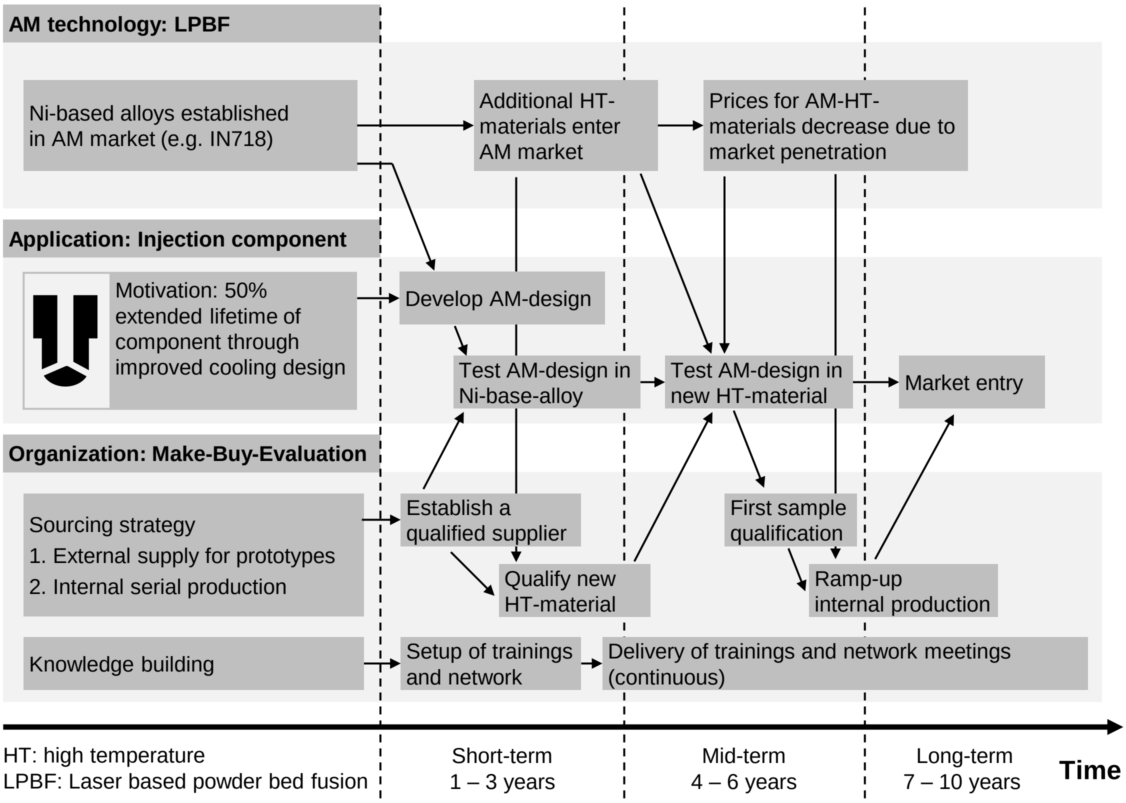


Figure 9.11: Excerpt of AM technology roadmap for the injection component.

In the planning level *Application*, the suitable AM applications (business cases) for each AM technology were visualized. The time-based planning objects were derived from the project plan, as provided in the *Application Assessment Sheet*. In addition, the prioritization of the AM business cases, which was based on the *Feasibility Index* and *Cost Factor*, is taken over from the part screening result. In the roadmap, the development steps for the injection component were indicated. First, an AM suitable design needs to be developed and tested on the basis of market-available Ni-based material In718. Because In718 did not meet all material requirements of the application, it was expected that utilizing a new emerging HT material with improved material performance would be developed in a second development step. The market entry of a serial AM component is expected on a long-term horizon.

The planning level *Organization* covered the organizational tasks to foster the change towards AM. In this planning level, the sourcing of the AM technology and the knowledge management were addressed. The planning objects were derived from the setup of the sourcing strategy and the identified knowledge building and exchange measures. In the roadmap for the injection component, the sourcing strategy of an external supply for prototypes and the ramp-up of an internal serial production was depicted. To ensure the supply of AM parts, a supplier for LPBF and In718 material needs to be selected and qualified on a short-term perspective. In the selection of the supplier, the material strategy of the supplier has to be considered because a change to another HT-material was expected in the future development of the application. Finally, a first sample qualification process has to be approved and the internal serial production is setup.

Summarizing all these aspects in the *AM Technology Roadmap* allowed for visualization of the dependency between planning objects and planning levels. Thus, it clarified which tasks to address at each planning level and time horizon. Providing a comprehensive overview of AM technologies, applications, and organizational tasks, it supported strategic decisions at the power engineering company to progress in AM.

9.5 Evaluation

The evaluation of the methodical approach to obtain a roadmap in AM technologies is built on three aspects. At first, the approach was used to investigate the AM technology potential in six manufacturing companies. Considering this industrial use cases, secondly, the requirements for the methodical approach (cf. section 3.2, page 49) are examined. As a third aspect, the economic issues of the methodical approach are discussed.

9.5.1 Application in Manufacturing Companies

The methodical approach to evaluate AM and derive strategical implications was applied in six manufacturing companies as industrial use cases. The application was executed on a project basis in the companies. The duration to apply the method ranged from 3 months to 4 years. Each company required a customized approach to integrate the specific framework conditions. Nevertheless, the motivation for the evaluation and several steps within the evaluation process were similar. Thus, the methodical approach was applied according to the company's requirements, including skipping evaluation steps or applying them only partially. An overview of the use cases and applied evaluation steps is shown in Table 9.2.

Table 9.2: Overview of industrial use cases.

	A	B	C	D	E	F
Project background						
Branch	Power engineering	Construction machinery	Mobility supplier	Mobility supplier	Drive technology	Fastener systems
Number of employees	13.500	1.500	28.000	2.800	1.000	1.400
Project focus	Business Unit	Company	Business Unit	Company	Company	Company
Duration in months	48	9	8	8	6	3
Application of methodical approach						
Action field A: Gather technology information						
Evaluated AM technologies	LPBF	LPBF MBJ WAAM	LPBF MBJ MFDM CS / LMD	LPBF	LPBF	LPBF
Formalized documentation of technology performance (*Technology Fact Sheet*)	✓	✓	(✓)	(✓)	(✓)	(✓)
Action field B: Evaluate applications						
Data-based part identification	✓	✓	✓	✕	✕	✕
Knowledge-based part identification / Workshops	✓	✓	✓	✓	✓	✓
Formalized documentation of applications (*Application Assessment Sheet*)	✓	✓	✓	✓	✓	✓
Action field C: Derive organizational tasks						
Evaluation of a make- or buy-strategy	✓	✕	✕	✓	(✓)	(✓)
Knowledge exchange / trainings	✓	(✓)	(✓)	✓	(✓)	(✓)
Derivation of AM Technology Roadmap						
Next steps for AM implementation identified (*AM Technology Roadmap*)	✓	✓	✓	✓	✓	✓

✓ = fully applied
(✓) = partially applied
✕ = not applied

LPBF: Laser-based powder bed fusion
MBJ: Metal binder jetting
MFDM: Metal Fused Deposition Modelling

WAAM: Wire Arc Additive Manufacturing
CS: Cold Spray
LMD: Laser Metal Deposition

Based on the steps of the method applied, the use cases are categorized in three groups: the full application of the method in company A, the focus on part screening for AM technologies in company B and C, and the evaluation of LPBF potential with a knowledge-based approach in company D, E and F.

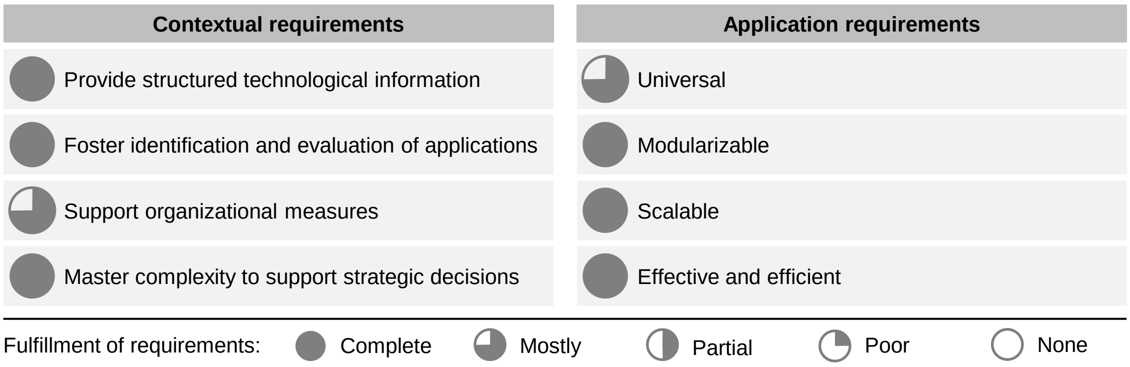
The most comprehensive approach to introduce AM technologies was undertaken in company A. The company develops and produces investment goods in the branch of power engineering. During the project duration of 48 months, the methodical approach was applied in full. For the focused business unit of the company, a comprehensive technology strategy was derived and also partially implemented (see section 9.1 to 9.4).

In company B and C, several metal-based AM technologies were evaluated. Moreover, both companies utilized the combined identification approach, consisting of data-based and knowledge-based part identification. In both companies the focus was on the part identification, whereas organizational measures were of lower priority. In particular, a make-buy strategy was not investigated. The aspect of knowledge building was integrated into the part identification workshops.

A focus to evaluate the potential of LPBF was set in companies D, E, and F. Therefore, a knowledge-based part screening approach was applied. The evaluation of organizational tasks was executed partially. Mostly, an estimated make scenario was developed, stating the AM system utilization on the basis of the company's AM applications.

9.5.2 Fulfillment of Requirements

Based on the analysis of hindrances for the adoption of AM technologies in industrial companies, the requirements for a methodical approach to overcome these hindrances were derived in section 3.2, page 49. The requirements were categorized into *contextual requirements* and *application requirements*. Based on the application of the methodical approach in six industrial use cases, the fulfillment of the requirements is evaluated. An overview of the fulfillment of the requirements is provided in Figure 9.12.



Contextual requirements	Application requirements
● Provide structured technological information	◕ Universal
● Foster identification and evaluation of applications	● Modularizable
◕ Support organizational measures	● Scalable
● Master complexity to support strategic decisions	● Effective and efficient

Fulfillment of requirements: ● Complete ◕ Mostly ◑ Partial ◔ Poor ○ None

Figure 9.12: Fulfillment of requirements.

The fulfillment of requirements is discussed in the context of the industrial use cases and the exemplary application of the evaluation steps in section 9.1 to 9.4. The contextual requirements are evaluated in the following:

- *Provide structured technology information:* A systematic structure to provide detailed information about an AM technology is provided in the *Technology Fact Sheet*. Due to the generality of the included aspects, it is suitable for different metal-based AM technologies. As exemplified for LPBF, the condensed information enables a comprehensive overview of the technology performance, derivation of key figures, and the outlook on future development.

- *Foster identification and evaluation of applications:* The identification of suitable applications is supported by a combined identification approach, based on a data-based and a knowledge-based part screening. As demonstrated in use cases A, the approach supports the identification of suitable applications. Moreover, the approach delivered meaningful results in use case B to F. To evaluate a specific application in the context of an AM technology, the *Application Assessment Sheet* is provided, consisting of the definition of development goals, a technical–economic evaluation, and the planning of the realization phase. The successful evaluation of a specific component was proved based on the exemplary AM application injection component.

- *Support organizational measures:* The change towards AM technologies in an organization is supported by a methodical approach to derive a sourcing strategy, especially to evaluate the make and buy scenario. Based on the exemplary injection component, a sourcing strategy was set up. To foster the building of knowledge, an analysis of target groups was provided, and appropriate measures for knowledge exchange were identified. The measures for building and disseminating knowledge were validated in use case A. Further aspects to support the change of the organization towards AM were not investigated, e.g. the evaluation of the suitable organizational structure within the company (decentral vs. central) or the setup of strategic partnerships, which is an appropriate option to reduce risks when investing in a new technology.

- *Master complexity to support strategic decisions:* A systematic approach to evaluate AM technologies was provided by proposing three fields of action, addressing the tasks of gathering technology information, evaluating applications, and deriving organizational tasks. Based on the results of the action fields, the *AM Technology Roadmap* is generated, visualizing the time depended connections between the planning objects. An *AM Technology Roadmap* was setup in use case A and the generation of the roadmap was demonstrated on the exemplary injection component. From the roadmap visualization, the required personnel, financial and structural resources became obvious, which was used to make strategic decisions for the further progression of AM technology in the company.

In the following, the application requirements are discussed:

- *Universal:* The universality of the method was proved by applying the method successfully in six different manufacturing companies, which were from different domains. The size of the companies in which the method was applied ranged from 1000 to 28000 employees. However, the method was not applied in companies smaller than 1000 employees, so that the applicability for smaller companies, and especially SMEs, was not validated.

- *Modularizable:* The parallel action fields of the method and final assembly of the *AM Technology Roadmap* yield a modular structure. As was seen in the industrial applications (use cases B and C), the method was also applicable partially without deriving organizational aspects and allowed for focusing on relevant evaluation steps, which was the part screening process.

