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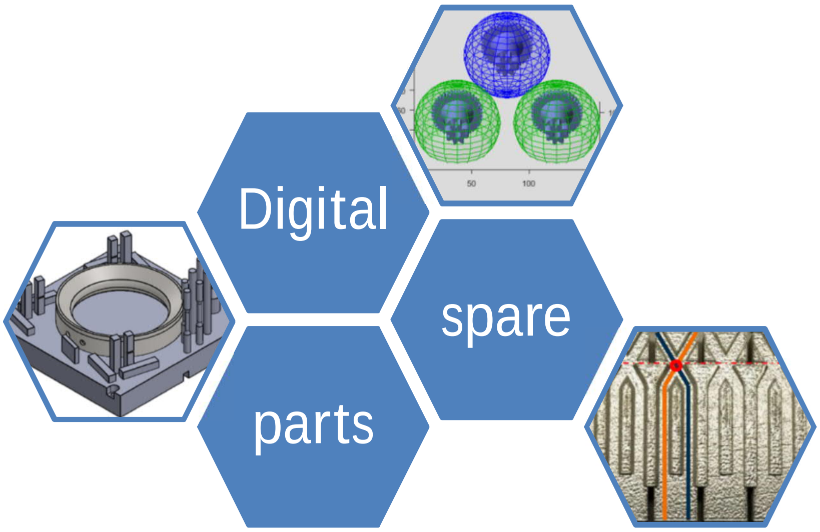

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Preface

This report summarises the results of the New Business From Digital Spare Parts project (DIVALIITO), managed and implemented by VTT Technical Research Centre of Finland and Aalto University during the years 2018–2020. DIVALIITO was a public part of a joint action also comprising the projects of Etteplan and 3DTech, all funded by Business Finland. The DIVALIITO research project was steered by 3DTech Oy, Etteplan Finland Oy, Kiwa Inspecta Oy, KONE Oyj, Valmet Technologies Oy, Wärtsilä Services Switzerland Ltd., Technology Industries of Finland and CECIMO.

The research themes of the DIVALIITO project were determined in close cooperation with industrial partners that actively participated in the planning and steering of the project. In addition, some themes were brought to light earlier during the previous project, Digital Spare Parts (DIVA), executed in the years 2016 and 2017. In the DIVALIITO project, methods for identification of 3D printable parts from the spare parts libraries were developed, and information available on materials for additive manufacturing were compiled, produced and compared with the conventional manufacturing materials and methods, taking into account different post-processing steps. New spare part concepts such as smart spare parts with embedded intelligence were investigated, and the connections of the process steps of the whole manufacturing chain of the digital spare part were clarified, especially from the workflow, quality control and automation perspectives. The ultimate goal of the research project was to promote the implementation of digital spare parts in Finland and to create new business opportunities from digital spare parts, increase the availability of spare parts, make spare part business more cost-effective and sustainable and strengthen additive manufacturing networks in Finland.

Open seminars, workshops and webinars were organised for companies during the project for collecting data on the current situation and for dissemination of the project results. In addition, extensive experimental studies were carried out in the project including demonstrations related to additive manufacturing and substitution of materials, embedded intelligence, corrosion, lattice structures, weathering tests, mechanical properties, heat treatments, manufacturing procedure specification and quality assurance.

This report is a compilation of results and it contains links to original documents where the results have been/will be presented more widely. These include scientific and conference publications and presentations, master's theses, dissertations, VTT Publications or other project documents.

We thank Business Finland, Kiwa Inspecta Oy, KONE Oyj, Valmet Technologies Oy and Wärtsilä Services Switzerland Ltd. for funding the project. We express our deepest gratitude to the members of the steering group for their active participation, fruitful discussions and provision of feedback and to all the company representatives who participated in the project demonstrations and events as well as all the stakeholder representatives involved in the project.

Espoo 19.10.2020

Authors

Contents

1. State-of-the-art and digital spare parts in short

Aftermarket services are an extremely important part of many OEM businesses as they usually offer more stable revenue than the sales of new equipment and other products. In a recent McKinsey publication, it was reported that average earnings-before-interest-and-taxes (EBIT) margin for aftermarket services was 25 percent, compared to 10 percent for new equipment (Ambadipudi et al. 2017). The estimated spare part market is a $400 billion business worldwide and many companies make extensive profit from spare parts (Gallagher et al. 2005).

Traditionally, spare parts have been manufactured and put into stock in varying batch sizes, possibly requiring their long-term storage. A lot of capital is tied to spare parts, and it is very difficult to anticipate when and how many spare parts are needed. It is therefore possible that some of the manufactured spare parts are never used. Many Finnish companies manufacture highly customised products, which further increases the number of spare parts and therefore increases the challenges of inventory management. As progress continues to accelerate, it is also possible that the spare parts in stock will no longer meet the performance requirements when they are needed. Companies are also often obligated to offer maintenance services for machines and equipment that are already so old that spare parts for them no longer exist. Today, manufacturing such parts is expensive and slow, particularly if manufacturing them requires tools and moulds to be made first.

Additive manufacturing (AM) / 3D printing technologies have reached the interest of the manufacturing industry as well as the public more than ever before. Many companies are currently evaluating the feasibility of adopting AM technologies into their business, whereas some companies did it decades ago. The potential benefits enabled by AM compared to conventional manufacturing are undeniable; simpler supply chains with shorter lead times and lower inventories, no need (or significantly less) for tooling, production of small batches becomes economically feasible, product optimisation for function, more economic manufacturing of custom designs (complex shapes) and significant reduction of waste material and off-site repair (Khajavi et al. 2014; Chekurov et al. 2017). In recent years, AM has been mostly used for producing functional parts, and the global market value of the AM industry has grown rapidly year after year; it was $2.0 billion in 2012 and it is estimated to reach $27.5 billion by 2024 (BCC Research).

> Digital spare parts is a concept where the spare parts and related data are transferred and stored digitally. The manufacturing of the spare part is done according to need with a 3D printer that is usually located physically close to the end-user.

Based on results of our studies, currently approximately 5% of all spare parts are suited for digital spare parts, and prognostication of the future is that 10% of spare parts will be digital, the technology will be reliable and high quality, and new spare part concepts such as smart spare parts with embedded intelligence will have entered the market. The main targets for the implementation of digital spare parts in companies are to make spare parts service businesses more efficient and to achieve significant cost savings: the availability of spare parts is improved, the customisation of parts is enabled, delivery times will become shorter and the manufacturing of individual parts or small batches will become cost-effective (Chekurov et al. 2018). In addition to manufacturing as well as warehousing or transportation costs, it is also important to be aware that the costs of downtime can become so significant that the price of the spare part itself is insignificant. Additionally, the design heavily affects the utilisation of digital spare parts given that the parts that can be used as the redesign are, redesigned for AM or in best cases, spare parts are already designed to be made by AM. (Chekurov 2019).

