Report

Smart Spare Parts Management

A digital supply network perspective

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SUMMARY
As additive manufacturing (AM) is being utilized across various sectors, value chains are disrupted and new approaches to spare parts management can be adopted. This report provides an introduction to the state-of-the-art regarding AM for the production of spare parts, along with complementary technologies including digital warehouses and distributed manufacturing. Initiatives in certification and qualification are described, and the need for competency is emphasized as a pivotal enabler for the industry to harvest the potential of AM for spare parts management in the coming years.

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1. Background and motivation

The industrialization of additive manufacturing (AM) technology continues to make great progress, with a rapidly increasing number of companies using AM as an integral part of their industrial production. In a recent survey, the professional services network Ernest & Young Global Limited (EY), reported that the share of companies with any experience with AM had risen from 24% in 2016 to 65% in 2019 [1]. The same survey reveals that the share of companies applying AM in production had grown from 5% to 18%. This number could mean that AM for final part production has grown out of the group of "early adopters" and is gaining momentum among the "early majority" of manufacturing industries. Furthermore, 15% of the surveyed companies used AM to produce tools, and 14% used AM to make spare parts.

As the technological maturity of AM has been demonstrated many times in specific industries, a key reason why the adoption has not been faster is that individual firms still struggle with the adoption and implementation of AM at an industrial scale. Companies often underestimate the extent to which the adoption of AM is first and foremost a learning process that must involve the entire value chain and requires the acquisition of specific AM expertise [2]. Several examples indicate that this tendency is not limited to industry but is also very much a constraining factor that hampers the development and application of AM competency in academia and at research institutes. Among the industries surveyed by EY in 2019, aerospace leads the way with over 78% of the respondents claiming to have experience with AM. This is further demonstrated in a complementary EY report from 2020 [3], where the companies from the aerospace industry expected that the use of AM for end-use part production would grow from 18% in 2019 to 59% in 2022. For the same period, the numbers for the chemical industry indicated an expected growth from 22% to 53%, and an increase from 17% to 44% is expected for the automotive industry (see Figure 1).

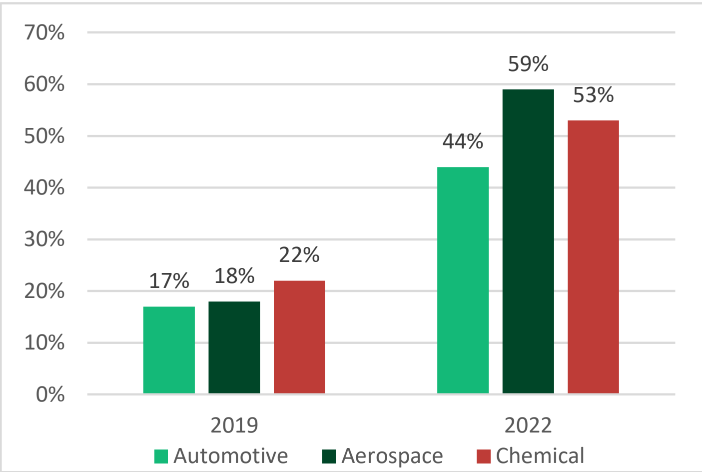

Figure 1: Expected end-part production by AM in certain industries [3].

The reason why automotive is lagging can be explained as a question of scale. The number of parts manufactured in a series production in the aerospace industry is most often rather small compared to the typical number of parts manufactured in a series production for the automotive industry. The high number of products needed for an automotive series production brings critical constraints in the productivity and speed of handling the parts during the break-out and unloading of the finished parts after each build cycle, -and throughout the post-processing operations. This challenge has been addressed by increasing the level of automation in the AM-enabled process chain. This trend has been demonstrated by the presentation of a rapidly growing number of systems for automation in the AM process chain at the annual Formnext fair in Frankfurt in recent years, and the impact of this development is also reaching into the production of leading automotive manufacturing companies.