- *Scalable*: The proposed evaluation steps of the method can be applied at varying levels of detail. For the identification of applications, the method was scalable through the data-based screening, which was skipped in use cases D to F. Nevertheless, the method provided a reliable result, but without the context of the product portfolio analysis from the data-based screening. Moreover, in use cases D to F, the organizational measures were investigated in less detail.

- *Effective and efficient:* The effectiveness of the method was proven by deriving the further steps of AM implementation in six industrial use cases. Moreover, an *AM Technology Roadmap* was derived for the power engineering company (use case A), which was demonstrated on the exemplary application injection component. Each substep of the method delivered a usable result for the final roadmap. Because the evaluation steps in the method were organized in action fields, it was possible to handle parallel tasks independently and prioritize them. Thus, the available capacity was focused on the most important tasks, which made the application of the method efficient.

The proposed methodical approach to derive a technology strategy in metal-based AM fulfilled all requirements, which were investigated in the context of six industrial use cases. Limitations occurred in the derivation of organizational measures and the applicability in organizations smaller than 1000 employees was not validated. In conclusion, the developed methodical approach proved a comprehensive applicability in an industrial context and delivered meaningful results to progress in metal-based AM in a producing company.

9.5.3 Economic Aspects

In the fulfillment of application requirements, it was determined that the methodical approach to obtain the technology roadmap was modular and scalable. Thus, the required resources to apply the method vary significantly.

For the discussion of economic aspects, a reference scenario was investigated. This scenario represented a project runtime of 5 to 8 months and was comparable to the industrial use cases C, D, and E. In the reference scenario, the required capacity for each action field and the derivation of the roadmap were estimated. In addition, the project lead, who is the responsible person or team to deliver the *AM Technology Roadmap*, and involved employees or supporting functional roles, which are involved in the project on request, were distinguished. To assess the economic aspect, the required capacity was transformed into cost on the basis of a fixed hourly rate. The capacity and cost of the reference scenario are depicted in Table 9.3.

In action field A, capacity was required to search for information of AM technologies and provide it as a *Technology Fact Sheet*. Because the derived measures of technology performance are fundamental for the project result, the search for information is extensive. Thus, the required capacity was estimated to be 20 working hours per AM technology. The evaluation of applications in action field B is the most important task to assess the potential of AM technologies in a company. Although the data-based approach is mainly executed by the project lead, the knowledge-based screening allocates the capacity of all involved employees. The knowledge-based screening is the most capacity-intense step in the methodical approach. In the reference scenario, one-third of the total required capacity was contributed by involved employees in the workshop setting.

Table 9.3: Reference scenario to estimate required capacity and cost.

	AM project lead	Working hours	Involved employees / supporting functions	Working hours
Action field A: Gather technology information				
Technology Fact Sheet	▪ Preparation per AM technology (4 technologies each 20 hours)	80		
Action field B: Evaluate applications				
Data-based screening	▪ Preparation ▪ Setup database ▪ Evaluation of AM technology ▪ Result preparation	50	▪ Support of IT department	20
Knowledge-based screening	▪ 1st Workshop (2 hours) ▪ Individual search for part candidates (4 hours) ▪ 2nd Workshop (3 hours) ▪ 3rd Workshop (1 hour)	90	▪ 20 employees involved in screening process (each 10 hours)	200
Action field C: Derive organizational tasks				
Sourcing strategy	▪ Setup of make and buy scenario	40	▪ Support of supply chain management department	20
Knowledge management	▪ Identification of target groups ▪ Derive measures for knowledge building and exchange	30	▪ Support of human resources, employee qualification	10
Derivation of *AM Technology Roadmap*				
Setup of roadmap	▪ Collection of results from action fields ▪ Preparation of roadmap document	60	▪ Coordination with other departments	20
Summarized working hours		350		270
Total working hours / Estimated cost (120 €/hour)				**620 hours / 74.400 €**

In action field C, the organizational changes were addressed. Based on the provided methods, the project lead prepared the organizational measures for the sourcing of AM technology and knowledge management, supported by appropriate departments of the company. The establishment of specialized trainings in AM technology was not covered by the reference scenario. Finally, the *AM Technology Roadmap* was derived from the results of all action fields. In this step, the involvement of participating departments is important because the final roadmap document is often presented to higher management levels. Thus, the project lead needs to prepare the roadmap document but must also safeguard the coordination with all participating departments.

According to the reference scenario, 620 working hours were required to obtain the *AM Technology Roadmap*. Based on an estimated hourly rate of €120/hour, the total cost to obtain the *AM Technology Roadmap* is €74.400.

10 Conclusion and Outlook

Metal-based Additive Manufacturing (AM) technologies offer potential for innovation in demanding applications through complexly shaped parts. Driven by the aerospace and medical sector, metal-based AM matured over recent years into a production technology for serial products. Thus, producing companies should investigate the potential of AM technologies for yielding process and product innovations. However, only 4% of companies have adopted a holistic strategic approach to implement AM technologies[1]. Due to the novelty and the fast development of AM technology, the main hindrances to implementation are limited availability of technology information, insufficient support to develop specific applications, and restrictions from existing organizational structures. In particular, the complexity of the implementation process in combination with a lack of internal knowledge about AM hinders the utilization of AM technology.

To unlock the innovation potential of metal-based AM for manufacturing companies and overcome the hindrances of technology implementation, a method to obtain a technology strategy for metal-based AM was developed. The technology strategy is derived and visualized as *AM Technology Roadmap*, covering the three decision levels of technologies, applications, and organization. Within the roadmap, the planning objects are clustered on a timeline, providing an overview of short-term, mid-term, and long-term potentials and tasks. The roadmap is derived from the results of three action fields.

Action field A covers the gathering of technology information. For that, appropriate information sources are identified, and the technology potential and limitations are summarized in a *Technology Fact Sheet*, covering several aspects of the AM technology and the corresponding ecosystem. In action field B, applications for the AM technology are identified and evaluated. Therefore, a combined part identification process was developed, which integrates a data-based part screening and a knowledge-based part screening in expert workshops. The evaluation of a specific application is based on the *Application Assessment Sheet*, providing methods to identify the AM benefits for the application and to execute a technical and economical evaluation. Finally, a maturity level for the specific application is obtained, and the further development process is planned. The third action field C covers the derivation of organizational tasks. In this context, the sourcing of AM technologies in an internal production facility and the external supply are evaluated

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[1] MÜLLER & KAREVSKA (2016): Report based on 900 companies from 9 branches and 12 countries.

(make-buy strategy). Moreover, the building and exchange of know-how is investigated. For that, an analysis of target groups in the organization and a training conceptualization for AM are provided.

The methodical approach was applied and evaluated in six manufacturing companies from different domains, having 1000 to 28000 employees. In this context, it supported the derivation of a technology strategy in a project setting from 3 to 48 months, which demonstrated the modular and scalable structure. Because the approach was not applied in a company with less than 1000 employees, the suitability for small and medium sized enterprises (SME) was not validated. In conclusion, the developed methodical approach proved a comprehensive applicability in an industrial context and delivered meaningful results to progress in metal-based AM in a producing company.

Based on the developed approach, further aspects of AM technology implementation can be investigated in future research. First, the capabilities of AM technology develop rapidly. Thus, the process to generate technology information could be shortened by providing comprehensive technology information in a database or report. Moreover, new emerging AM technologies need to be integrated. Second, the applicability in SMEs should be proved to support the implementation of AM technology in SMEs, which often have only limited capacity to identify new technologies. Third, it should be investigated whether the approach can be extended to other AM technologies. While the approach is focused on metal-based AM, it is assumed that comparable processes can be developed for all AM technologies, utilized to process polymers, composites, ceramics and further materials. Such a future approach could generate a holistic AM technology strategy covering all AM technologies and materials.

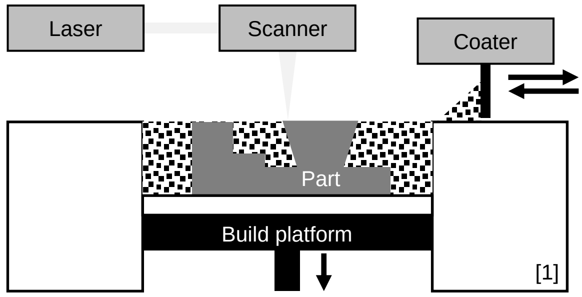
Appendix

A: Screening Parameter for Data-based Part Identification

Screening parameter		Relevance for AM technology evaluation
Mandatory screening parameter		
Material number / part ID		Unique identification number of the dataset
Mass		Mass of the application; check if mass suits the AM technology; volume or dimension are also suitable, but mostly not stated within the database
Material or material specification		Matching with available AM materials; ideally the material is provided as standardized material number, if not a matching of material specification and material number is required
Cost / mass-based cost		Internal manufacturing cost; due to the availability of mass and cost information, a mass-based cost indicator is used
Optional screening parameter		
Actuality of the dataset		Activity state in the database; alternative information source e.g. last movement of component in store, last order date, last update of the dataset
Part properties	Volume	Check if the volume corresponds to available build chamber sizes of AM systems
	Dimensions / bounding box	Check if the dimension corresponds to available build chamber sizes of AM systems
	Categorization	Using one or more categories provided by the origin database (e.g. material classes in PDM system)
	Parts per assembly	Amount of subordinate parts within an assembly group; The function of subordinate parts may be integrated in a monolithic design for AM.
	Certification	Indication if a part needs a certification; Additive Manufacturing must be approved by the certifying body, what may cause additional efforts
	Validation process	Internal or external validation obligatory, when part or production process changes (e.g. approval by test in test rig, field test)
Production	Conventional manufacturing process	Main production technology of the part, e.g. casting, forging, sheet metal forming, cutting; Evaluation of AM may focus on part clusters based on conventional production technology
	Annual volume	Production or sales volume per year
	Lead time	Lead time of the current process chain
	Production lot size	Batch size of a production lot
	Steps in manufacturing process	Long manufacturing process chain may profit from replacement of manufacturing steps by AM
	State of production	Prototype, serial, end of production, end of service
Supply chain	Supply chain configuration	In-house production (make) or external supply (buy)
	ABC / XYZ category	Turnover and predictability of spare parts
	Order decoupling point	Part is delivered from stock or produced on customer request; capital in stock may be reduced by a more flexible (AM) process chain
	Supplier unavailable	Former supplier of the component is no longer on the market
	Mold or tooling unavailable	A necessary mold or tool is no longer available; reproduction needs prior invest in tooling

B: Technology Fact Sheet "Laser-based Powder Bed Fusion"

<table>
<tr><td>Technology Fact Sheet</td><td>Page 1 – Technology overview
AM Technology: LPBF</td><td>Date: 05/2020
Version: V1</td></tr>
<tr><td colspan="2">Laser-based Powder Bed Fusion (abbrev. LPBF)

Layer wise generation of a part by using a laser beam to melt metallic powder locally in an inert gas atmosphere.
 </td><td>Classification according to ISO/ASTM 52900:
☐ Binder Jetting
☐ Directed Energy Deposition
☐ Material Extrusion
☐ Material Jetting
☒ Powder Bed Fusion
☐ Sheet Lamination
☐ Vat Photopolymerization
☐ Classification undefined</td></tr>
</table>

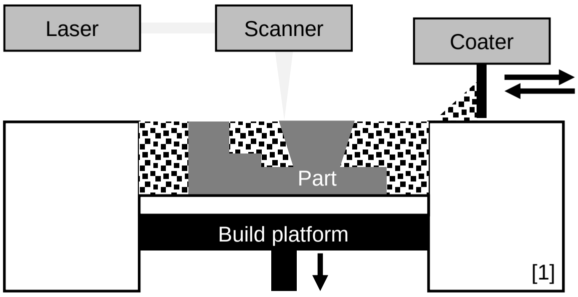
Technology key figures

	Page			Unit	Value
Materials overview	2	Number of materials	market available	-	Total: 49 Ni-alloys: 8
			under development	-	Ni-alloys: 11
Material properties	3	Available for the following materials		-	2.4668
Machine equipment	4	Build volume	10%-percentile, corresponding cubic dimension	mm	93
			90%-percentile, corresponding cubic dimension	mm	404
Process chain	5	Classification according to ISO / ASTM 52900		-	☒ **Single step process** ☐ Multi step process
Reference applications	6	Part mass	10%-percentile	kg	0.047
			90%-percentile	kg	1.229
Cost	7	Cost indicator (Average / min / max)		€/kg	2.4668: 1074 / 441 / 4036
Technology maturity	8	MRL level (1-10)		-	9 - 10

Technology Fact Sheet	**Page 1.1 – Technology overview** **AM Technology: LPBF**	**Date: 05/2020** **Version: V1**

Laser-based Powder Bed Fusion (abbrev. LPBF)

Layer wise generation of a part by using a laser beam to melt metallic powder locally in an inert gas atmosphere.