There are already some early adopters who have started to utilise digital spare parts. Most of the examples come from the mobility sector such as automotive and railway companies but AM spare parts have also been adopted by other industry like aerospace, military and machinery. It also seems that the AM companies or service providers are increasingly manufacturing various spare parts (car parts, machine and equipment parts, consumer products). Reasons for the use of AM include the design defects of certain products, the poor or non-existent availability of spare parts, and the need for customised parts. Individual or several parts are usually manufactured into stock, but short-run production has also been done, and this is what companies strive for. In addition to 3D printing companies, some new logistic or supply platform companies have been established. These companies provide cloud-based services that connect customers (including OEM companies) to a network of AM service providers.

Based on focus group interviews and SME clinic conducted during the project, major barriers for digital spare parts include the quality of additively manufactured parts, the lack of expertise in AM and the importance of data availability and quality (Chekurov et al. 2020).

2. Objectives of the DIVALIITO project

The DIVALIITO project addressed for following challenges related to AM spare parts. Spare parts suitable for AM should be identified from the spare parts libraries, there should be more information available on the AM materials and the quality of the AM parts, and new future spare part concepts such as smart spare parts should be developed and studied in more detail. In addition, methods for automation of processes need to be developed.

The objectives of the DIVALIITO project were:

- To develop systematic approaches for identifying the technologically and economically feasible parts from spare part libraries and to determine spare part information needed in digital stocks enabling the automatic order-delivery process for digital manufacturing.
- To study and collect AM material properties and manufacturing information that forms a basis for a quality assurance of digital spare parts.
- To demonstrate digital spare parts with embedded intelligence.
- To develop process automation chains related to digital spare parts.
- To support companies in the implementation of digital spare parts in their business and to strengthen the ecosystem around digital spare parts.

3. Identification of spare parts suitable for AM

There is a challenge to identify spare parts suitable for AM from spare part libraries since there are certain technological and economical limitations for a spare part to be additively manufactured: the part should fit the building chambers of the available AM machines, it should preferably be only single material, there should be suitable AM material available, and the precision requirements, tolerances and surface quality should be met with AM and/or some post-processing steps. The AM of the spare part should also be economically feasible when taking into account not only the costs of actual 3D printing but also warehousing, transportation and the costs of downtime. In general, one of the main challenges for automatic identification is incomplete data related to spare parts. The task would be easy with complete data, including 3D models of spares with all annotations.

In the DIVALIITO project, a holistic tool for feasibility evaluation and cost-calculation of AM spare parts was built, a method for recognition of spare parts suitable for AM based on images was developed and finally, a commercially available tool for automatic identification of relevant spare parts for AM was tested.

3.1 Cost-calculation tool and part identification approaches

In 3D printing, orientation and packing have a huge effect on costs and productivity (Salmi et al. 2016). Cost-calculation tools are needed to evaluate suitable business cases for different parts and applications in different patches and orientations in terms of cost and manufacturing time (Kretzschmar 2020).

AMDSP 2.0, which describes the second version of the “additively manufactured digital spare parts” online tool, was revised and expanded. In this version, not only metal-based additive manufacturing (AM) processes, machines, and materials are selectable, but also plastic-based selective laser sintering.

In total, the following 10 systems and materials are included:

AM systems	AM materials
case 'EOS M 290 (400W)’	case 'AlSi10Mg'
case 'EOS M 400 (1000W)’	case 'Maraging Steel 1.2709'
case 'EOS M 400-4 (4 x 400W)’	case 'Ti6Al4V'
case 'SLM 280 Production (400W)’	case 'PA12'
case 'SLM 500 (4 x 400W)’	case 'PA11'
case 'EOS P 396 (70W)’	
case 'EOS P 500 (2 x 70W)’	
case 'EOS P 770 (2 x 70W)’	
case 'Pro Maker P1000 (30W)’	
case 'Pro Maker P4500 HT (100W)’	

The user uploads binary standard tessellation language (STL) files and selects at least the AM machine, material, and the production volume to obtain results. Consequently, the component is visualised and packed into a sphere, also showing the selected distance between two components.

Besides the visualisation of the component, its orientation and supports, the cost over the production volume, the lead time over the production volume, and the cost associated with the machine’s utilisation percentage (max. 100%) and the production volume, is presented.

Furthermore, the tool comprises the following characteristics:

- Nesting hexagonal close packing (fundamentally different from bounding box-based nesting)
- Support generation & orientation (based on min. support volumes)
- Nearly full control over the algorithm (distances, support angle, recoating times, etc.)
- Java-based front-end, back-end originally coded in MathWorks Matlab

The tool is available for use online at https://amdsp.org.aalto.fi/; any uploaded files are removed from the server and not reused for any kind of purpose. Any kind of reuse of software of the tool (e.g., for publications, dissemination) requires the permission of the developer. More information and instructions can be found within the tool.

3.2 Automatic Identification of 3D printable spare parts from images

OEMs that produce and maintain machinery with lifetimes spanning several decades have tens of thousands of spare parts in their inventory. Therefore, a key question for the application of 3D printable spare parts is the ability to automatically identify those spare parts that could be 3D printable. 3D printability can be considered from two perspectives: is the part technologically and/or economically 3D printable? As described in chapter 3.3, commercial tools and services for assessing 3D printability are now available, however these tools rely on comprehensive, structured spare part data from the ERP system to be available for all the spare parts. The data needed for such analysis, especially for the technological feasibility assessment, is often incomplete in the ERP systems of OEMs. In addition to the ERP data, many OEMs store images of their spare parts. Therefore, it was studied whether these images could be used as input data for a novel way of identifying 3D printable spare parts automatically.

In this study, three different state-of-the-art open source deep convolutional neural network algorithms (DenseNet, InceptionV3, ResNet) were used to classify spare part images into 10 different categories, as shown in Figure 1. Transfer learning for these categories was applied to the algorithms that had been pre-trained using the ImageNet1000 dataset (http://www.image-net.org/) by using the ImageAI (http://imageai.org/) python library. The training images were collected from three sources: images provided by OEM1 (~11,000), images provided by OEM2 (~25,000) and images collected from a few companies that openly share their spare part images on their websites (~19,000). These in total ~55,000 images were then manually classified into the target categories and further split into training (80%) and validation (20%) datasets. Top-1 validation accuracy and validation loss were monitored as the results of the training. A high accuracy with low loss would indicate good learning performance.

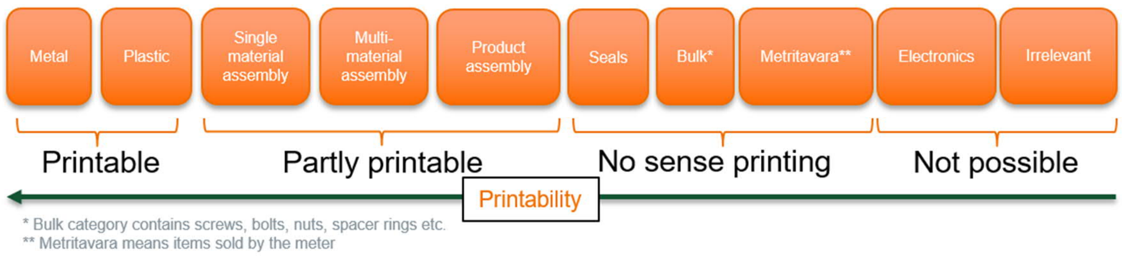

Figure 1. Classification categories and their relation to the 3D-printability of a spare part.