BMW have reported that their initiative for industrialization and digitalization of AM-based production of automotive components in serial production has been successful [4]. The solution is described as "*a digitally connected, fully automated additive manufacturing line, specifically for series production of automotive* *components*", which has the capacity for cost-effective annual production of 50 000 components in serial production, -and in addition to this, 10 000 custom or new components. This solution means that certain tools are no longer required for manufacturing these components, which reduces design constraints and thus enables new product solutions, and much-increased manufacturing flexibility.

There are several advantages that AM technology offers compared to traditional manufacturing processes. Overall, AM offers a toolless manufacturing process, reductions in material waste, and the ability to produce complex geometries such as internal cooling channels. In addition, AM offers the possibility of on-demand manufacturing with minimal need for preparation before production. As a result of these advantages, AM could potentially replace several of the traditional steps often included in a manufacturing process. Compared to casting, AM eliminates the need to produce expensive casting molds and drastically reduces the need for post-production operations, including heat treatments and machining.

This report provides readers with an introduction to the application of AM for the production of spare parts, as well as an overview of the current state-of-the-art of practices within the industry. We highlight diverse examples from the oil & gas, automotive, and maritime industries. The report also highlights the potential related to spare parts production in terms of digitalization and distributed manufacturing.

2. AM of spare parts

The emergence of on-demand production reduces the need for inventory storage of spare parts. Currently, the possibility of using AM for spare parts production has reached a large interest within the oil & gas industry. The main reason to keep spare parts is to avoid unplanned downtime and long lead times when a component fails. However, with the introduction of AM, the need for large warehouses for storing spare parts can be reduced, and instead, digital warehouses can be established, with the AM technology offering "on-time" "on-site" and "on-demand" solutions when a spare part is needed. The on-demand production of one-off products reduces the need for costly inventories and facilitates the production of legacy components for old machines and equipment. Inventories can be further reduced by getting rid of molds and dies as AM requires no tooling.

2.1. Additive manufacturing technologies, evaluations before production

In principle, all AM technologies can be used for the production of the desired product. It is just a matter of the requirements for the final product, i.e., type of material, mechanical properties, size, geometric tolerances, and surface quality which must be assessed on a case-by-case evaluation [5]. Compared to traditional manufacturing processes, the advantages of AM related to product complexity and price are illustrated in Figure 2 (in Norwegian).

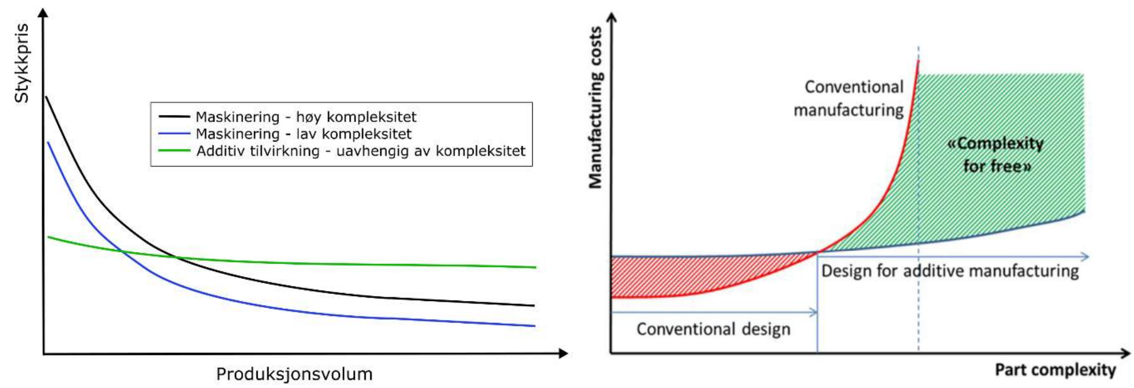

Figure 2. (a) Illustration of the relationship between cost and production volume for machining and AM. (b) Relationship between part complexity and cost for traditional manufacturing compared to AM [6].