Classification according to ISO/ASTM 52900:

☐ Binder Jetting
☐ Directed Energy Deposition
☐ Material Extrusion
☐ Material Jetting
☒ **Powder Bed Fusion**
☐ Sheet Lamination
☐ Vat Photopolymerization
☐ Classification undefined

Technology development

Near (1-3 years)	▪ **Market:** Market growth in total is still strong, but decreases compared to previous years. Global AM market ~1% of the manufacturing market, market volume of ~$24 billion in 2022 [47]. Centralization to larger manufacturing units and large suppliers with several systems is expected, due the overhead cost of LPBF. ▪ **AM systems:** New system features (e.g. heating over 500 °C, green laser source) enter the market and become available through AM contract manufacturer. [46] ▪ **Materials:** New AM system features foster the development of materials, which will enter the market. Few materials, which are currently in the market entry phase, will become widespread available. The most production volume is still generated by the five most established materials (1.2709, 1.4404, 2.4668, 2.4856, 3.2381). ▪ **Cost of AM:** Cost for AM materials in the market entry phase will drop significantly due to a competitive environment of many suppliers. Cost of established materials will just slightly decrease due to scale effects [47]. Cost limit with current system architecture is ~500 €/kg for 2.4668 (In718).
Mid (4-6 years)	▪ **Market:** Market growth rates will further decrease. A market consolidation is expected, because large companies try to stabilize their supply chain by acquisition activities. [47] ▪ **AM systems:** Hybrid manufacturing approaches and multi-material-technology will become available in serial AM systems. [46] ▪ **Materials:** 15-20 fully established AM materials expected. Most of them are already available today, but at limited availability. Materials, which are under development today, become available through suppliers (market entry). Material properties can be locally adjusted within the part through part-based parameter optimization and process simulation [47]. ▪ **Cost of AM:** New AM-Processes or system configurations may show an AM-process with significant cost reduction at the same quality as LPBF. Raising knowledge about the creation of high-value products based on AM technology in the organizations.
Long (> 7 years)	▪ **Market:** Established size, continuously growing at single digit rates. Potential of 5% of the global manufacturing market (~$640 billion) [47]. ▪ **AM systems:** Highly automated digital and hardware process chains. [46] ▪ **Materials:** AM-tailored materials are available on the market and exceed established material properties. The manufacturing process is well-understood and material properties cover local requirements in the part with a reliability for serial production. Multi-material LPBF processes are available. ▪ **Cost of AM:** Further decrease of cost by scale effects, due to raising market volume. Large batch production of AM raw materials.

Technology Fact Sheet	**Page 2.1 – Materials overview: Market available[1]** **AM Technology: LPBF**				**Date: 05/2020** **Version: V1**		
Categorization			AM material				
Density	Melting temperature	Base alloy	Alloy composition	Material number	Material name	Number of suppliers	Ref.
Light metals ($\delta < 5$ kg/dm^3)	--	Al	AlSi9Cu3	3.2163		3	[22]
			AlSi7Mg0.6	3.2371	EN AC-42200	2	[2, 17]
			ALSi10Mg	3.2381	EN AC-43000	14	[23]
			AlSi12	3.2582	EN AC-44300	2	[2, 20]
			AlMgSi0.5	3.3206	EN AW-6060	1	[14]
			AlMgSc		Scalmalloy	4	[24]
		Ti	Ti	3.7024 / 3.7025	Grade 1	1	[2]
			Ti	3.7034 / 3.7035	Grade 2	4	[36]
			TiAl6V4	3.7164 / 3.7165	Ti Grade 5	9	[37]
			TiAl6V4 ELI	3.7164 / 3.7165	Ti Grade 23	9	[38]
			Ti6Al2Zr1Mo1V		TA15	2	[8, 17]
Heavy metals ($\delta > 5$ kg/dm^3)	Low melting ($T_S < 1000$ °C)	Zn	ZnAl4Cu1		Zamak 5	1	[14]
	High melting (1000 °C < T_S < 2000 °C)	Cu	CuNi2SiCr	2.0855		4	[26]
			CuSn10	CC480K	Bronze 90/10	4	[27]
			Cu		Cu-ETP	2	[14]
			CuZn		Brass	1	[14]
		Ni	Ni36	1.3912	Alloy 36 / Invar	2	[17,19]
			NiCr22Fe18Mo	2.4665	Alloy HX	6	[33]
			NiCrFeNbMo	2.4668	IN718	18	[34]
			NiCrWMoAlTi	2.4733	Haynes 230	1	[12]
			NiCr22Mo9Nb	2.4856	IN625	12	[35]
			NiCr17Al7Ti7Co9W3Mo2Ta2		IN738	1	[12]
			NiCr20Co10Mo9		Haynes 282	1	[19]
			NiCr22Co19Ti4W2Al2Ta1.5		IN939	1	[17]
		Co	CoNiCrW	2.4683	Alloy 188	1	[12]
			CoCr28Mo6 / CoCr29Mo6	2.4979	CoCr-0404	4	[25]
			CoCr25Mo5W5		Melidoy S-Co	1	[20]
			CoCr		CoCr F75	2	[2, 7]
			CoCrMo			2	[8, 17]
			CoCrMoW			1	[8]
			CoCrW			1	[14]
			CoNiCrWTa		Mar-M-509	1	[12]
		Fe	X37CrMoV5-1	1.2343	H11	2	[12,19]
			X40CrMoV5-1	1.2344	H13	3	[28]
			X3NiCoMoTi 18-9-5	1.2709		17	[29]
			XCrNi12-9	1.4003	CX	2	[7, 14]
			X46Cr13	1.4034		1	[8]
			X17CrNi16-2	1.4057		1	[4]
			X2CrNiMo17-12-2	1.4404	316L	15	[30]
			X4CrNiCuNb16-4	1.4540	PH1	2	[7, 14]
			X5CrNiCuNb16-4	1.4542	17-4PH	9	[31]
			X5CrNiCu15-5	1.4545	15-5PH	3	[32]
			X15CrNiSi20-12	1.4828		1	[19]
			X22CrMoV12-1	1.4923		1	[16]
	Precious metals	Ag	Ag 925/1000			2	[5, 20]
		Au	18K White Gold			1	[5]
			18K Yellow Gold			1	[5]
			18K Rose Gold			1	[5]
		Pt	950 Pt/Ru			1	[5]
1. Market available: Data retrieved from service provider or AM system manufacturer							

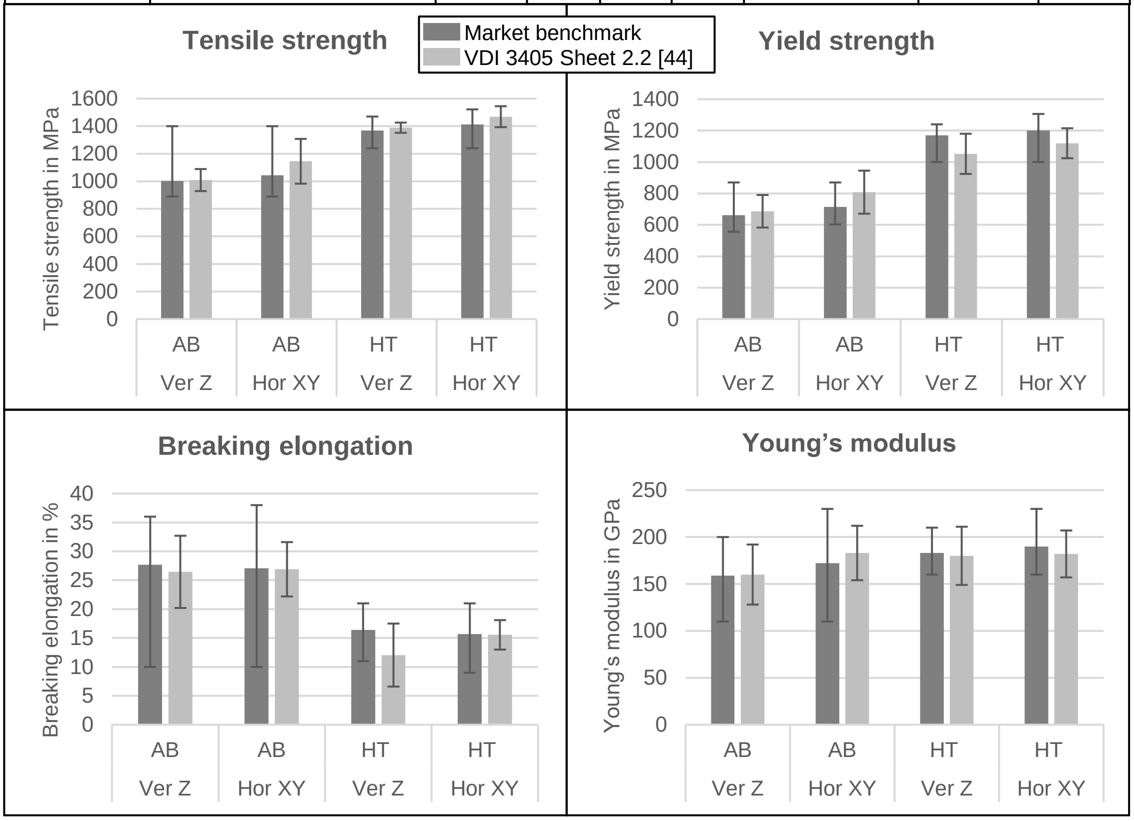
Technology Fact Sheet	**Page 2.2 – Materials overview: Under development[1]** **AM Technology: LPBF of Ni-base alloys**	**Date: 05/2020** **Version: V1**

Categorization			AM material			
Density	Melting temperature	Base alloy	Alloy composition	Material number	Material name	Ref.
Light metals ($\delta < 5$ kg/dm^3)	--	Al				
		Ti				
Heavy metals ($\delta > 5$ kg/dm^3)	Low melting ($T_S < 1000$ °C)	Zn				
	High melting (1000 °C $< T_S <$ 2000 °C)	Cu				
		Ni	Ni15.5Co9.5Mo8Al4.3Ti3.6		C1023	[40]
			NiCo9.7Cr6.5Ta6.5W6.4AlReTi		CMSX-4	[41]
			NiCo9.6Cr6.5Ta6.5W6.4Al5.6Re3		CMSX486	[40]
			NiCo15Cr10TiAlMo		IN100	[41]
			NiCr12.5Al6.2Mo4.3Nb2.1Fe1TiCB		IN713C / K418	[42]
			NiCr16Co8.3Al3.5Ti3.3W2.6		IN738 LC	[40]
			NiW9.3Co9.1Cr8Al5.7		MAR-M247	[40]
			NiW9.3Co9.1Cr8Al5.7		MAR-M247 LC	[40]
			NiCr19.5Co19.2Mo6Ti2.4AlFeSiCu		Nimonic 263	[43]
			NiCr14Co8Mo3.5W3.5Nb3.5Al3.5		René 80	[40]
			NiCo8Cr7.1Ta7Al6WReMo		René N5	[41]
		Co				
		Fe				
	Very high melting ($T_S > 2000$ °C)	W				
	Precious metals	Ag				
		Au				
		Pt				

[1] Under development: Data retrieved from announcements of service provider / AM system manufacturer or scientific sources.

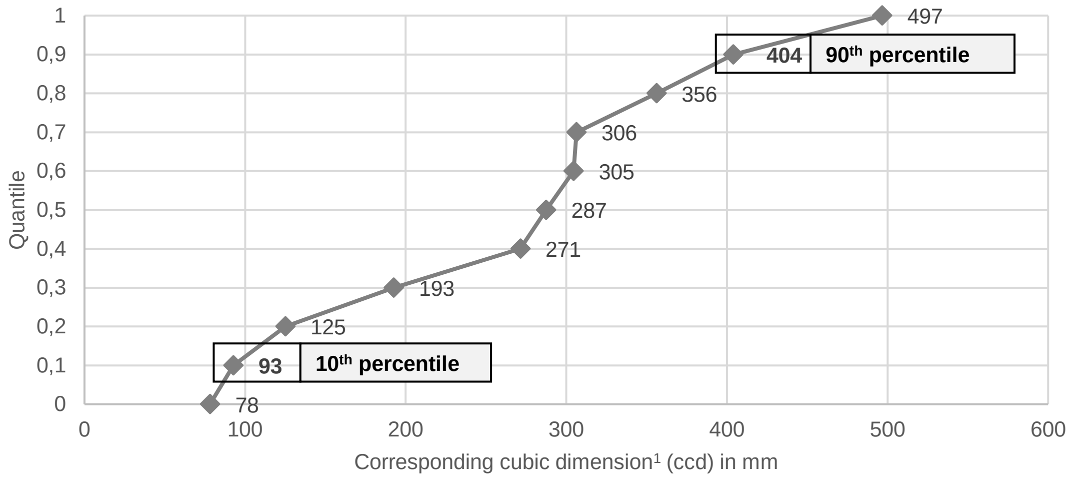
Technology Fact Sheet	**Page 3 – Material properties: 2.4668** **AM Technology: LPBF of In718 (2.4668)**	**Date: 05/2020** **Version: V1**