Within the studied three neural network architectures, there was no significant difference in their performance. In Figure 2, the results of using InceptionV3 are shown as this was computationally most efficient (using Nvidia Quadro P4000 8GB GPU). Convergence was seen after 24 epochs and this was the version of the neural network used for further tests. At this condition, the validation accuracy reached 71.2% and the validation loss stood at 0.87.

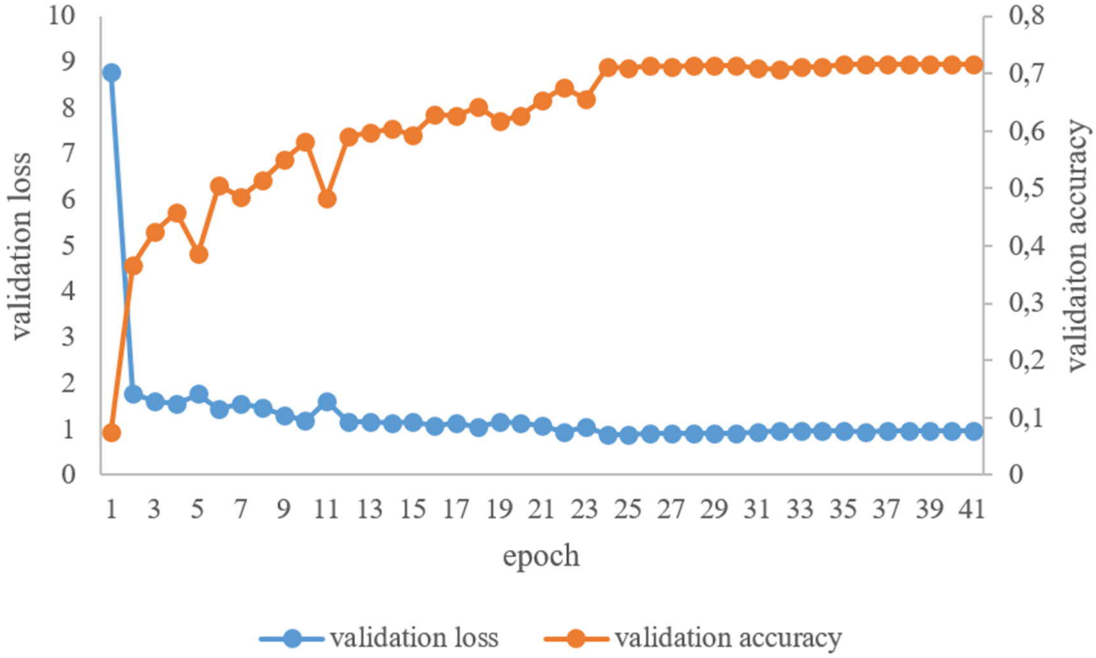

Figure 2. Top-1 validation accuracy and validation loss for the ~55,000 training images.

After the training, ~400 images of spare parts from a third OEM were used to test how well the algorithm generalises performance on images coming from a different industrial sector than those images that were used for training purposes. Figure 3 shows the top-1 and top-3 accuracies for this test. Top-3 accuracy considers predictions done by the algorithm where the correct answer is within the three highest probability predictions made by the algorithm.

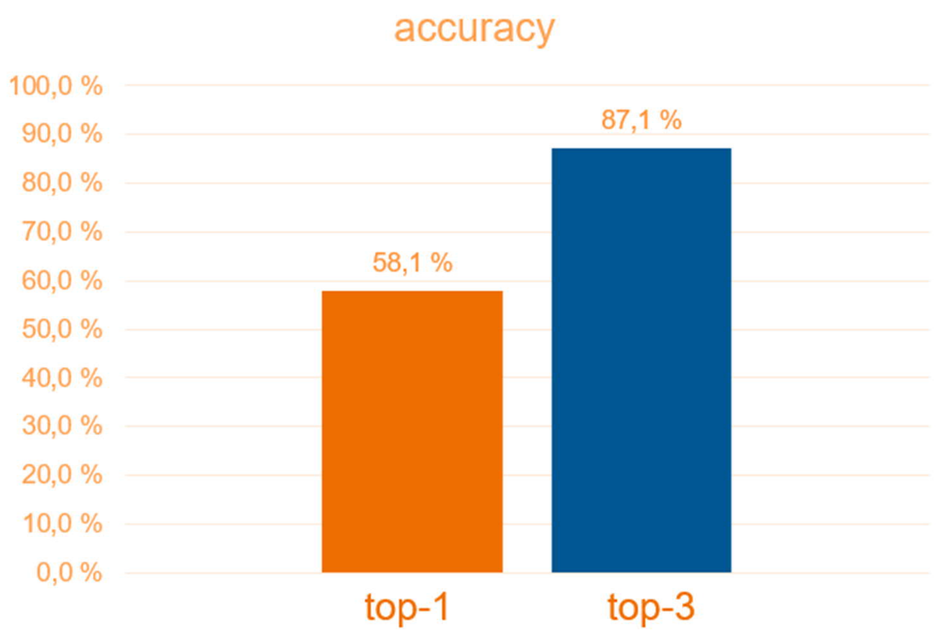

Figure 3. Top-1 and top-3 accuracy for testing the generalisation capability of the trained algorithm.

This study demonstrated that the algorithm is learning something useful for the given classification task (71.2% top-1 accuracy vs. 10% that would be achievable with random guesswork) and therefore this approach seems to be a potential method for identifying 3D printable spare parts. The top-1 accuracy was lower at 58.1% when images from a different industrial sector than those used in training were predicted, highlighting the importance of training the algorithm with highly diverse spare part data. The top-3 accuracy was 87.1%, showing great potential for further developing the methodology to perform even better in the top-1 accuracy as well.

This approach does not consider economic supply chain information in the classification, but rather can be used as the first screening of all the spare parts of an OEM, which can be then supplemented by an economic analysis based on the ERP-data, by using, for example, tools such as those discussed in 3.3. A more detailed technical analysis of whether the part can be printed is also necessary at a later stage, as this approach does not give insight to the detailed geometrical features, part size or material composition, which may still render a part identified here as 3D printable to actually be impossible to 3D print.