2.2. The implications of AM on value chains

The advantages of AM are in many industries considered common knowledge and have received much attention over the last decades. Now as the technology is becoming more known, people are also starting to see the large effect that the technology can have on the value chain, especially the supply chain and the relationship between suppliers [7]. As a result of the shorter value chain, both lead time and costs can be significantly reduced, and the desired product can be produced on demand. As stated by Ôzceylan et al., *"Traditionally, raw materials or components are supplied from suppliers, assembled in manufacturers and shipped to customers through retailers or distribution centers. On the contrary, 3D printing technology enables organizations to bypass the traditional supply chain and manufacture a product themselves with a digital design"* [8, pp. 1–2]. This concept is illustrated in Figure 3 and has the potential to realize significant reductions in both lead time and cost.

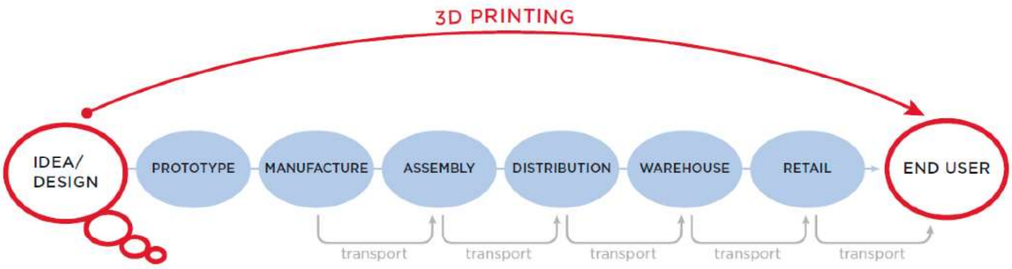

Figure 3: Implications of utilizing additive manufacturing for spare parts manufacturing. From [8].

The huge potential on-demand manufacturing provides was demonstrated during the COVID-19 pandemic. Hospitals and healthcare providers were lacking various equipment, including protective gear. The digital model for the plastic component crucial for producing a visor was shared among the AM community, i.e., people, universities, local groups, etc. with small AM machines who all started producing the plastic component [9]. This contributed to providing necessary protective gear to healthcare providers during the beginning of the pandemic, bypassing the traditional supply chains by simply sharing the digital model of the component to be produced. The on-demand production that the AM technology offers reduces the need for inventory storage of spare parts. The possibilities of using AM for spare parts production have recently sparked large interest within the oil & gas industry.

When a company decides to make use of AM in production, three levels of integration can be identified; (i) buy components directly from a third party, (ii) engage in a partnership with one or more suppliers of AM products and services, or (iii) invest in the necessary hardware and competency for in-house production [10]. Regardless of which option is chosen, the need for innovation and change within the organization is substantial. The largest impact on the supply chain is related to the second option where a supply network may emerge and yield major environmental and financial benefits. A simulation study comparing a conventional supply chain of spare parts on one side with centralized and de-centralized supply chains utilizing AM technology on the other, indicates savings both in terms of cost and environmental impact [11]. Similar results are found in multiple other studies that show that also shorter lead times and better quality may be achieved [10].

As more components are designed to be produced by AM and AM-enabled production chains (as in the example from BMW above), it is not likely that these components ever will be made by any other technology. This will reduce the need for specialized tooling and systems' setup, which bring a situation where the manufacturing of components and spare parts can be much more flexible and adaptable according to market demands and customer needs. The sizes of the series are not as critical, and smaller series can be produced closer to the market and when they are needed.

3. Industry examples related to spare parts production

Since they started to investigate the possibilities of AM in the energy sector in 2016, Equinor has studied potential applications where AM could provide a competitive alternative production route. Over time, the number of identified cases where AM can offer a clear business case has grown to more than a hundred different products. Since the keeping and maintaining of a necessary supply of spare parts, represents a significant cost for Equinor, AM offers an attractive possibility to reduce large sections of the physical inventory, and replace it in the form of a digital inventory to be combined with AM enabled, on-demand, manufacturing. The outcome of Equinor's investigations has been carried forward by the establishment of a "Centre of AM Excellence".