Material		**2.4668 (Inconel 718)**						
Parameter		Unit	Value	Deviation		Specification	Number of datasets	Ref.
				Min	Max	AB: As built HT: Heat treated Z: Vertical XY: Horizontal		
Geometry properties	Resolution	µm	50	40	60			[9]
	Surface roughness (Ra)	Ra, µm	7	5	9	shot blasted		[9]
	(Rz)		9	7	11	Z, shot blasted		[20]
		Rz, µm	36	28	44	shot blasted		[9]
			38	25	51	shot blasted		[44]
			72	52	91	AB		[44]
Static material properties	Tensile strength	MPa	1002	890	1400	Z, AB	21	
			1043	890	1400	XY, AB	20	
			1369	1240	1470	Z, HT	21	
			1413	1240	1522	XY, HT	17	
	Yield strength	MPa	662	556	870	Z, AB	20	
			715	603	870	XY, AB	17	
			1170	1000	1240	Z, HT	19	
			1200	1000	1306	XY, HT	16	
	Breaking elongation	%	27.7	10	36	Z, AB	20	
			27.1	10	38	XY, AB	19	
			16.4	11	21	Z, HT	18	
			15.7	9	21	XY, HT	17	
	Young's modulus	GPa	159	110	200	Z, AB	14	
			172	110	230	XY, AB	15	
			183	160	210	Z, HT	11	
			190	160	230	XY, HT	10	
	Surface hardness	HV10	293	290	296	AB		[9]
		HRC	32	28	36	AB		[20]
			29	24	33	HT		[20]



Technology Fact Sheet	**Page 4 – Machine equipment** **AM Technology: LPBF**	**Date: 05/2020** **Version: V1**

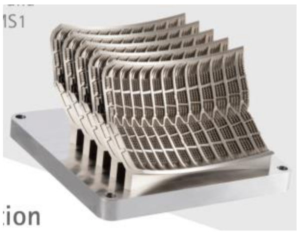
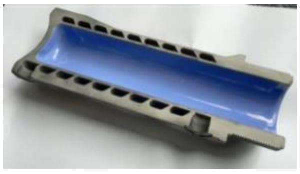
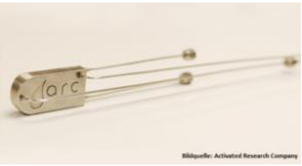
System provider	System name	Build chamber	
		Shape	Dimension (X Y Z) in mm³
3D Systems	DMP Flex 100	Cubic	100x100x80
3D Systems	DMP ProX 200	Cubic	140x140x100
3D Systems	DMP ProX 300	Cubic	250x250x300
3D Systems	DMP ProX 320	Cubic	275x275x380
Additive Industries	MetalFAB1	Cubic	420x420x400
DMG Mori	LASERTEC 12 SLM	Cubic	125x125x300
DMG Mori	LASERTEC 30 SLM	Cubic	300x300x300
EOS	Precious M 080	Cylinder	D80x95
EOS	EOS M 100	Cylinder	D100x95
EOS	EOS M 290	Cubic	250x250x325
EOS	EOS M 300-4	Cubic	300x300x400
EOS	EOS M 400	Cubic	400x400x400
EOS	EOS M 400-4	Cubic	400x400x400
Farsoon Technologies	FS121M	Cubic	120x120x100
Farsoon Technologies	FS271M	Cubic	275x275x340
Farsoon Technologies	FS301M	Cubic	305x305x400
Farsoon Technologies	FS421M	Cubic	425x425x420
GE Additive	Concept Laser M2 Series 5	Cubic	245x245x350
Renishaw	AM 400	Cubic	250x250x300
Renishaw	RenAM 500 Serie	Cubic	250x250x350
SLM Solutions	SLM 125	Cubic	125x125x125
SLM Solutions	SLM 280	Cubic	280x280x365
SLM Solutions	SLM 500	Cubic	500x280x365
SLM Solutions	SLM 800	Cubic	500x280x875
Trumpf	TruPrint 1000	Cylinder	D100x100
Trumpf	TruPrint 2000	Cylinder	D200x200
Trumpf	TruPrint 3000	Cylinder	D300x400
Trumpf	TruPrint 5000	Cylinder	D300x400



1. Corresponding cubic dimension represents the edge length of a cube with the same volume: ccd = $\sqrt[3]{V_{Build\ chamber}}$

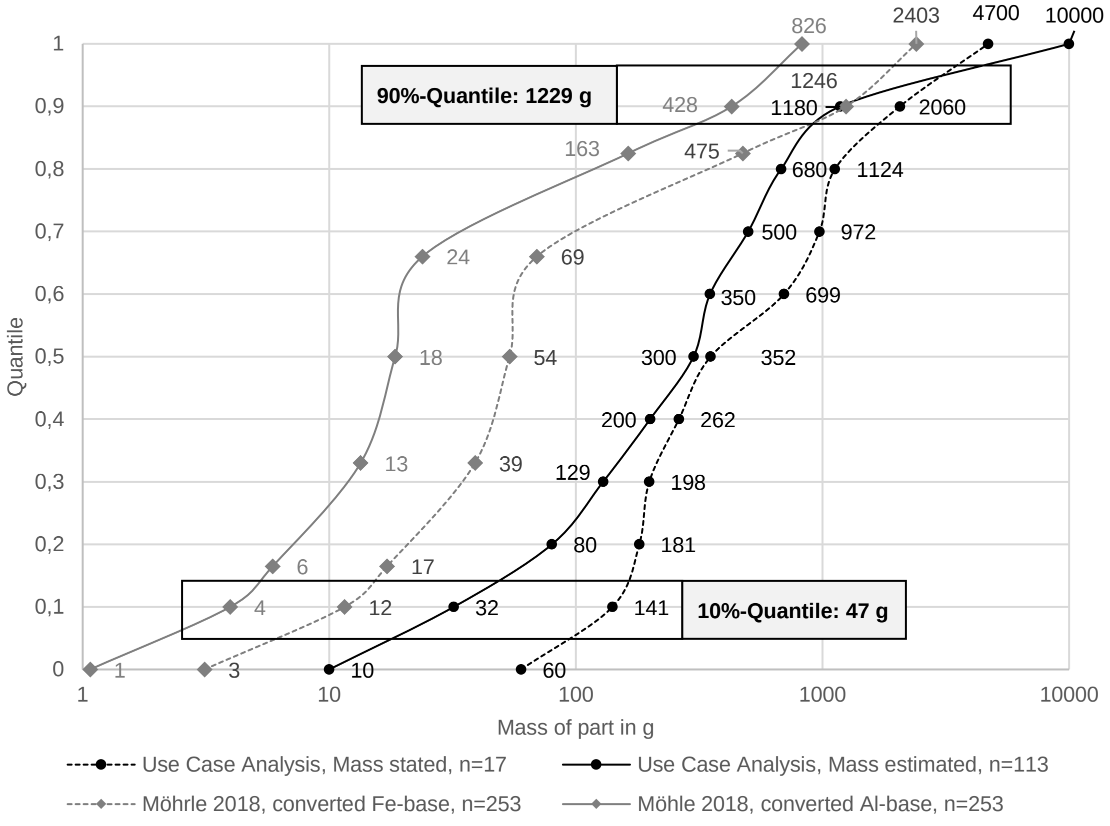
Technology Fact Sheet	**Page 5 – Process chain** **AM Technology: LPBF**	**Date: 05/2020** **Version: V1**

Generalized process steps in AM process chain (VDI 3405)		Mandatory process steps in AM process chain
Pre-process	▪ All necessary operations before the parts can be fabricated in the additive manufacturing system ▪ Data processing ▪ Preparing auxiliary structures ▪ Arranging parts in build space ▪ Generating layer or tool path data ▪ Preparation of the AM manufacturing system	Data collection / creation ☒ Creation of a 3D-model ☐ …
		AM related data preparation ☒ Design of auxiliary structures (e.g. supports) ☐ No nesting: one piece flow ☒ Planar nesting of parts in the build space (X- and Y-direction) ☐ Volume-based nesting of parts in the build space (X-, Y- and Z-direction) ☒ Apply material specific production parameter ☐ Apply part specific production parameter ☒ Generation of a layer-based toolpath ☐ Generation of a feature-based 3-dimensional toolpath ☐ …
In-process	▪ All manufacturing operations performed by the AM manufacturing system ▪ Part loading and unloading	Execution of build process
Post-process	▪ All operations after the part has been removed from the AM system to produce the technologically feasible component characteristics	Removing of parts and over material from build job ☒ Removing of loose powder from build job ☐ Removing of coherent powder from build job ☒ Separation of parts from build plate ☒ Removing of auxiliary structures (e.g. supports) ☐ …
		Material property adoption by heat treatment ☐ Burning/Washing out of auxiliary materials ☐ Sintering ☒ Stress-relief annealing ☐ Hot isostatic pressing (HIP) ☐ Hardening ☐ …
		Geometry finalization ☒ Machining of functional surfaces (e.g. fits, threads, tolerances) ☐ …
		Surface property finalization ☒ Blasting / shot peening ☐ Chemical process (e.g. etching) ☐ Electro-chemical process ☐ Mechanical process (e.g. flow grinding, barrel finishing, polishing) ☐ Coating process ☐ …

Technology Fact Sheet	**Page 6.1 – Reference applications** **AM Technology: LPBF**	**Date: 05/2020** **Version: V1**
	Application name	Hinge of engine hood
	Branch & Company	Automotive; EDAG Engineering, Voestalpine, Simufact
	AM benefits	Lightweight design (50% mass reduction)
	Material	Metal
	Part dimension	< 400x400x400 mm³
	Art mass	600 g (estimated)
	Application type	☐ Serial application ☒ Prototype
	Application name	Mold segment for tires
	Branch & Company	Automotive; EOS
	AM benefits	Complex design only producible by AM
	Material	Steel
	Part dimension	< 400x400x400 mm³
	Part mass	500 g (estimated)
	Application type	☒ Serial application ☐ Prototype
	Application name	Piston
	Branch & Company	Automotive; HardMarque Future Factories, Altair
	AM benefits	Lightweight design, Topology optimization
	Material	Titanium
	Part dimension	< 100x100x100 mm³
	Part mass	300 g (estimated)
	Application type	☒ Serial application ☐ Prototype
	Application name	Reactor vessel
	Branch & Company	Industrial application; Thaltec GmbH, Jurec
	AM benefits	Cooling channels, Thin walls
	Material	Steel
	Part dimension (bounding box) in mm³	D80 x 300 mm³
	Part mass	4.7 kg
	Application type	☐ Serial application ☒ Prototype
 Bildquelle: Activated Research Company	Application name	Polyarc™-Micro reactor
	Branch & Company	Industrial application; Activated Research Company, Protolabs (Industry)
	AM benefits	Very small and complex design
	Material	Stainless steel
	Part dimension	< 50x50x50 mm³
	Part mass	100 g (estimated)
	Application type	☒ Serial application ☐ Prototype
	Application name	Burner for surface treatment of glas
	Branch & Company	Industrial application; Linde, EOS (Industry)
	AM benefits	Complex channel system with integrated cooling, Lattice structures, Part integration (15 → 1)
	Material	Steel
	Part dimension (bounding box) in mm³	< 150x150x150 mm³
	Part mass	300 g (estimated)
	Application type	☒ Serial application ☐ Prototype

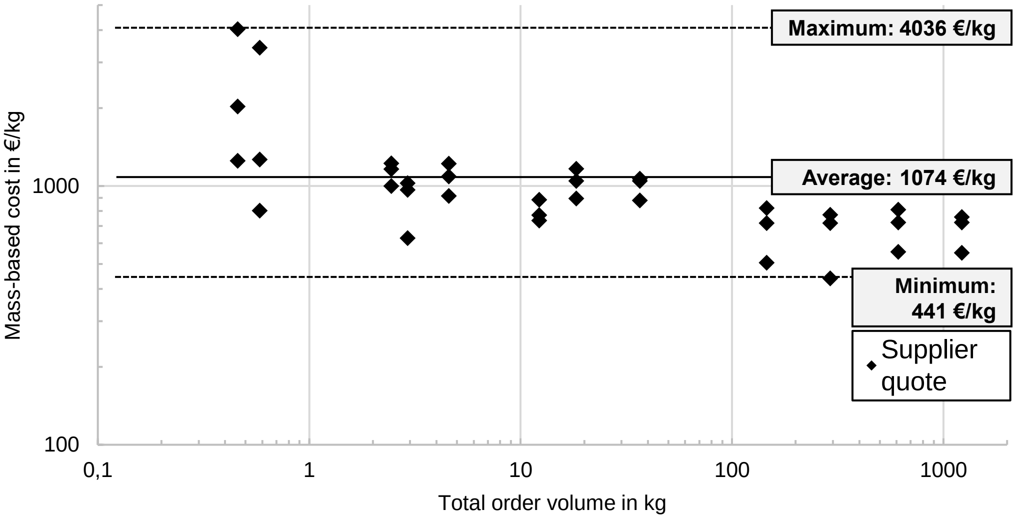
Technology Fact Sheet	**Page 6.2 – Reference applications** **AM Technology: LPBF**	**Date: 05/2020** **Version: V1**
	Application name	Antenna holder
	Branch & Company	Aerospace: Thales Alenia Space, Poly-Shape
	AM benefits	Lightweight design
	Material	Aluminum
	Part dimension	447x205x391 mm³
	Part mass in kg	1.13 kg
	Application type	☐ Serial application ☒ Prototype
	Application name	Antenna holder
	Branch & Company	Aerospace; Thales Alenia Space, Poly-Shape
	AM benefits	Lightweight design
	Material	Titanium
	Part dimension	189x230x288 mm³
	Part mass	500 g (estimated)
	Application type	☒ Serial application ☐ Prototype
	Application name	Hydraulic block
	Branch & Company	Aerospace; Liebherr, EOS
	AM benefits	Lightweight design, flow optimization, part integration
	Material	Titanium
	Part dimension	< 200x200x200 mm³
	Part mass	900 g (estimated)
	Application type	☒ Serial application ☐ Prototype
	Application name	Scull implant
	Branch & Company	Medical; GE Additive
	AM benefits	Individualization
	Material	Titanium
	Part dimension	< 200x200x200 mm³
	Part mass	200 g (estimated)
	Application type	☐ Serial application ☒ Prototype
	Application name	Spine implant
	Branch & Company	Medical; K2M, 3D Systems
	AM benefits	Lattice structure
	Material	Titanium
	Part dimension	< 50x50x50 mm³
	Part mass	80 g (estimated)
	Application type	☒ Serial application ☐ Prototype
	Application name	Hip joint implant
	Branch & Company	Medical; Stryker
	AM benefits	Lattice structure,
	Material	Titanium
	Part dimension	< 100x100x100 mm³
	Part mass	150 g (estimated)
	Application type	☒ Serial application ☐ Prototype