3.3 Analysis of a commercial supply chain inspection tool for identification of 3D printable parts

In recent years, novel companies such as SpareParts3D, LEO Lane, Fictiv, Xometry and DiManEx, which provide cloud-based services that connect customers including OEM companies to a network of AM partners have been established. Some of these companies offer services for identification of 3D printable parts - both from bottom up (spare part libraries) and top-down (individual parts) manners. The DIVALIITO project cooperated with DiManEx, a digital supply chain platform founded in Amsterdam, the Netherlands, and carried out a more detailed exploration of the Supply Chain Inspector, the analytics engine the company has developed for automatic parts identification as part of the company's cloud-based end-to-end platform. In addition, the platform digitises inventory and prints parts on demand through a global network of industrial-quality facilities.

DiManEx provided a data set for the analysis comprising altogether 104 original parts from 3 different types of companies: a service organisation, a capital goods company and one from the appliances industry. DiManEx utilised this data set in the analysis of which the goal for the DIVALIITO project was to understand how such a digital supply platform operates, which kind of data from parts is needed for the tool and what the potential limitations and outcome of the analysis are.

The analysis is based on differentiation of mandatory and non-mandatory data points, which typically are sourced from ERP and PLM systems of companies. The mandatory data points include both technical e.g. material, diameters, drawings and weight, and also supply chain specification on part availability, service lifetime, minimum order quantity, demand, cost information, etc. In most cases, some mandatory information is missing and in these cases, DiManEx decides together with the customer which data points are used for the analysis, e.g., if there's no minimum order quantity data points available, it is possible to carry out the analysis based on data on the last ordered amount. Once data points are collected in a template, the platform runs the analytics engine and presents the parts' printability potential. It has to be noted here that initial collection of data points may be a time-consuming operation, especially if the number of spare parts in the library is high and lots of information is missing or has to be collected from several sources or systems.

The analytics engine of DiManEx allows for parametrisation of certain data points specific/relevant to the customer. This is typically done in close cooperation with the customer. The assumptions in this demonstration were:

- Dimensions: max 400 x 400 x 400 mm
- Weight: < 2.5 kg
- Remaining service life: < 2 years
- Demand: > 0 for the last 36 months.

The Supply Chain Inspector of DiManEx categorises the parts into different classes: 1) parts having immediate potential (both technical and supply chain potential), 2) parts with technical eligibility (technical potential, but, e.g., enough stock, low demand or supply chain data is missing) and 3) no eligibility parts which are lacking both supply chain and technical data and parts which are out of scope due to the fact that dimensions make it impossible to 3D print the part.

The outcome of the analysis of the data set of 104 parts is shown in Figure 4. As summarised, 35 parts had immediate potential, 27 parts had technical potential and 42 parts had no eligibility at this point in time. Based on our earlier experience, the number of parts that have immediate potential in this demonstration is higher than expected, which may be a consequence of the fact that the data set utilised in the analysis was a group of selected parts and not a representative group of spare parts of one company or the whole spare part library of a company (Reijonen 2017). In addition, more information is usually missing, ranging from material information to supply chain-related data, which often leads to a situation in which approximately 5-10% of spare parts are potential digital spare parts.

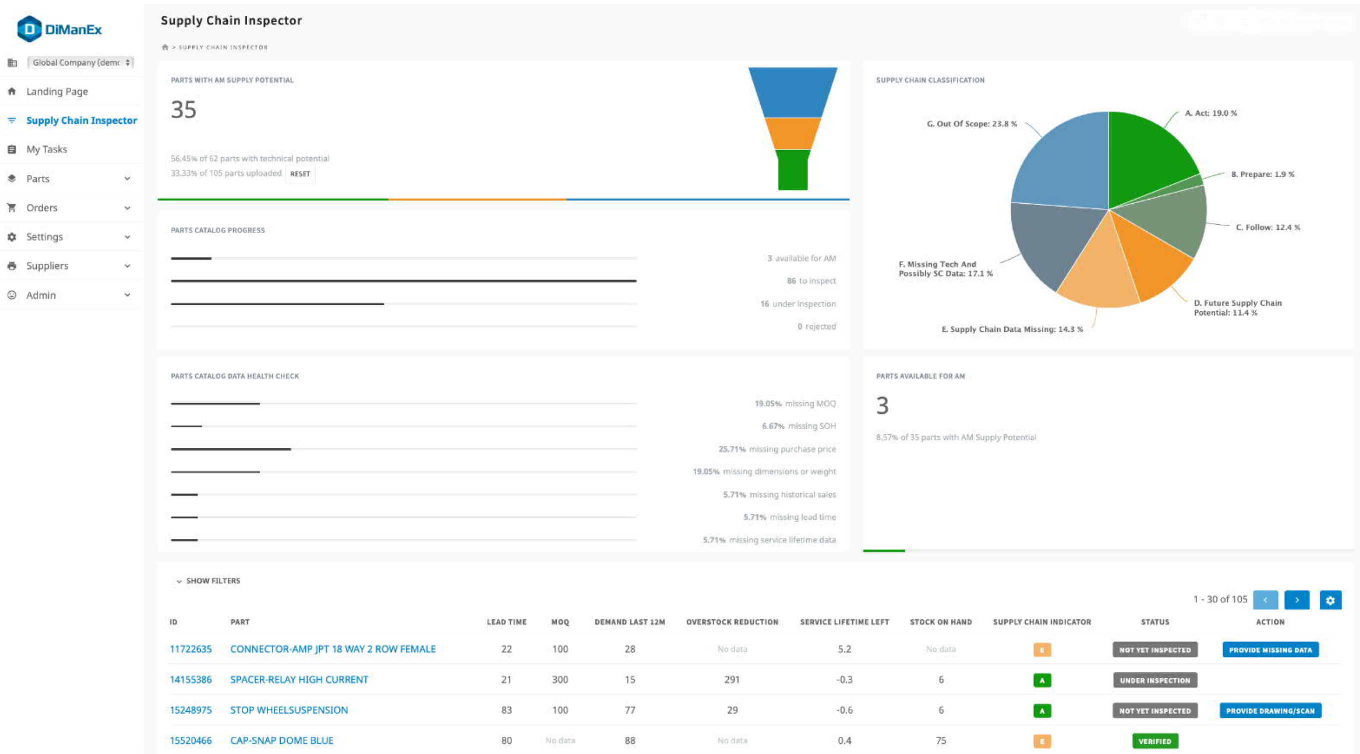

Figure 4. Outcome of the analysis: a data set comprising 104 parts with DiManEx Supply Chain Inspector.

There is a parts data health check feature in the *Supply Chain Inspector*, which labels each of the parts from which technical and/or supply chain data is missing. With this demo set of 104 parts, the results of the health check was as follows:

- Minimum order quantity missing: 18.3%
- Stock on hand missing: 5.8%
- Purchase price missing: 25%
- Dimensions or weight missing: 18.3%
- Lead time missing: 4.8%
- Service lifetime missing: 4.8%.

Based on DiManEx, the customer will have a possibility to complete the missing data and have then updated results.