One illustrative example from Equinor’s cases is the replacement of a set of obsolete locking screws for switch cabinets used on offshore installations. Spare parts for the locking system are no longer available, and the only solution offered by the cabinet supplier was to replace the entire cabinet as the locking screws failed. However, changing a cabinet would require rewiring and installation of a parallel system to be operated while the original cabinet is changed. This was not very attractive since it would be both very costly, labor-intensive as well as time-consuming.

As an alternative solution, Equinor collaborated with electromechanical supplier Karsten Moholt, to find a different source of spare parts for the locking screws. It was found that reverse-engineered polyamide PA12 screws built by PBF-LB fulfilled the requirements for installations and Ex-markings. A conservative estimate concluded that this solution would save Equinor over 100 million NOK annually (see Figure 4).

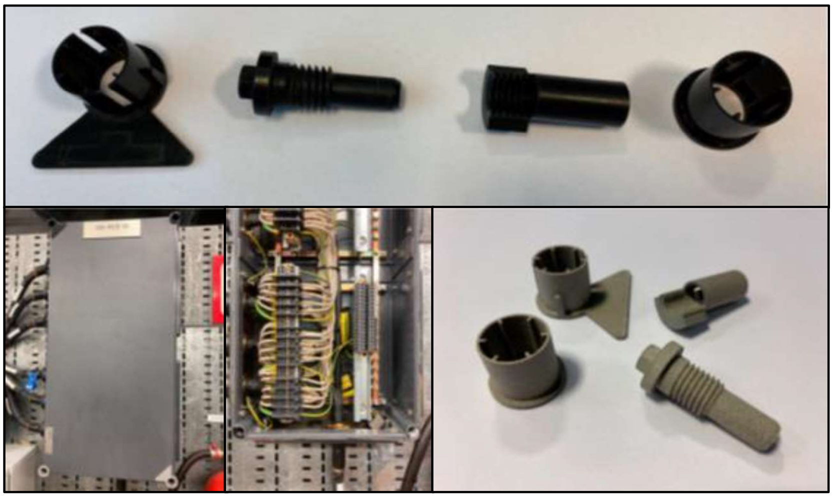

Figure 4: Spare parts for a switch cabinet: the original locking screws (a), positions in the cabinet (b & c), and the spare parts, manufactured by PBF-LB/PA12 (d). (Images provided by courtesy of Equinor and Karsten Moholt)

Besides substantial economical savings, the AM-enabled production of spare parts can also bring a significant decrease in environmental impact. In a previous case, in 2018, the fan for a motor unit at Equinor's plant at Tjeldbergodden had broken down, and there were no spare parts available. The supplier recommended that the entire motor unit should be replaced, which would both cost a lot of money, and certainly would have a significant environmental impact. As an alternative solution, Equinor turned to upstart company Fieldmade, who specializes in on-site and on-demand spare parts production, thus were able to successfully recreate the digital model for the spare part by reverse engineering, and built a replacement for the broken fan by AM (see Figure 5). A calculation of the environmental impact has concluded that changing the entire motor unit would have had an impact of 4600 Kg of CO_2, while the impact of producing the spare part by AM was only 3.8 Kg of CO_2. -The difference in cost was of the same magnitude.

Supported by an industry consortium headed by Equinor, Fieldmade have developed a solution for a "Digital Inventory" which enables the distribution of product designs for on-demand, local manufacturing of spare parts, and was launched through the newly established start-up "Fieldnode" in May 2022. Equinor estimates

Figure 5: Fan for a motor and replacement part, made in the field by Fieldmade for Equinor during Trident Juncture 18. Since the original fan had gone out of production, reverse engineering and reproduction of this part was the only alternative to replacing the entire motor unit. Courtesy of Fieldmade and Equinor.

that the application and exploitation of AM in their supply chain will save the company around 470 million NOK during 2022.