Technology Fact Sheet	**Page 6.3 – Reference applications** **AM Technology: LPBF**	**Date: 05/2020** **Version: V1**
	Application name	Bicycle frame
	Branch & Company	Lifestyle; Empire, Renishaw, Altair
	AM benefits	Lightweight design, Integrated connectors
	Material	Aluminum
	Part dimension (bounding box) in mm³	< 300x300x300 mm³
	Part mass in kg	1.4 kg
	Application type	☒ Serial application ☐ Prototype
	Application name	Jewelry
	Branch & Company	Lifestyle; ConceptLaser
	AM benefits	Individualization
	Material	Precious metals
	Part dimension (bounding box) in mm³	30x20x5 mm³
	Part mass	10 g (estimated)
	Application type	☒ Serial application ☐ Prototype
	Application name	Cutting body
	Branch & Company	Tooling; Sandvik Coromant
	AM benefits	Lightweight design, Imprved productivity
	Material	Titanium
	Part dimension (bounding box) in mm³	D50x50 mm³
	Part mass	150 g (estimated)
	Application type	☒ Serial application ☐ Prototype



Technology Fact Sheet	**Page 7 – Cost estimation** **AM Technology: LPBF of In718 (2.4668)**	**Date: 05/2020** **Version: V1**

Material number	Amount of parts	Mass per part	Total order volume	Cost per part	Total cost of order	Cost indicator[1]	Type of source			Ref / Remarks
							Analytical cost model	Literature review	Supplier quotes	
	-	kg	kg	€	€	€/kg				
2.4668			0,46			4036,16	☐	☐	☒	
			0,46			2028,99				
			0,46			1252,52				
			0,58			3425,06				
			0,58			1267,27				
			0,58			804,41				
			2,45			1225,46				
			2,45			1000,79				
			2,45			1163,16				
			2,92			1027,52				
			2,92			965,87				
			2,92			629,32				
			4,58			1090,86				
			4,58			1221,76				
			4,58			916,75				
			12,24			735,27				
			12,24			886,41				
			12,24			772,93				
			18,33			1047,22				
			18,33			1167,22				
			18,33			896,25				
			36,67			1047,22				
			36,67			1069,04				
			36,67			879,45				
			145,98			719,26				
			145,98			822,01				
			145,98			505,95				
			291,97			719,26				
			291,97			774,06				
			291,97			440,57				
			612,02			723,02				
			612,02			810,44				
			612,02			556,44				
			1224,03			723,02				
			1224,03			759,78				
			1224,03			552,97				



Technology Fact Sheet	**Page 8 – Technology Maturity Level MRL** **AM Technology: LPBF**	**Date: 05/2020** **Version: V1**

Section in Technology Fact Sheet	**Early development phase**	**Beginning of market introduction**	**Full serial production**
	MRL 1 – 5	**MRL 6 – 8**	**MRL 9 – 10**
Materials overview	☐ Only materials under development	☐ Market available materials, but not from service providers	☒ Material data from service providers is available
Machine equipment	☐ No AM system provider is on the market; Only principles and prototype systems are known	☐ At least one AM system provider is on the market with a serial AM system	☒ More than one AM system provider is on the market
Reference applications	☐ Reference applications in industry could not be identified	☐ Only prototypes for industrial applications are identified; no serial use documented	☒ Serial applications are identified
Cost estimation	☐ Cost information could not be obtained	☐ Cost models and literature references about cost are available	☒ At least two service providers on the market; Cost benchmarking possible
Assessment of MRL for AM technology	☐ **MRL 1 – 5**	☐ **MRL 6 – 8**	☒ **MRL 9 – 10**
			☐ Checkbox blank ☒ Checkbox marked

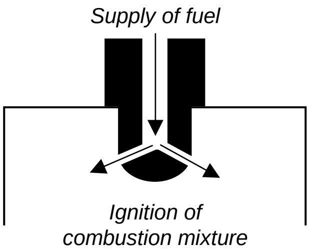
Technology Fact Sheet	**References**	**Date: 05/2020** **Version: V1**

[1]	Based on VDI 3405
[2]	3D Systems; https://www.3dsystems.com/materials/metal; Last Access: 03.05.20
[3]	Additive Industries; https://www.additiveindustries.com/systems/materials; Last Access: 03.05.20
[4]	Bosch; Flyer „3D-Druckzentrum“; 02/2020
[5]	Cookson Gold; https://www.cooksongold-am.com/products-services/powders/; Last Access: 03.05.20
[6]	DMG Mori; https://shop.dmgmori.com/b2b/de/DMQP/AM-Pulver/c/AMPowder; Last Access: 03.05.20
[7]	EOS GmbH; https://www.eos.info/werkstoffe-m ; Last Access: 03.05.20
[8]	Farsoon Technologies; http://en.farsoon.com; Last Access: 03.05.20
[9]	FIT AG; https://fit.technology/materialien.php; Last Access: 03.05.20
[10]	GKN Powder Metallurgy; https://www.gknpm.com/en/our-businesses/gkn-additive/download-archive/; Last Access: 03.05.20
[11]	Material Solutions (Siemens); http://materialssolutions.co.uk/; Last Access: 03.05.20
[12]	Oerlikon AM; https://www.oerlikon.com/am/de/was-wir-bieten/am-metallelpulver/; Last Access: 03.05.20
[13]	Prima Additive; https://www.primaadditive.com/; Last Access: 03.05.20
[14]	Protiq; https://www.protiq.com/3d-druck/materialien/metall/; Last Access: 03.05.20
[15]	Renishaw; https://www.renishaw.de/de/datenblaetter-additive-fertigung--17862; Last Access: 03.05.20
[16]	Rosswag; https://rosswag-engineering.de/metallpulver-3d-druck; Last Access: 03.05.20
[17]	SLM Solutions; https://www.slm-solutions.com/de/produkte/zubehoer-verbrauchsmaterialien/slmr-metallpulver/; Last Access: 03.05.20
[18]	Thyssenkrupp; https://www.thyssenkrupp-additive-manufacturing.com/de/materialien; Last Access: 03.05.20
[19]	Toolcraft; https://www.toolcraft.de/dimensionen/metall-laserschmelzen.html; Last Access: 03.05.20
[20]	Trumpf; https://www.trumpf.com/de_DE/produkte/maschinen-systeme/additive-fertigungssysteme/truservices-pulver/ ; Last Access: 03.05.20
[21]	Velo3D; https://www.velo3d.com/; Last Access: 03.05.20
[22]	14, 17, 20
[23]	2, 4, 6, 7, 8, 9, 13, 14, 15, 16, 17, 18, 19, 20
[24]	6, 9, 18, 19
[25]	12, 15, 17, 20
[26]	9, 14, 17, 20
[27]	8, 13, 17, 20
[28]	10, 12, 17
[29]	2, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
[30]	2, 4, 6, 7, 8, 9, 12, 13, 14, 15, 16, 17, 18, 19, 20
[31]	2, 4, 7, 8, 9, 12, 13, 17, 20
[32]	8, 12, 17
[33]	7, 8, 9, 12, 17, 20
[34]	2, 3, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21
[35]	2, 6, 7, 8, 9, 12, 13, 14, 15, 17, 19, 20
[36]	7, 9, 17, 20
[37]	2, 6, 7, 8, 9, 13, 14, 16, 18
[38]	2, 6, 7, 14, 15, 17, 19, 20, 21
[40]	Summarized in Schlick 2017
[41]	Basak 2017
[42]	Chen et al. 2018
[43]	Graybill et al. 2018
[44]	VDI 3405 Sheet 2.2
[45]	Möhrle 2018
[46]	Schleifenbaum et al. 2019
[47]	Wohler's Report 2019

C: Application Assessment Sheet "Injection Component"

Application Assessment Sheet	**Page 1 – Application overview** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

Note: Commercially sensitive data has been obscured and financial values have been changed.

Functional principle / sketch / description *Supply of a specific mass of fuel with a predefined pressure in the burning chamber. Requirements for the component arise from chemical, abrasive and temperature load. The component is a wear part, which lifetime is critical to the overall function of the engine.* 	Part dimension (LxBxH)	***60 x 60 x 140 mm³***
	Part mass	*< 0.35 kg*
	Cost or target cost	*[available]*
	Quantity per year	*< 5000*
	Number of variants	*None*
	Lead time	*Not relevant; delivery from stock*
Material / material requirements *Withstand chemical, mechanical abrasive and temperature cyclic loads with minimum wear*		
Idea for improvements through AM *Extended lifetime of the component by AM-customized materials and/or improved cooling behavior.*		

Application Assessment

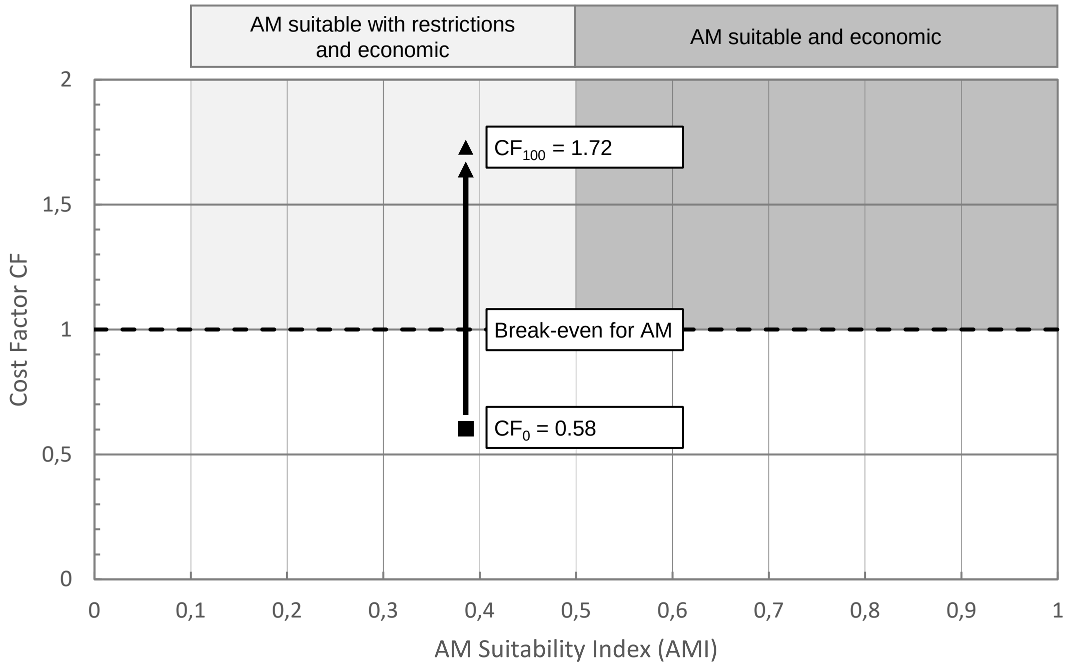
Evaluated AM technology	***Laser-based powder bed fusion LPBF of In718***

Quantified development goals for the application (→ page 3)	
1	*50% extended lifetime of component through advanced cooling design*
2	--
3	--

Technical evaluation **1. Section: AM technology (→ page 4)**	AM highly suitable (2 points)	AM suitable with restrictions (1 points)	AM not suitable / Major hindrances (0 points)
Dimension	☒	☐	☐
Similarity analysis	☒	☐	☐
Mass of application	☒	☐	☐
Material availability	☐	☒	☐
Material properties	☐	☒	☐
MRL level of AM technology	☒	☐	☐
2. Section: Process chain (→ page 5)			
Pre-process: 3D-Model	☐	☒	☐
Post-Process: Manual efforts	☐	☒	☐
Post-Process: Finalize material properties	☒	☐	☐
Post-Process: Finalize geometry	☐	☒	☐
Post-Process: Finalize surface properties	☒	☐	☐
→ **AM Suitability Index (AMI)** Formula: $m_1 * (s_1 + s_2) / 44$	*1 * (10+7) / 44 =* ***0.386***		