In conclusion, identification of 3D printable parts may be very challenging, especially if the number of spare parts is high, which is typically the case with OEMs carrying hundreds of thousands of service and spare parts, and the input data is incomplete. The identification may be carried out part-by-part, but for more automatic analysis of 3D printability potential and for larger spare part groups, these kinds of analytics tools, platforms and services are very valuable and welcome, when input data can be gathered effectively. It is essential, especially in the case of spare parts, that supply chain-related data points are also taken into account in addition to the technical data (as costs of 3D printing can be higher than conventional manufacturing), but the cost efficiency can still be followed by, e.g., shorter delivery times and smaller minimum order quantities.

4. Properties and performance of AM parts

It is essential that the quality and performance (geometry, tolerances, mechanical properties, long-term performance) of additively manufactured spare parts will meet the requirements that have been set for the original parts. The availability of materials for additive manufacturing is limited, therefore quite often substitutive materials have to be used. In the case of metal alloys, AM may produce different microstructure than other manufacturing methods such as casting or moulding, which has to be taken into account in post-processing, especially in the selection of heat treatment procedures.

4.1 Study and publication on AM materials and heat treatments

A report “Heat treatment of AM alloys” (Riipinen 2020) was prepared as part of WP2 providing an overview of conventional heat-treatment practices for steels, aluminium, titanium and nickel superalloys that are widely used in laser powder bed fusion (L-PBF) processes as well as a short literature review on the effects of different heat treatments on material properties. AM alloys differ from conventionally manufactured alloys in terms of microstructure, hence often resulting in different material properties. AM-specific standards, such as the ASTM standards, provide heat treatment guidance for a few L-PBF processed AM alloys that are largely based on or are directly adapted from Aerospace Material Specifications (SAE AMS). The L-PBF process produces anisotropic structures characterised by non-equiaxed grain morphology, texture, high dislocation density and micro segregation of alloying elements, among other phenomena. The response of the as-built AM alloys to different heat treatments differs from that of wrought or cast alloys.

The materials discussed in the report are: steels (316L, Maraging, 17-4 PH, H13), AlSi10Mg, Ti6Al4V and nickel superalloys (Inconel 625, Inconel 718). These materials represent the majority of AM alloys used by commercial L-PBF part manufacturers. The purpose of heat treatments is to remove residual stresses induced during the L-PBF process and/or change the microstructure of semi-finished products for further processing and to achieve final material properties dictated by the application, e.g., higher strength or toughness. The advantage of AM is the possibility to manufacture near net-shaped parts, therefore not requiring any additional processing steps to induce plastic deformation. L-PBF parts are attached to the build platform by support structures to facilitate the production process and it is recommended that the parts are heat-treated prior to removal from the platform to release the internal stresses to prevent deformation of the parts. Stress relieving is the common practice to achieve this where the parts are heat-treated at low-to-moderate temperatures to release peak stresses prior to the removal of parts. For conventional alloys, stress relief is used to release stresses induced by processing such as machining, welding, casting, etc. As an example, the susceptibility of 316L to stress corrosion can be reduced if its stress is relieved. However, for AM alloys, the recommended stress relieving temperatures are not high enough to induce much change to the microstructure, thus the unique AM microstructure largely remains after stress relief. AM alloys typically have high strength in the as-built condition due to the unique microstructure induced by rapid solidification and consecutive heat flow from melting the subsequent layers. This often results in a cellular/dendritic solidification structure with dislocation entanglement and columnar grain structure in solidified melt pools.

Many alloys are strengthened by aging heat treatment with the goal of precipitation of second-phase particles from the supersaturated matrix that pins dislocation movement, hence increasing the strength of the material. Prior to aging, the precipitates are dissolved into a solid solution by a solution-annealing process, where the material is heated in a single-phase region for a sufficient amount of time and typically cooled down quickly. It has been observed that small nano-sized precipitates often form in AM alloys during the rapid solidification and reheating of layers during L-PBF processing. Therefore, the solution treatment temperatures and hold times should be selected carefully to ensure the full dissolution of the elements. HIP processing is commonly applied to AM parts to effectively reduce porosity induced by the printing process. The reduction in the amount and size of pores improves fatigue performance and tensile properties. However, in some cases, HIP results in the growth of precipitates / inclusions having an unfavourable effect on the mechanical properties.

Table 1 provides a short summary of the typical heat treatment for each alloy comparing the microstructure and mechanical properties between AM and conventionally (wrought / cast) manufactured material based on literature. A more detailed explanation for the effect of heat treatment on microstructure and mechanical properties can be found in the report “Heat treatment of AM alloys”.

Table 1. Summary of heat treatments for AM alloys.

Alloy	Thermal post-processing guidance in ASTM standard	Typical heat treatment	Microstructure after heat treatment (conventional)	Heat treatment considerations for AM alloy	AM microstructure	Mechanical properties
316L	yes (ASTM F3184-16)	Annealing	Austenitic, equiaxed	Heat treatment above 900°C is required for maximum stress relief. Solution annealing typically does not result in homogenous microstructure but rather coarsening of as-built grain structure or partial recrystallisation. HIP as per ASTM F3184-16 produces recrystallised structure.	AM microstructure is anisotropic with elongated grains, fine dendrites and microsegregation. Annealing results in grain growth and partial recovery. HIP results in partial or full recrystallisation. Oxide inclusions tend to grow during heat treatments.	AM alloy has its highest strength in the as-built condition (superior to wrought alloy). Tensile properties are comparable/ superior to wrought alloy in annealed/ HIP'd condition. Impact toughness is lower than that of wrought alloy.
Maraging	no	Solution anneal & age hardening	Martensite & second-phase precipitates (Ni3Mo, Ni3Ti)	Conventional heat treatment procedure is sufficient for AM alloy: Solution anneal at 820°C followed by ageing at 460-480°C. Higher aging temperatures can be used for improved	Mostly martensitic with some retained austenite. The texture present in the as-built material is reduced after annealing.	Strength increases with annealing and aging heat treatments and is comparable to conventional age-hardened maraging.

Alloy	Thermal post-processing guidance in ASTM standard	Typical heat treatment	Microstructure after heat treatment (conventional)	Heat treatment considerations for AM alloy	AM microstructure	Mechanical properties
				ductility and lower strength.		
17-4 PH	no	Solution treatment & ageing	Martensite (lath) & second phase precipitates	Solution annealing at ~1040°C and ageing at ~480°C (H900) can be considered an effective heat treatment procedure for the AM alloy.	Fine martensitic grain structure after solution anneal and ageing. As-built material has some retained austenite. High nitrogen concentration in feedstock powder can increase the fraction of retained austenite.	Tensile properties comparable to wrought alloy can be obtained for AM alloy by using appropriate solution annealing and ageing parameters. Some anisotropy between samples built in different orientations is likely to remain after heat treatments.
H13	no	Hardening & double tempering	Tempered martensite,& vanadium carbides	Quencing (1020°C, AC) and double tempering (~600°C) results in high strength but low ductility. HIP (1130°C / 6 h,100MPa) performed prior to quenching and tempering improves ductility and strength.	The microstructure after hardening and double tempering consists of tempered martensite with some retained austenite and relatively homogenous precipitation of fine secondary carbides. Heat treatment at austenite temperature removes the cellular/dendritic solidification structure.	Quenched and double tempered alloy has comparable/ superior strength and lower ductility than wrought alloy.
AlSi10Mg	yes (ASTM F3318 - 18)	T6: Solution treatment & artificial ageing	α(Al) + Si dendritic structure, Mg2Si precipitates	Solution treatment temperature above 480°C is recommended to produce a homogenous solid solution. The growth of hydrogen porosity has been reported at temperatures >525°C. Ageing temperatures between 160-180°C have been utilised effectively, but the hold times have to be adjusted accordingly.	Solution annealing leads to coarsening of Al-rich cellular grains and Si-particles surrounding the grains. Artificial ageing leads to precipitation of Mg2Si.	Solution-treated and aged AM alloy has similar strength as a cast- and heat-treated alloy (T6) but has higher ductility.