In a Joint Industry Project (ProGRAM JIP) [12], three means of production of a crank disk were compared: (i) conventional manufacturing by forging and machining, (ii) hybrid manufacturing by building the critical pin feature by DED (Directed Energy Deposition) on a conventionally manufactured disk, and (iii) repairing an old crank disk by machining damages and filling cracks and pores by DED as well as the pin feature. The hybrid approach only required 50% of the energy compared to conventional manufacturing, and repairing used components allowed energy consumption to be reduced by approximately 95%. In terms of CO_2 emissions, a reduction of 33% and 90% was calculated for the two approaches respectively. Another case study in the same project investigated Electron Beam Powder Bed Fusion for manufacturing impellers. While the quality is found to match and exceed that of the cast counterpart, the ability to manufacture multiple parts in the same build envelope result in 10–30% shorter lead times. In this particular case, the lead time was reduced from 24 weeks to only 4 weeks [12].

A shift from conventional supply chains towards a digital supply network is eminent as AM and digital technologies become more mature. These technologies have reached a point where designs can be effortlessly shared between different actors for redesign, optimization, and production by AM. Such ecosystems do not only utilize the expert knowledge and skills of each partner, but also have the potential for major savings in terms of cost, energy consumption, and emissions from distributed manufacturing of spare parts on demand. One such network is being orchestrated by Equinor with Korall Engineering contributing AM design expertise, f3nice bringing technology for transforming old parts into powder for AM, and Fieldnode connecting the partners through a digital inventory [13].

4. Distributed manufacturing and digital warehouses

Historically, additive manufacturing has also been referred to as Direct Digital Manufacturing (DDM), thus referring to AM as a process that directly produces parts from a CAD file. As the first break-through application, AM was most commonly used for prototyping for many years, while now the majority of parts produced by AM are for DDM and rapid tooling [14]. However, the digital nature of AM is a key feature which allows for the establishment of digital warehouses for storing spare parts designs ready to be built when needed.

The benefits include but is not limited to easily the reduced need for inventory and storage, reduced downtime as spare parts can be manufactured on-demand, and the potential for distributed manufacturing, reducing the need for transportation and long lead times [15]. However, literature has highlighted some of the challenges related to the digital spare parts market, such as quality management for instance. More standards and guidelines are being developed for process and product quality control, but these are still not covering all aspects of AM within manufacturing. More information about standards and guidelines are provided in chapter 5. Secondly, development of a system for protection of intellectual property (IP) rights of CAD files could become necessary. Further harmonization of the EU (European Union) legal framework, the interpretation of claims, and the scope of protection offered in the context of spare parts will also be important [16].

As a toolless manufacturing technology, AM allows for unique products to be manufactured in succession without changeover, and even simultaneously in a single machine. By utilizing a limited selection of feedstock material, the actual manufacturing can be shifted from major factories toward the location where the product is to be used. This may entail smaller, mobile facilities such as the Nomad demonstrated by Fieldmade [17], or small manufacturing centers at strategic locations such as ports and other critical infrastructure.

The maritime group Wilh. Wilhelmsen has embraced AM as a means of distributed manufacturing of spare parts through their partnership with Thyssenkrupp and Ivaldi [18]. With vessels traveling across the globe, centralized inventories of spare parts lead to long downtimes while the parts are transported to the ship's location. Alternatively, large inventories can be maintained in strategic ports just in case – most of which will never be used. By replacing the spare parts inventories with AM facilities and feedstock – serviced by a common digital warehouse – the downtime may be drastically reduced together with the cost of inventories, and the environmental impact.

Another approach is adopted by Daimler Buses who are establishing mobile AM centers that can produce spare parts on demand within days (as opposed to several weeks when producing by conventional technologies) [19]. The company estimates nearly 40 000 spare parts to be feasible candidates for AM whereof 7 000 are being digitized and prepared for the mobile AM center.

Deutsche Bahn has completed extensive investigations into the use of AM for spare parts production and has developed a growing network of suppliers to sustain the needs for a growing number of components. The present inventory for AM parts includes over 100 components including a wide array of products, from simple things that make a big difference, such as spare parts for coffee machines and coat hangers to massive metal parts such as wheelset bearing covers and engine parts [18], [20].