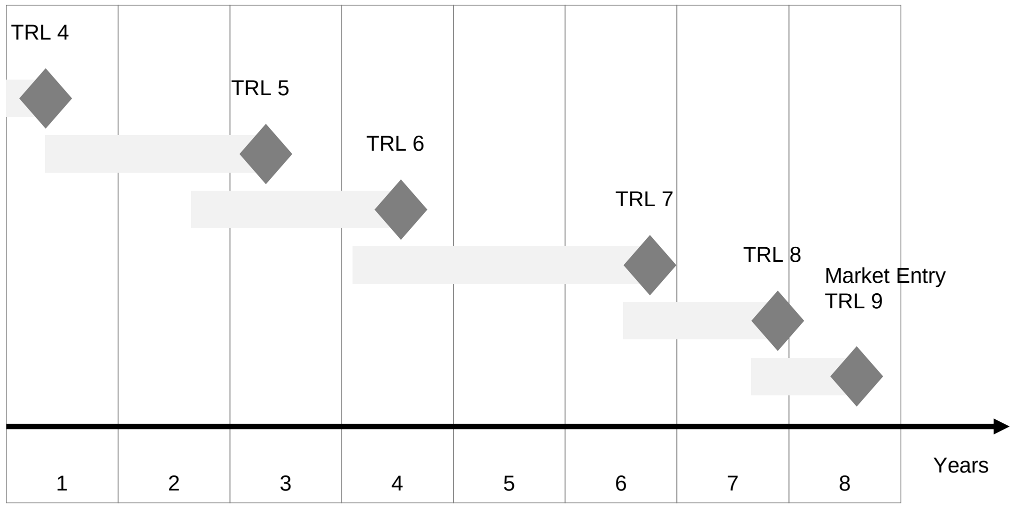
Application Assessment Sheet	**Page 2 – Application overview** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

Economic evaluation (→ page 6 & 7)		
Cost factor, when AM benefits are not utilized	CF_0 (■)	*0.58*
Cost factor, when AM benefits are fully utilized	CF_{100} (▲)	*1.72*
Condition for break-even of AM technology (optional)	$CF_{BE} = 1$	*Break-Even for AM technology at lifetime enhancement of 18.4%.*



Planning of realization phase (→ page 8 & 9)	
Current TRL level of AM application	*3*

Project plan



Application Assessment Sheet	**Page 3 – AM benefits and development goals** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

Definition of development goals

		Enabler		Objective
		AM technology inherent properties	Technical possibilities	AM benefit utilization
Product	Geometry	☒ Monolithic design ☒ Freeform surfaces ☒ Undercuts ☐ Gaps between volumes	☒ Complexly shaped structures and cavities, e.g. cooling channels ☐ Mesoscopic structures (regular, irregular, graded), e.g. thin walls, lattices, honeycombs, foams ☐ Movable objects , e.g. joints, limb objects, nets ☐ Bionic and simulation-driven designs, e.g. topology optimization	Optimized functionality in… ☐ Mechanics: Lightweight design, static and dynamic structural strength, damping ☒ Thermodynamics: Insulation, Energy absorption, heat transfer, energy conversion and transport ☐ Fluid dynamics: Streamline optimization, Pressure losses ☒ Lifetime: Wear resistance, reliability ☐ Aesthetics / Optical appearance / Ergonomics ☐ Individualization / Customization
	Material	☒ Unique AM material properties ☐ Material combination (graded and discrete) ☒ Local adjustment of material properties ☐ Local adjustment of surface textures	☐ Porous structures ☒ Surface textures ☐ Material properties optimization	
Product life cycle	Manufacturing process	☐ Building on existing structures / conventional parts ☐ Integration of components within AM process	☒ Less interfaces in assembly, e.g. fewer but more complex parts ☐ Less production or assembly steps ☐ Material efficiency ☐ Reduced machining volumes ☐ No invest in tools if part geometry changes ☐ Product identification by hidden marks or component integration ☐ Tools and manufacturing aids by AM	Improvements in… ☐ Development phase → Time to product / to market, digitalization of product, enables continuous innovation ☐ Production process → Flexibility, lead time, manufacturing cost ☐ Logistics → Decentralized production ☒ Use phase → Operating cost, resource consumption, emissions ☐ Services → Repair, maintenance, protection against plagiarism ☐ Recycling
	Digital process chain	☐ Each produced part can be individual ☐ Manufacturing directly from digital part representation ☐ Transmit and provide digital data	☐ Reproduction from 3-d-scanning ☐ Customer as designer ☐ Decentralized production ☐ Production-on-demand / digital warehouse ☐ Trade barrier bypassing	
				☐ Checkbox blank ☒ Checkbox marked

Quantified development goals for the AM application	
1	*50% extended lifetime of component through advanced cooling design*
2	--
3	--

Application Assessment Sheet	**Page 4 – Technical evaluation – AM technology** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

Technical evaluation of AM technology	AM suitability		
	AM suitable (2 points)	AM suitable with restrictions (1 points)	AM not suitable (0 points)
Dimension	☒ Application fits build volume of available AM systems (up to 90th percentile)	☐ Application fits build volume of available AM systems (exceeds 90th percentile) ☐ Fit of application in build chamber is expected after redesign for AM: Expected dimension after redesign: ____________	☐ Application exceeds available build spaces
Similarity analysis	☒ Serial parts with comparable dimensions are known	☐ Demonstrator parts with comparable dimensions are known	☐ Parts of the intended dimensions are unknown
Mass	☒ Application matches the established mass range (10th to 90th percentile)	☐ Application matches the established mass range (out of 10th to 90th percentile) ☐ Match of established mass range is expected after redesign. Expected mass: ____________	☐ Application exceeds the established mass range
Material availability	☐ Material is market available	☐ Material is under development ☒ Another available AM material suits the material requirements. Alternative AM material choice: *In718 / 2.4668*	☐ Material non-processable or unknown in AM technology
Material properties	☐ Required material properties are known or easy to access (e.g. tensile strength, surface hardness)	☒ Required material properties must be investigated for the application (e.g. fatigue behavior, wear resistance)	☐ AM material insufficient for required material properties
MRL level of AM technology	☒ MRL 9 – 10	☐ MRL 6 – 8	☐ MRL 1 – 5
Minimum point score in all criteria (m_1)	1		
Sum of points (s_1)	10		

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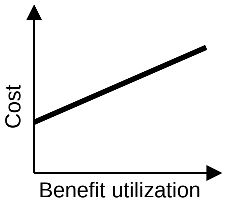
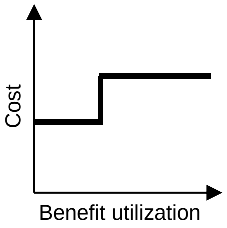
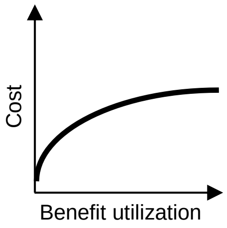
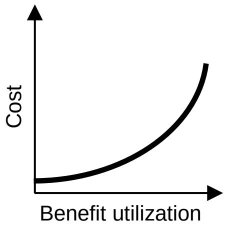
Application Assessment Sheet	**Page 5 – Technical evaluation – Process chain** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

Technical evaluation of AM process chain	AM process chain suitability		
	AM process chain suitable (2 points)	AM process chain suitable with restrictions (1 points)	AM process chain cause major hindrances (0 points)
Pre-processing: 3D-Model	☐ 3D-model is available and printable with AM technology	☒ 3D-model is available but must be optimized for AM technology ☐ Generation of a 3D model is already planned (e.g. in a development project)	☐ 3D-model is not available; The model must be created (e.g. based on available drawings or hardware parts) and optimized for AM
Post-processing: Manual efforts; Removing of support	☐ Parts need little or no manual work to remove support ☐ Processing steps are automated	☒ Parts need manual work to remove supports; Good accessibility of supported facets	☐ Extensive manual work is necessary; Accessibility of surfaces with support is limited
Post-processing: Finalize material properties	☐ Material properties in as-build condition are sufficient ☒ Basic heat treatment is sufficient (e.g. stress-relief annealing); Material properties after heat treatment are available from multiple independent sources (e.g. material data sheets)	☐ Adoption of material properties by heat treatment necessary; Material properties after heat treatment process are available from few suppliers and/or described in scientific sources (e.g. hardening of AM materials)	☐ Unclear if necessary material properties can be obtained by heat treatment; The required process is not fully described in literature; Heat treatment process must be customized for the application
Post-processing: Finalize geometry	☐ Resolution and accuracy of AM process are sufficient for final part	☒ Few easy accessible facets need to be machined (e.g. threads, fits, tolerances); clamping position is clear and standardized fixtures are appropriate	☐ Machining of AM part is complex (e.g. multiple undercuts need to be machined, fragile load-optimized structure); specialized clamping features or aids are necessary
Post-processing Finalize surface properties	☐ Surface roughness in as-build condition sufficient ☐ Slight reworking of surface necessary (e.g. blasting process) ☒ Surface specifications do only apply to surface facets that are machined	☐ Surface specifications require separate process steps; Surface specifications are met by batch-wise working processes (e.g. trowalization, barrel finishing)	☐ Demanding surface specifications and high geometrical tolerances apply to the same surface facets; Surfaces are complexly shaped and require freeform finishing processes (e.g. electro-chemical processes, manual polishing)
Sum of points (s_2)	7		
			☐ Checkbox blank ☒ Checkbox marked

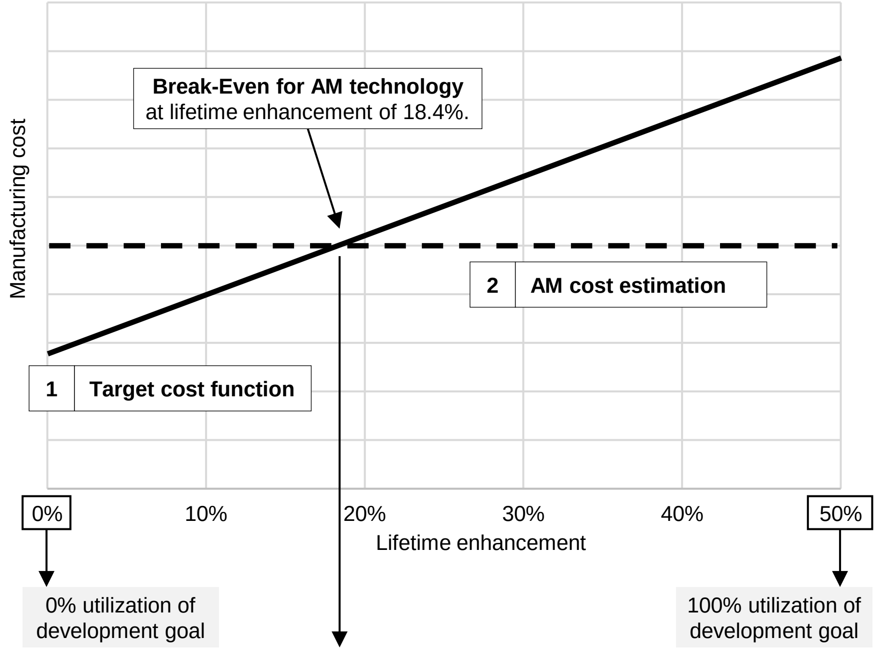
Application Assessment Sheet	**Page 6 – Economical evaluation** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

1. Definition of target cost function	
	**Linear function** → Appropriate to model target cost over lifetime extension Description: The linkage of benefit and cost is linear. Each incremental benefit utilization allows to raise the cost. Example: Lightweight design in aerospace industry allows to raise production cost at 500 – 1000 € per kg reduced mass.
	**Jump function** Description: The linkage of benefit and cost is discrete. A specific level of benefit utilization is required to effect the cost. Example: Lightweight design of a gear. When reaching a specific level of mass reduction a smaller and cheaper power unit can be used. The saved cost from the smaller power unit add up to the cost for the lightweight gear.
	**Logarithmic function** Description: The linkage of benefit and cost is degressiv. Whereas an improvement has a strong influence on the cost in the beginning, the impact reduces for further improvements. Example: Improvement of wear behavior. Because wear is a non-linear process, a small improvement in wear resistance can cause significant cost advantages.
	**Exponential function** Description: The linkage of benefit and cost is exponential. Whereas a slight improvement has only little impact on the cost, further benefit utilization allows increasing cost. Example: Individualized products. For a product with more degrees of individualization higher cost can be realized.