Alloy	Thermal post-processing guidance in ASTM standard	Typical heat treatment	Microstructure after heat treatment (conventional)	Heat treatment considerations for AM alloy	AM microstructure	Mechanical properties
Ti6Al4V	yes (ASTM F2924 - 14, ASTM F3001 - 14)	Solution treatment & ageing	α + transformed β	Stress relief at 900°C was recommended over the lower temperatures as it produced α + β lamellar structure with good mechanical properties. The traditional solution annealing + ageing process does not necessarily produce optimal microstructure for AM alloys but is still applicable in terms of tensile properties. HIP processing in accordance with ASTM F2924-14 produced a structure with α grains embedded in β grain boundaries.	Fully martensitic α´ structure within prior β grains in the as-built condition. Annealing produces a lamellar α + β structure. Quenching from solution anneal temperature transforms β into α'. Some β forms during ageing heat treatment.	The as-built material with acicular α´ structure has the highest strength, which is superior to a wrought and annealed alloy, but has lower ductility. Annealing improves ductility due to formation of a + β structure with a decrease in strength. Solution-treated and aged material has slightly lower strength than a wrought and heat-treated alloy. HIP processing improves ductility and fatigue strength more effectively than the as-built condition.
Inconel 625	yes (ASTM F3056 - 14e1)	Solution anneal	Austenitic (solution strengthened)	The typical solution annealing at 1150°C followed by a water quench produced a ductile recrystallised structure. Ageing increases strength but reduces ductility due to precipitations.	Equiaxed recrystallised grain structure after solution annealing and quenching. Primary MC carbides and secondary carbides.	As-built material has higher strength and ductility comparable to wrought and annealed alloy. Slight improvement in mechanical properties are achievable via an appropriate solution-annealing process.
Inconel 718	yes (ASTM F3055 - 14a)	Solution anneal & ageing	Austenitic with γ' & γ'' precipitates (+ carbides)	The solution-annealing temperature should be above 980°C to dissolve second phases. Solution treatment temperature 1020°C has been proven effective. A single ageing step at 720°C is potentially more effective than the traditional two-step aging treatment. HIP	Solution anneal at sufficient temperature results in a recrystallised equiaxed microstructure. Typical ageing procedure was found to be suboptimal for AM alloy in terms of γ´/ γ'' phase structure. HIP can produce intergranular precipitations that are detrimental to mechanical properties.	The tensile properties of solution-annealed and aged AM alloy are comparable to a wrought and heat-treated alloy. HIP can result in precipitation of the δ phase, decreasing the strength of the material.

Alloy	Thermal post-processing guidance in ASTM standard	Typical heat treatment	Microstructure after heat treatment (conventional)	Heat treatment considerations for AM alloy	AM microstructure	Mechanical properties
				at 1200°C resulted in precipitation of δ at grain boundaries.		

The heat treatment guidance for AM alloys is largely based on aerospace specifications that are not designed for L-PFB materials. According to the research papers reviewed in the report (Riipinen 2020), traditional heat treatment procedures can result in satisfactory mechanical properties and even performance superior to wrought/cast alloys and in some instances, a modification to the practices are found to improve the material performance. However, often the microstructure and thus the material properties are different for AM alloys after heat treatment compared to conventionally manufactured alloys, which demonstrates a need to develop heat treatment practices specifically for AM alloys and to adopt and modify the existing practices to better suit the L-PBF process.

4.2 Demonstration of a safety critical component

A demonstration was conducted by additively manufacturing (L-PBF) a safety-critical component for destructive testing together with the original OEM part for comparison. The original part is an aluminum casting containing features that are designed to break under external load while undergoing little plastic deformation. The purpose of the demonstration was to study how the printed parts compare to the OEM part where one of the printed parts was in as-built condition and the other was stress-relieved. The AM parts were built from AlSi10Mg alloy and the OEM part was made from cast AlSi9Cu3. The mechanical properties of L-PBF processed AlSi10Mg (SLM Solutions Group AG, 2019a) and AlSi9Cu3 (SLM Solutions Group AG, 2019b) are similar, leading to the decision to use AlSi10Mg powder to manufacture the parts. The destructive testing produced useful data showing that additively manufactured parts could be used instead of the castings in terms of material performance in a critical application, with the benefits of on-demand production capability and flexibility in material selection and component design.

Two parts were printed at VTT premises using the SLM Solutions 125HL system under argon atmosphere and constant gas flow (industrial argon). AlSi10Mg alloy powder, supplied by SLM Solutions, was used as feedstock material. General AlSi10Mg process parameters, provided by a machine vendor, were used for 50µm layer thickness, where the parts were printed on an aluminum platform that was pre-heated to 200°C. The height of the build was 109.2 mm, consisting of 2,184 layers and the estimated build time was calculated as 29 h 32 min. The powder ran out 100 layers (5 mm) before the completion of the build, which did not affect the testing in any way.

After printing, the parts were removed from the platform using EDM and the supports were removed by machining. One printed part was heat treated (stress relieved) by holding the part at 285°C for 2 h in an air furnace and cooled in air, following the specification of the standard ASTM F3301 − 18a. Stress relief was chosen, as it is a common practice after the printing process to reduce the risk of plastic deformation and cracking of parts during removal from the baseplate caused by internal stresses. One of the parts was left in as-built condition, which is more brittle than the heat-treated material and corresponds better to the cast aluminum.

The testing was conducted by mounting the parts to a Universal testing machine using a custom fixture and applying a transverse load to the parts using hardened steel rod at constant crosshead speed of 1 mm/min. The applied force as a function of displacement for all of the tested samples is shown in . The direction of the force was downwards and is thus negative in . The average maximum forces and the corresponding displacements are presented in Table 2 (mean ± standard deviation). The values in Table 2 correspond to the breaking strain that caused failure of the tested features. The features on the cast component failed on average at 376 ± 12 N force and 0.9 ± 0.1 mm displacement, while the printed features in as-built condition required a larger force of 517 ± 13 N and were slightly more ductile as indicated by the larger displacement (1.4 ± 0.1 mm). On average, the printed material required 37% more force to fail and had 55% greater displacement. Both the cast and the printed material were relatively brittle and behaved in a similar manner. However, the printed part which was stress relieved was significantly more ductile than the as-built counterpart and the tests were halted before the maximum displacement was reached. The maximum force was reached as indicated by the data in , which was lower than the as-built material, as expected.