As the market and application of AM technologies become more mature, the number of AM service providers increases exponentially. In 2022, Siemens Energy together with Zeiss and a number of venture capital investors announced the investment in a new digital platform MakerVerse where services can be sourced from AM service providers [21].

5. Qualification and certification

5.1. Standards

The development of international standards is a crucial steppingstone for the industrialization of any technology. Standards are critical to establishing a common baseline for the specification of requirements, communication, documentation of best practices, qualification of processes and products, defining test methods and protocols, and documenting technical data. Certifying bodies rely their work on referring to publicly available standards. In a unique collaboration, ISO and ASTM International have agreed to develop a joint set of international standards for AM technology. This work is driven by the commitment of members from technical committees ISO/TC261 and ASTM F42 to put in their time and effort to develop consistent and coherent standards to cover the ever-expanding needs for the industrial application of AM technology. At present (November 2022), there are 22 published ISO/ASTM standards, with an additional 33 under development and 3 unique ISO standards on AM. ASTM International has a different system for the development and publication of standards, and in addition to the ISO/ASTM joint standards has published 20 unique standards for AM, but in most cases with the intention that they should be submitted for publication as joint ISO/ASTM standards. Furthermore, following the Vienna agreement, standards that have been published by ISO/TC261 are also brought forward as European standards by CEN/TC438. This also makes them default national standards in all member states on CEN/CENELEC, -including Norway. Some standards of particular relevance for spare parts manufacturing are tabulated in Table 1, and a complete list can be found on ISO web pages[1]. Both ISO- and ASTM standards can be found at the respective websites[2] by searching for <keyword> + "additive manufacturing". Other organizations are also publishing their own series of guidelines and recommendations, such as DNV [22].

Table 1: Important standards related to AM in the context of spare parts manufacturing.

Standard ID	Description
ISO/ASTM 52901	Requirements for purchasing parts made from AM and guidelines on what information are to be exchanged between the customer and AM supplier
ISO/ASTM52907	Methods for characterizing metallic powder
ISO/ASTM52910	Requirements, guidelines, and recommendations for using additive manufacturing in product design
ISO/ASTM 52900 and ISO 17296-2	Standard terminology in AM process specification

5.2. Guidelines, qualifications, and certification

In many sectors, components need to be classified and certified by the appropriate class society dedicated to the intended application area. DNV is for instance one such class society dedicated to the marine and offshore industries. DNV is currently heading and industry consortium in a so-called JIP (Joint Industry Program) project to establish qualification guidelines for different AM technologies for applications in the marine and offshore industry [23]. The guidelines are established to ensure that AM-produced components are approved in the end for the desired application, and approval is given by the class society, in this case, DNV. For instance, the DNV-ST-B203 Additive manufacturing of metallic parts guideline (edition 2022-10) describes the process for qualifying a part produced by different AM technologies, such as different types of DED processes and different types of PBF (Powder Bed Fusion) processes, the manufacturing process and guidance for purchasing AM produced parts.

Based on the guidelines, manufacturers can become certified/approved for AM production according to the DNV guidelines and can achieve approval for manufacturing components with given materials after documenting achieved properties. This pathway is illustrated in Figure 6.