2. Cost estimation for AM application	
	1. Cost for AM blank part from *Technology Fact Sheet*: *Annual production volume: 5000 * 0.35 kg = 1750 kg* *Cost indicator from Technology Fact Sheet: 441 €/kg, 1074 €/kg* *0.35 kg * 441 €/kg = 154.35 €* *0.35 kg * 1074 €/kg = 375.90 €* 2. Derivation of additional cost for finalized assembly group (additional parts, assembly process) → **Result: Cost estimation for additively manufactured injection component.**

Application Assessment Sheet	**Page 7 – Economical evaluation** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

3. Derivation of cost factors and break-even point



3	**Cost factors**	$CF_0 = 0.58$	$CF_{BE} = 1$	$CF_{100} = 1.72$

Application Assessment Sheet	**Page 8 – Technology Readiness Level TRL** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**

Technology readiness level TRL (DIN ISO 16290)		Adaption to AM application	Terms to be defined for specific AM application
1	Basic principles observed and reported	☒ Idea for AM application proposed (e.g. 1st section of Application Assessment Sheet)	
2	Technology concept and/or application formulated	☒ Idea for AM application refined ☒ Development goal and AM benefits analyzed ☒ Suitable AM process identified ☒ First draft of AM design	
3	Analytical and experimental critical function and/or characteristic proof-of-concept	☒ Development goals quantified ☒ Conceptualization of the AM application ☒ Suitability of AM technology approved by a non-functional manufacturing prototype ☒ Estimation of the performance by analytical models and supporting laboratory tests	Analytical models: *Simulation of cooling impact and combustion process* Supporting laboratory test: *Test rig with spray test*
4	Component functional verification in laboratory environment	☒ Development goals quantified ☒ Conceptualization of the AM application ☒ Plan for functional testing established ☐ Functional prototype tested in a laboratory environment	Laboratory environment: *1-cylinder test rig with combustion process*
5	Component critical function verification in a relevant environment	☐ Definition of performance requirements ☐ Identification and analysis of critical functions ☐ Verification of the functional prototype in a relevant environment for the target application	Critical functions: *Lifetime / Wear of component* Relevant environment: *Testbed engine*
6	Model demonstrating the critical functions of the element in a relevant environment	☐ Functional prototype demonstrating the critical functions in a relevant environment	
7	Model demonstrating the element performance for the operational environment	☐ Use of the AM application in the final environment as beta version	Final environment: *Engine in field / at customer site*
8	Actual system completed and accepted for flight (flight qualified)	☐ AM application has completed all required tests and qualifications ☐ AM application is ready for market introduction	Required test and qualifications: *Long-term field testing on test engine*
9	Actual system “flight proven” through successful mission operations	☐ AM application successful established in the market delivering the intended performance	

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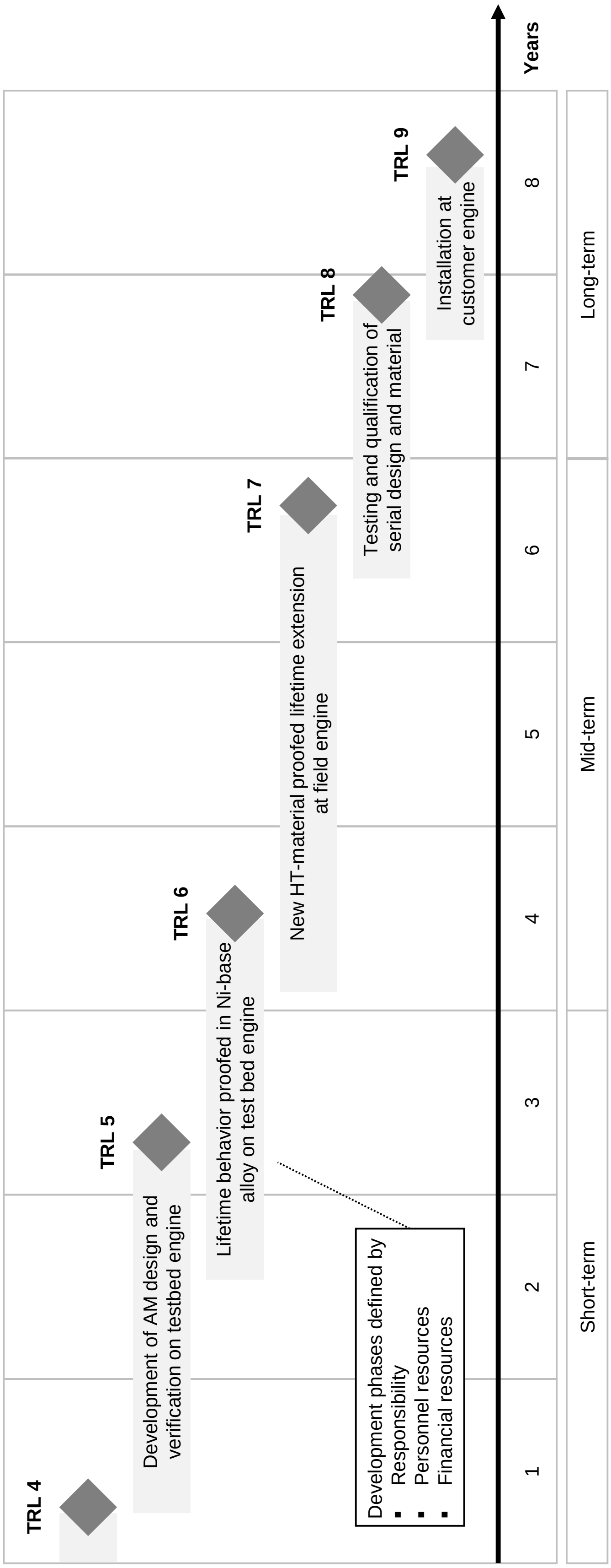
Application Assessment Sheet	**Page 9 – Project plan** **Application name and ID: Injection component, P_001**	**Date: 05/2020** **Version: V1**



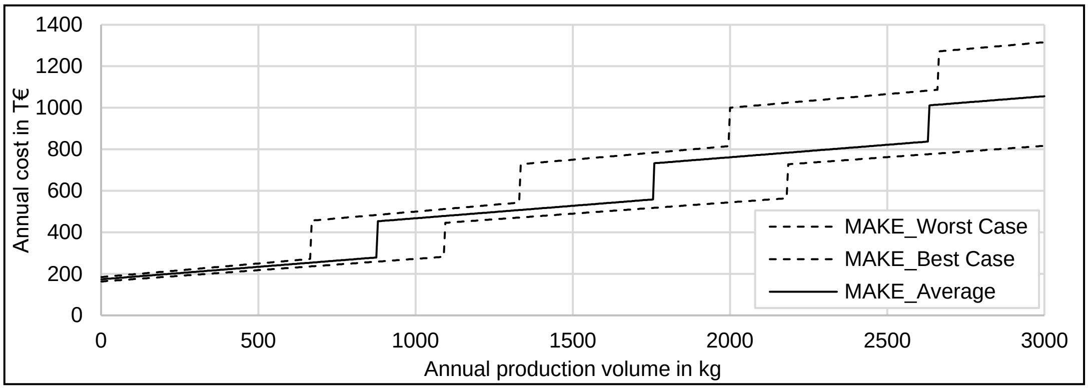
D: Make-buy Strategy and Cost Model

	Make scenario	Rating	**Buy scenario**
Current state analysis			
Production and supply scenario	☐ Production integration ☐ Capacity enlargement ☐ Material diversification ☐ Capacity enlargement and material diversification ☒ Technology implementation		☐ Supply chain integration ☐ Material diversification ☒ Supply chain extension ☐ Supply chain generation
Cost benchmark			
Annual production volume *1750 kg*	Average cost for make scenario: *319 €* *(295 – 447 €)*	☒ ☐ ☐ ☐ ☐	Average cost for buy scenario: *598 €* *(461 – 735 €)*
Strategic aspects			
Technology portfolio	▪ Homogeneous portfolio of AM technologies among the intended applications	☒ ☐ ☐ ☐ ☐	▪ Heterogeneous portfolio of AM technologies among the intended applications
Material portfolio	▪ Homogeneous portfolio of materials among the intended applications ▪ Materials belong to the same material group and can be processed on a single AM system	☒ ☐ ☐ ☐ ☐	▪ Heterogeneous portfolio of materials among the intended applications ▪ Processing of materials need multiple AM systems (material changes not feasible)
Production volume / Risk of AM system utilization	▪ Annual production volume needs several AM systems ▪ Constant production volume available (base load) ▪ Outlook for production volume indicates comparable applications / development tasks clear and scheduled	☒ ☐ ☐ ☐ ☐	▪ Annual production volume is significantly less than annual machine capacity ▪ High volatility in production volume ▪ Outlook for production volume is uncertain, high risks in the development projects
AM process know-how	▪ Comprehensive know-how necessary to fully utilize AM potential in the product (process optimization, process parameters)	☐ ☐ ☐ ☒ ☐	▪ Established and market available know-how sufficient to exploit AM potential
AM market development	▪ Current state of AM systems sufficient to exploit AM benefits for applications	☒ ☐ ☐ ☐ ☐	▪ Applications require newest AM technology on the market (e.g. type of energy source, heating)
Supplier availability / Sourcing risk	▪ No or very few supplier on the market → Risk of single-sourcing with high dependency from supplier	☐ ☐ ☐ ☐ ☒	▪ Several suppliers on the market for AM technology and material → Multi-sourcing strategy applicable (benchmarking, price negotiations)
Relevance of AM applications	▪ AM applications cover core functions of the product	☐ ☒ ☐ ☐ ☐	▪ AM applications do not cover core functions of the product
Strategic framework	▪ Technology strategy of technological leadership ▪ Constant invest in new technologies	☐ ☐ ☒ ☐ ☐	▪ Technology strategy of cost leadership ▪ As little capital lock-up as possible
Production depth	▪ High production depth in the organization	☒ ☐ ☐ ☐ ☐	▪ Low production depth in the organization
Confidentiality	▪ Necessity to keep design and/or process data strictly internal ▪ Insecure process chain with supplier	☐ ☐ ☒ ☐ ☐	▪ Long and trustable relationship to supplier, comprehensive supplier contracts → Low risk for outsourcing
Summary	**Make scenario in favor**	☐ ☒ ☐ ☐ ☐	**Buy scenario in favor**

Calculation Make Scenario

The cost calculation evaluates Laser-based powder bed fusion (LPBF) for In718 / 2.4668.

	Unit	Formula	Best-Case	Worst-Case	Reference / Remark
Fixed costs					
One-time invest					
AM production systems incl. peripheral systems	T€	f1	707,00	707,00	Reference price for SLM 280 twin (Date of quote: 10.01.20)
Infrastructure	T€	f2	20,00	20,00	Assumption for cabin without ventilation system; Invest up to 1 Mio€ for production system with hall-in-hall concept
Annual costs					
Maintenance of AM systems, peripheral systems and infrastructure	T€	f3	35,35	56,56	Assumptions: 5% and 8% of system price
Fixed labor cost	T€	f4	24,00	24,00	20% of process engineer; salary 120 T€
Space requirement	T€	f5	1,50	1,50	Space requirement 15 m²; Rent 100 €/m²
Variable costs					
Raw material	€/kg	v1	84,50	91,00	Auxiliary calculation 1.)
Consumables	€/kg	v2	2,54	4,17	Auxiliary calculation 1.)
Working time	€/kg	v3=30%*80T€/r5	22,00	36,07	30% machine operator; salary 80 T€
Output of AM production system					
Productive time per year	hours	pt	3750,00	3750,00	2 shift system
System build rate	kg/h	r	0,29	0,18	Auxiliary calculation 2.)
Model assumptions					
Depreciation time AM system	years	a1	7,00	7,00	Assumption
Depreciation time infrastructure	years	a2	15,00	15,00	Assumption
Interim Results					
Cost for infrastructure	T€	r1=f2/a2	1,33	1,33	
Cost per AM system	T€	r2=f1/a2+f3+f4+f5	161,85	183,06	
Results					
Fixed cost per AM system and year	T€	r3=r1+r2	**163,18**	**184,39**	
Variable cost	€/kg	r4=v1+v2+v3	**109,05**	**131,24**	
Production volume per AM system and year	kg	r5=pt*r	**1090,83**	**665,43**	



1. Auxiliary calculation: Variable cost

	Unit	Formula	Best-Case	Worst-Case	Reference / Remark
Raw material					
Purchase price	€/kg		65,00	70,00	Supplier quotes
Factor for powder losses	%	a3	30,00	30,00	Assumption
Raw material cost	**€/kg**		**84,50**	**91,00**	
Consumables					
Reference build job					Assumption
Pre-heating	h	t1	0,25		
Build time	h	t2	10,00		
Part removel	h	t3	0,75		
Production mass	kg	pm=r*t2	2,91	1,77	
Electric energy					
Consumption Pre-heating	W	ce1	2182,00		Lutter-Günther et al. 2018; Mid-size system
Consumption Build	W	ce2	2614,00		Lutter-Günther et al. 2018; Mid-size system
Consumption Part removal	W	ce3	827,00		Lutter-Günther et al. 2018; Mid-size system
Total energy consumption	kWh	ce4=t1*ce1+t2*ce2+t3*ce3	27,31		
Energy cost	€/kWh	ce5	0,17		Assumption
Energy cost	€/kg	ce6=ce4*ce5/pm	1,60	2,62	
Shield gas					
Consumption Pre-heating	m³/h	ce7	1,40		Lutter-Günther et al. 2018; Mid-size system
Consumption Build	m³/h	ce8	0,08		Lutter-Günther et al. 2018; Mid-size system
Consumption Part removal	m³/h	ce9	0,00		Lutter-Günther et al. 2018; Mid-size system
Total shiel gas consumption	m³	ce10=t1*ce7+t2*ce8+t3*ce9	1,15		
Shield gas cost	€/m³	ce11	2,40		for Argon
Shield gas cost	€/kg	ce12=ce11*ce10/pm	0,95	1,56	
Total cost for consumables	**€/kg**	ce13=ce6+ce12	**2,54**	**4,17**	