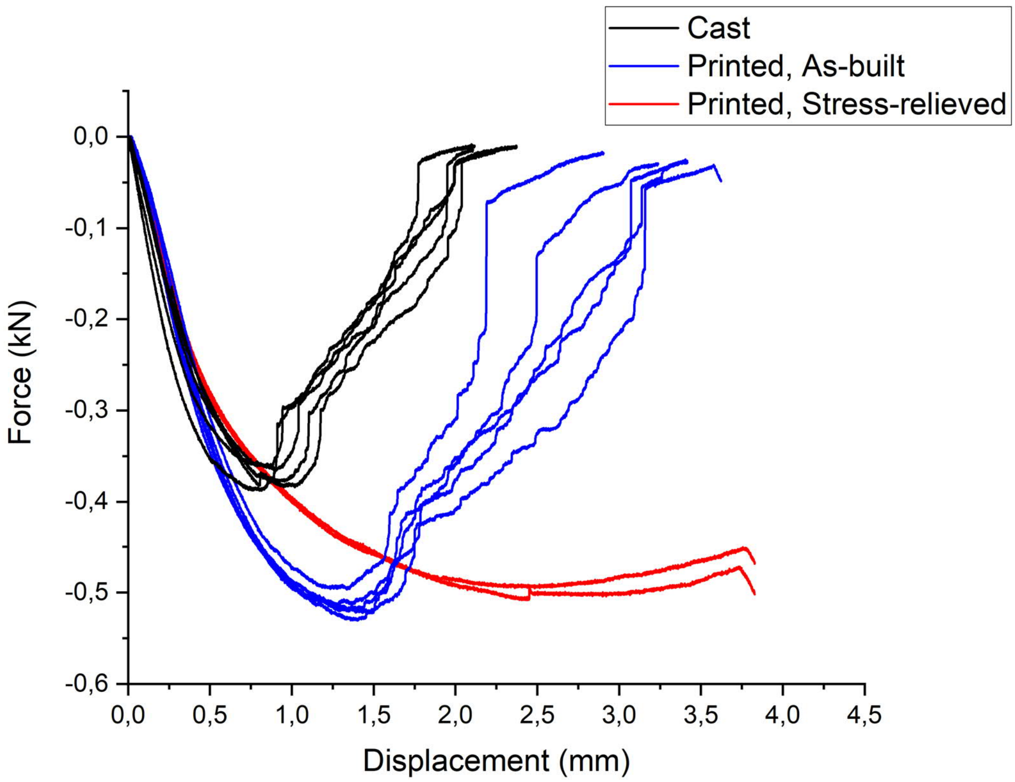

Figure 5. Force-Displacement curves obtained from the tests.

Table 2. Results of the mechanical testing.

Material	**Max. Force (N)**	**Displacement at Max. Force (mm)**
Cast, AS9U3	376 ± 12	0.9 ± 0.1
Printed, AlSi10Mg (As-built)	517 ± 13	1.4 ± 0.1
Printed, AlSi10Mg (Stress-relieved)	502 ± 9	2.5 ± 0.03

The thickness of the tested features were 0.2 mm thicker in the printed parts than in the OEM reference part, making direct comparison between part geometries impossible. Despite this, both the printed (as-built) and cast parts performed in a similar manner under load. Having the same geometry for the printed parts would have resulted in a smaller difference in the maximum force. Based on the results of the mechanical testing, the printed AlSi10Mg parts can be considered a suitable replacement for the original cast parts. The alloy composition of the printed and cast parts do not necessarily have to be identical if the higher strength of the printed material is acceptable. The printable AlSi9Cu alloy, which has a chemical composition comparable to that of the cast AS9U3 alloy, has slightly lower strength in as-built condition compared to the AlSi10Mg and could offer a slightly closer match to the OEM part. In addition, the geometry of the part could easily be modified to accommodate the difference in material properties. Such a structure could be made lighter by replacing solid material with lattice structures while still maintaining high stiffness and strength.

4.3 Variability in mechanical properties between AM machines and the effect of heat treatments

For distributed manufacturing of digital spare parts by AM, it is important to quantify the level of variability in mechanical properties of parts produced using AM machines and powders from different vendors, as would be the case when different AM service providers are used for the production of spare parts. A study was conducted with two different machines and two different powders of the same nominal composition (AISI 316L) by building an identical set of material testing specimens (Reijonen et al. 2020). In addition, the specimens were subjected to three different heat treatments to test whether standardised heat treatments are an effective method to reduce variability due to the use of a different machine/powder combination.

4.4 Methods to reverse-engineer spare parts

The thesis *Methods to reverse-engineer spare parts* (Colombo 2019) explored reverse-engineering methodologies to obtain a 3D model from each of the single and combined input data available from a spare part: a 2D paper drawing, a 2D digital drawing, the physical spare part or the physical mold/tool used to produce it, a nominal 3D model, and their combinations. It also highlights the quality control of reverse-engineered spare parts.

4.5 Accelerated weathering of AM plastics

One of the project objectives was to provide new information about the long-term environmental performance of additively manufactured materials. The information is essential for engineers and designers in product development to foresee the performance of parts, improve designs, and avoid safety hazards. An accelerated weathering test and a tensile test was conducted to study a selection of plastic materials, both conventionally made and 3D-printed. The weathering test simulates a prolonged exposure to the outdoor environment, namely temperature, humidity, and ultraviolet (UV) radiation.

Plastics are polymers with a high molecular mass. They consist of tightly packed, long chains of repeating monomer units. The backbone of the chain is often composed of carbon. UV radiation, temperature differences, and moisture will gradually degrade all plastics. Some wavelengths are absorbed by the material and in the presence of oxygen, water, ozone, and impurities can cause photolytic, photo-oxidative, and thermo-oxidative reactions that lead to material degradation. On the molecular level, the bonds between the monomer units are broken (chain scission). The changes will affect the molecular weight of the material and its optical and mechanical properties. Visually the degradation is seen as discoloration (yellowing), cracking, or erosion. Other degradation pathways include ozone-induced degradation, mechanochemical degradation, catalytic degradation, and biodegradation. The sensitivity of a polymer to a certain wavelength of UV radiation is mostly based on the type of chemical bonds present in the structure (Singh et al. 2008). The resistance of a polymer to photo and thermal degradation can be improved with certain additives, photostabilisers, which will either absorb and radiate excess energy, or block some of the chemical pathways that lead to material changes (Feldman 2002). In 3D printing, the layer-by-layer manufacturing process not only affects layer bonding, but also the crystallisation of polymer chains across consecutive layers (Chatham et al. 2019). As a result, the properties of printed materials may differ significantly from materials manufactured conventionally.