[1] https://www.iso.org/standards.html
[2] https://www.astm.org/

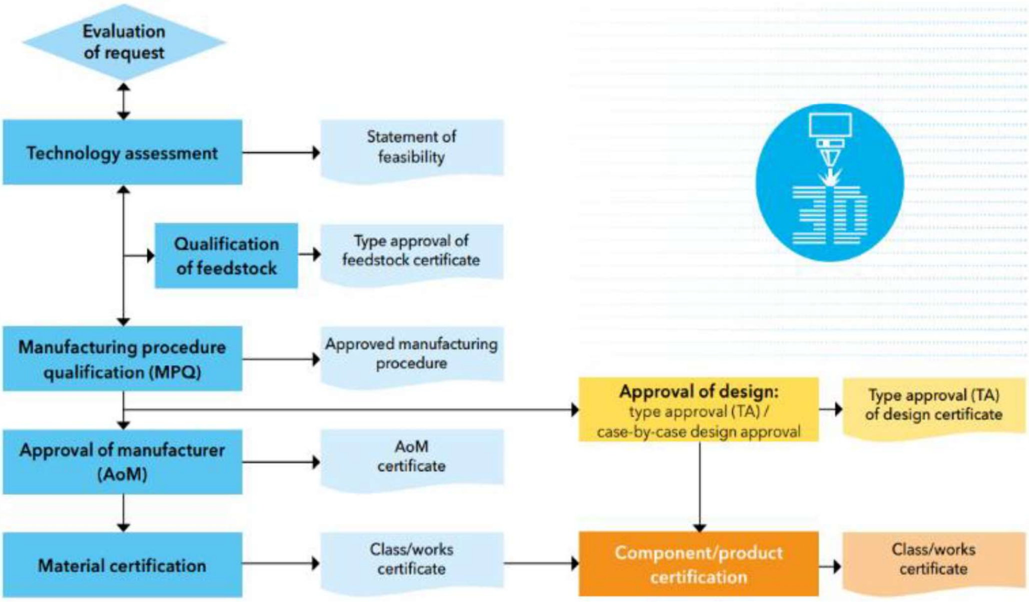

Figure 6: Certification pathway for AM [24].

Lloyds Register (LR), a UK based technical and professional services organization and maritime classification society, has in collaboration with TWI developed a broad-based AM part certification service that spans "all industries" from marine classification to oil and gas verification [25]. The service catalog includes programs to help manufacturers to prove that their parts meet the codes, standards, quality controls and assurance requirements. Including:

- Material certification
- Facility qualification
- Part certification

The certification services include the application of published and evolving international standards for AM, setting the requirements for proving the equivalence with existing manufacturing methods, codes, and standards, thus fulfilling the requirements for qualification and certification.

TÜV SÜD, a German independent service company that test, inspect and certify technical systems, facilities and objects of all kinds has developed a portfolio of services for qualification and certification of AM material, parts, and production facilities [26]. Services include:

- Security: Ensuring the security for hardware and software, such as secure data streams, electrical safety, Environment Health, and Safety (EHS) for process' equipment and facilities.
- Materials: Testing and certification of feedstock. Material testing and materials properties certification.
- Production workflow: Part-specific workflow certification including design, manufacturing process and regulatory conformity to ensure products are designed for manufacturability and reliably lie within defined specifications.
- Products: Testing, certification, and approval to ensure that processes and products conform with all relevant industry standards while meeting AM process requirements.
- Production facility: Assessment and certification of an industrial additive manufacturing production site that provides a reliable base for serial production of parts by AM technology.

6. Summary and outlook

AM technologies have reached a level of maturity where on-demand production is a valid option for spare parts management. Companies within the energy sector, shipping, and transportation are making major investments in digital warehouses and new supply networks for spare parts. The technology has been tested, but infrastructure and value chains have yet to adapt, and the mechanisms required for integration in existing systems are being developed. This report has shown the major efforts in technology development and proof of concept for smart spare parts management through a variety of industry examples. However, the ranges of products and technologies are still limited, and new applications emerge from an increasing number of businesses.

This high pace of adoption must be accompanied by equal developments in competency to match. As these solutions become integrated into value chains, the need for knowledge and experience will increase significantly at all levels of the organization – from operators, designers, and engineers to managers and decision-makers. Both national and international funding bodies are promoting research, development, and innovation within related areas such as digital manufacturing and Manufacturing-as-a-Service. One example is the recently funded project DAVAMS where a digital supply chain of spare parts for the maritime industry is being developed. More projects on this and related areas are expected to lift technology and competency to a level of industrialization within a few years. At the same time, standardization initiatives are underway to facilitate cooperation and integration across value chains. The technology is already here – the missing ingredients are competency and scale.

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