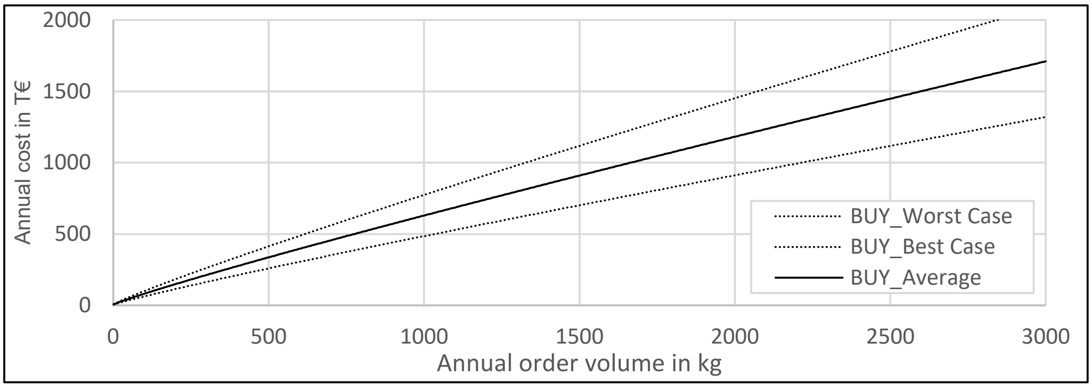
2. Auxiliary calculation: Build rate

	Unit	Formula	Best-Case	Worst-Case	Reference / Remark
Input values					
Exposure build rate	cm³/h	r_exp	25,92		SLM data sheet; Layer thickness 60 µm; for each laser source
Material density	g/cm³	rho	8,15		
AM system utilization					
Utilization rate of 2nd laser	%	ur	70,00	60,00	depended on product portfolio
Share of auxiliary times	%	s1	10,00	25,00	depended on product portfolio
Share of coating time during build	%	s2	10,00	30,00	depended on product portfolio
Exposure build rate, single laser	g/h	r_exp1=r_exp*rho	211,25		
Exposure build rate, both lasers	g/h	r_exp2=r_exp*rho*(1+ur)	359,12	338,00	
Process build rate	g/h	r_pro=r_exp2*(1-s2)	323,21	236,60	

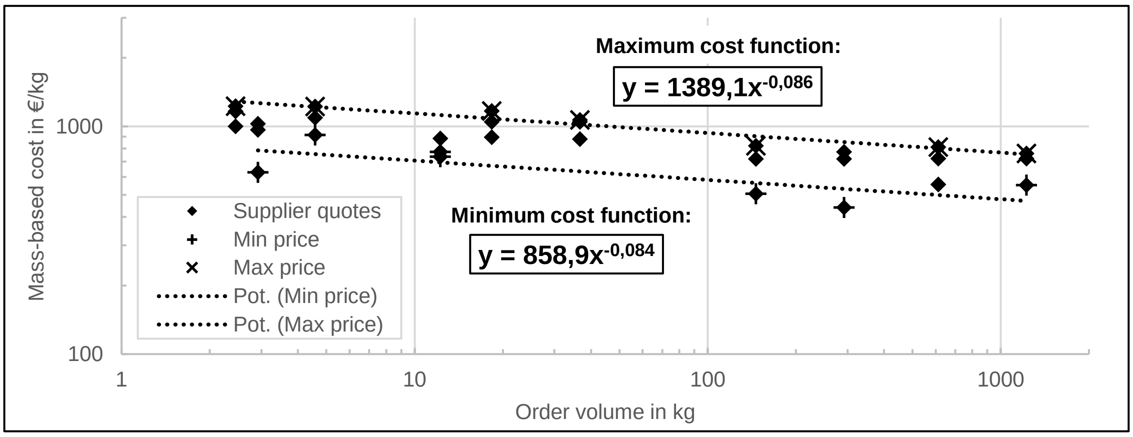
Calculation Buy Scenario

The cost calculation evaluates Laser-based powder bed fusion (LPBF) for In718 / 2.4668.

			Unit	Formula	Best-Case	Worst-Case	Reference / Remark
Fixed costs							
	One-time invest						
		Supplier selection and qualification	T€	f1	10,00	15,00	Assumption
		First sample qualification process	T€	f2			
		Material qualification process	T€	f3			
	Annual costs						
		Maintenance of supply chain (e.g. audits)	T€	f4	3,00	5,00	Assumption
Variable costs							
		Order volume	€/kg		$858{,}9x^{-0{,}084}$	$1389{,}1x^{-0{,}086}$	derived from quotes; Auxiliary calculation 3.)
Output of supply chain							
		Delivered volume	kg				
Model assumptions							
		"Depreciation time" for fixed costs	years	a1	7,00	7,00	Assumption
Results							
		Fixed cost per year	T€	r3= (f1+f2+f3)/a1+f4	**4,43**	**7,14**	
		Variable cost	€/kg		**$858{,}9x^{-0{,}084}$**	**$1389{,}1x^{-0{,}086}$**	



3. Auxiliary calculation: Variable cost for buy-option



E: List of Publications

Publications of the author are listed as Schneck, M. and Illgner, M.
OrcidID 0000-0002-1721-297X

Peer-reviewed publications:

- Schneck, M.; Horn, M.; Schmitt, M.; Seidel, C.; Schlick, G.; Reinhart, G.: Review on Additive Hybrid- and Multi-Material-Manufacturing of Metals by Powder Bed Fusion – State of Technology and Development Potential. Progress in Additive Manufacturing (2021).
  DOI: 10.1007/s40964-021-00205-2
- Schneck, M.; Schmitt, M.; Schlick, G.: Supply Chain and Cost Evaluation for Additive Manufacturing. Proceedings of the IEEE International Conference on Nanomaterials: Applications & Properties (NAP-2020). IEEE Xplore (2021). DOI 10.1109/NAP51477.2020.9309677
- Schneck, M.; Schmitt, M.; Schlick, G.; Reinhart, G.: Validated Cost Prediction for Additive Manufacturing – Combination of a Model Based Approach with an Empirical Study (2020). In: Müller, B. (Ed.): Fraunhofer Direct Digital Manufacturing Conference DDMC 2020, Fraunhofer Verlag, 2020, ISBN 978-3-8396-1521-8.
- Schneck, M.; Gollnau, M.; Lutter-Günther, M.; Haller, B.; Schlick, G.; Lakomiec, M.; Reinhart, G.: Evaluating the Use of Additive Manufacturing in Industry Applications. Procedia CIRP 81 (2019), S. 19-23.
  DOI 10.1016/j.procir.2019.03.004
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Publications without peer-review and conference speeches:

- Trechow, P.: Additive Fertigung im Großmotorenbau – ein Projekt. MaschienMarkt, 9/10 2020, ISSN 0341-5775, p. 58 – 59. Participation as interviewee.
- Schneck, M.: Training in Additive Manufacturing – How to Implement AM in your Company. formnext conference, Frankfurt, Germany, 19.11.2019.
- Schneck, M.: Gezielter Wissensaufbau zu AM im Unternehmen – Herausforderungen und Lösungsbausteine. ADDKON, St. Wolfgang im Salzkammergut, Austria, 07.06.2019.
- Schneck, M.: Weiterbildung im Bereich Additive Fertigung. AM Conference, Luzern, Suisse, 30.10.2018.
- Illgner, M.; Anstätt, C.; Binder, M.; Seidel, C.: Next Steps in Laser Beam Melting – Multi-Material processing and sensor integration. Stuttgarter Laser Tage, Stuttgart, Germany, 05.06.2018.
- Illgner, M; Schäuble, A.; Binder, M.; Urban, N.; Schlick, G.: Design of Lattice and Honeycomb Structures for Laser Beam Melting. formnext conference, Frankfurt, Germany, 17.11.2017.

F: List of Supervised Student Thesis

During the generation of this doctoral thesis in the field of technology strategies for metal-based Additive Manufacturing, the following student theses have been written at the Fraunhofer IGCV in Augsburg. During this collaborative research, the students have been extensively guided and supervised by the author in terms of the research clarification, objectives, research questions, approach, activities, and content. Selected results of the student thesis have contributed to this thesis and supported several projects of industrial application. My special recognition to all students, who accepted the challenge to write their thesis in the context of an industrial project.

Thank you!

Student	**Type**	**Year**	**Topic**
Maximilian Thonfeld	BA	2020	Patentstrategie für additive Fertigung
Marcus Bernhard	MA	2020	Untersuchung und Bewertung von Produktionsprozessen beim selektivem Laserschmelzen zur Darstellung metallischer Werkstoffverbunde
Barbara Kneißl	BA	2020	Entwicklung von Designkonzepten für Einspritzdüsen auf Basis additiver Fertigung
Benedikt Altmann	MA	2019	Strömungsoptimierte Konstruktion im Kontext additiver Fertigung
Christina Figalist	MA	2019	Subjektives Erleben von emotionalem Design der Produktentwicklung im Bereich des multimedialen Lernens – ein qualitatives Experiment
Christina Jegel	BA	2019	Analytische Ableitung von Designpotenzialen der additiven Fertigung für metallische Bauteile
Florian Wagner	MA	2019	Review and evaluation of non-destructive test methods for metal-based additive manufacturing
Yogeshkumar Katrodiya	MA	2019	Design and Optimization of Streamlining Parts for Additive Manufacturing
Ludwig Haas	MA	2019	Entwicklung eines Verfahrens zur Eignungsbeurteilung von Bauteilen für die additive Fertigung in einem frühen Entwicklungsstadium
Marina Seelos	BA	2018	Kennzahlbasierte Bewertung von Prozessketten für additiv gefertigte Bauteile
Matthias Gollnau	MA	2018	Entwicklung einer Methodik zur Bewertung der Mehrwerte in der Nutzungsphase additiv gefertigter Produkte
Maximilian Steinhardt	BA	2018	Kostenstrukturen metallbasierter additiver Fertigung
Mohamed Addassi	MA	2018	Strategische Entscheidungsfindung und Technologiefrühbewertung von metallbasierten additiven Technologien
Philipp Kindermann	MA	2018	Konzeptionierung einer innovativen Einlegeeinheit für metallbasierten 3D-Druck
Simon Bohnacker	MA	2018	Identifikation von aktuellen und zukünftigen Anwendungsmöglichkeiten der metallbasierten, additiven Fertigung in der Automobilindustrie
Andreas Schäuble	MA	2017	Gitterstrukturen als Konstruktionselement im Kontext der additiven Fertigung

MA: Master thesis; BA: Bachelor thesis

List of Abbreviations

AIM	Aachen Innovation Model, proposed by Eversheim (2009)
AM	Additive Manufacturing, defined in ISO/ASTM 52900
AMI	AM Suitability Index; Value to rate the suitability of an AM process for a specific application; Derived from a checklist with point scoring system; Based on VDI 2225-3
ccd	Corresponding cubic dimension; Measure for the available build volume in AM systems; States the edge length of a cube with the same volume as the AM build volume
cf, cf_0, cf_{100}	Cost factor; Expresses the ratio between the cost of an AM solution and a reference for the full utilization of AM benefits (cf_{100}) and if AM benefits are not realized (cf_0); Based on VDI 2225-3
DRM	Design Research Methodology, proposed by Blessing & Chakrabarti (2009)
EBM	Electron beam melting; AM process utilizing the powder bed fusion principle
ETM	Experience-based Transfer Model for the implementation of AM technologies, proposed by Leutenecker-Twelsiek (2019)
FDM	Fused desposition modeling; AM process utilizing the extrusion principle
HGB	German Commercial Code / Handelsgesetzbuch
LMD	Powder feed laser material deposition; AM process utilizing the directed energy deposition principle
LPBF	Laser-based powder bed fusion; AM process utilizing the powder bed fusion principle
LS	Laser sintering; AM process utilizing the powder bed fusion principle for polymer parts
M-FDM	Metal fused desposition modeling; AM process utilizing the extrusion principle for metal parts
MRL	Manufacturing Readiness Level, defined in Department of Defense (2018)
PBF	Powder bed fusion; Fundamental functional principle for AM processes, defined in ISO/ASTM 52900
PDM	Part data management system; Database storing information about products and processes within a company
PLM	Part lifecycle management system; Database storing information about products and processes within a company
R&D	Research and development; Function of a company, which identifies and develops product and process innovations; closely linked to technology and innovation management
SAP	Widespread proprietary software for business management from SAP AG; Here: Database storing information about products and processes within a company
SGMK	St. Gallen Management Concept; holistic framework for the management of organizations; developed by Bleicher (2017) and Rüegg-Stürm & Grand (2017)
SL	Stereolithography process; AM process utilizing the vat photopolymerization principle
SME	Small and medium sized enterprises
TOM	Trade-off matrix to evaluate the suitability of AM processes; proposed by Lindemann et al. (2014) and Lindemann (2017)
TRL	Technology Readiness Level; defines the maturity of a product for space missions, standardized in DIN ISO 16290
VDI	Verein Deutscher Ingenieure; Community of german engineers, providing guidelines for technical aspects
WAAM	Wire are additive manufacturing; AM process utilizing the directed energy deposition principle

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