In order to understand the performance of 3D-printed plastic in outdoor environments, a test setup with two consecutive steps was implemented. First the test samples underwent an accelerated weathering test according to ISO 4892-3. The weathering test was followed by a tensile test as per the ISO 527 standard. A total of 21 material types (or print orientations) were tested. Half of the samples went through the weathering cycle. The 3D-printed materials were PA2200 and PA3200GF (selective laser sintering), PA12 (multi jet fusion), and continuous carbon fibre reinforced polyamide (material extrusion). In addition, three different UV-resistant coatings were tested on the 3D-printed parts. Conventionally produced materials were included as additional references. These included ABS, PMMA, PC, PA12G, PA66GF30, and PA66MoS2.

For 3D-printed polyamide samples made with selective laser sintering and multi jet fusion, the average tensile strength was 58% for the flat print orientation and 62% for the upright print orientation as compared to the values of the non-weathered samples. Similarly, the elongation at break value was as low as 12% (flat) and 19% (upright). Such brittleness caused by the weathering was witnessed for most of the tested plastics. UV resistant coatings did reduce the effects. The detailed results for all the material types will be published as a scientific article (Puttonen *et al*., 2021a).

4.6 Corrosion testing and micro-computed tomography of selectively laser melted 316L stainless steel

The corrosion of additively manufactured metal components is still scarcely researched. Parts created with the selective laser melting (SLM) process are clearly different from their wrought counterparts. In SLM, the grain size is generally smaller and the grains are aligned along the build direction. In 316L stainless steel, variations of alloying elements such as Mo or Cr may occur in the matrix. Mn-Si oxides have been reported instead of the typical MnS inclusions. SLM-induced residual stress has been shown to increase corrosion susceptibility (Sander *et al.*, 2018). In addition, the geometrical complexity of additively manufactured parts may play a role in the equation. This possibility has not, to the authors' knowledge, been studied in the literature. If topology or lattice optimisation is utilised in design, the amount of surface area per volume increases. In combination with a rough surface, the features may be susceptible to localised corrosion.

As part of this project, the question of geometrical complexity in combination with corrosion was explored. Two types of triply periodic minimal structure (TPMS) lattices, the gyroid and the diamond structure, were manufactured with the SLM process in 316L stainless steel. 316L has been shown to be one of the most commonly used materials in spare parts production (Kretzschmar et al. 2018). The three-dimensional structure of the samples was evaluated with micro-computed tomography (μCT) prior to and after an immersion corrosion test in a 3.5 wt. % sodium chloride (salt) solution. The results will be published as a journal article with a preliminary title: "The effect of lattice geometry and unit cell size on corrosion of selective laser-melted 316L stainless steel" (Puttonen *et al*., 2021b).

In order to manufacture the lattice parts, a few digital and physical steps of the process were explored and piloted first. Test geometries were created and printed at Aalto University to understand the lattice creation process and possible printability limitations of the geometries. Software tools and light scripting was developed to process the μCT raw data using open-source software such as ImageJ and CloudCompare. These efforts were documented and have been accepted as a conference article (Puttonen, 2020) to be presented at the ASME IMECE 2020 virtual conference scheduled for 15–18 November 2020.

The goal is to provide data about the corrosion susceptibility of complex geometries manufactured with AM, which could have design implications related to topology optimisation and lattice design. A secondary goal is to learn about the current possibilities and limitations of µCT scanning as a research and validation tool, and improve its accessibility by developing and publishing open-source methods for anyone to process µCT data for their specific needs, be they academic or industrial.

4.7 Metal-fused filament fabrication

Several spare parts were 3D-printed by using the metal fused filament fabrication (mFFF) approach. In this manufacturing process, a plastic-metal filament is applied to manufacture “green” parts. Afterwards, all components need to be sintered to remove the plastic matrix from the parts, ending up in metal components. Challenges are related to shrinkage, dimensional inaccuracies, and manufacturing process parameters. More info can be found in an associated publication (Ait-Mansour et al. 2020).

5. Process workflow and quality assurance

Automated manufacturing and monitoring/quality control procedures are developed for ensuring high quality and performance of the parts and profitable business around digital spare parts. Automation is needed in both the order-delivery process and the different phases of the manufacturing chain related to AM. The target is to have watertight and secure flow of information and fluent communication between the customer and service provider throughout all phases related to 3D printing of spare parts.

In DIVALIITO, phases of the order-delivery process were studied and discussed in an internal workshop of the project, especially the communication challenges and possibilities, and a manufacturing procedure specification including quality assurance was made and demonstrated.

5.1 The order-delivery process of a 3D-printed spare part

Communication in an order-delivery process of a 3D-printed spare part can be divided into three phases: before the order, between the order and the delivery and after the delivery. In addition, there may be some initial steps before the actual order phase related to pre-qualification of service providers, NDAs and audits. Based on the workshop with industrial partners, the offer requests are often made using email or phone, which may be quite time consuming, and the history of communication is not stored in one place. Therefore, there is room for improvement, and one option could be a purchase system, where all information on the parts including 3D models, material information, tolerances, etc. could be delivered once and then centrally stored. The system should ensure short response time to an order request and it could generate automated price estimates at least for parts with simple geometries. For parts missing a 3D model including design for AM cases and complex parts, we see that manual operations are still needed, especially if several post-processing steps are required. Besides the automated system, the service provider should also give any necessary guidance and ask further questions related to the data sharing and all phases related to manufacturing to ensure that the 3D-printed and finalised part will meet the requirements that the customer has set for it.

After the customer has ordered the part, it is essential that the progress of the manufacturing and changes related to operations are efficiently communicated as these may affect the delivery time of the part. A transparent, web-based database was recommended by workshop attendees as a good tool to track the progress of a part being delivered. For example, all changes related to the manufacturing operations could be communicated and reviewed through this tool and in addition, the system would verify that the latest versions (3D models) are used. After the delivery, the customer would decide how long to store the part-related data, communication history as well as data related to manufacturing operations such as parameter and monitoring data.

Service providers already have developed their own systems for part-related data delivery and communication. In the future, these systems could be connected with customers' databases, especially if the security of the system can be assured. These kind of lean processes would enhance the implementation of digital spare parts and make automated orders and manufacturing of the parts possible.

5.2 Case valve seat ring: Qualification of critical spare part for additive manufacturing

A joint case involving VTT, a design and engineering company, an original equipment manufacturer (OEM), an additive manufacturing service bureau and a notified body was conducted to develop the methodology for qualification of critical spare parts to be manufactured with L-PBF additive manufacturing. DNVGL CG 0197 class guideline: *Additive manufacturing - qualification and certification process for materials and components* (11/2017) was used as the basis for the qualification procedure. The study started with establishing the qualification scope and requirements, after which two integral documents to the qualification process were prepared: manufacturing procedure specification (MPS) and the test plan. The MPS contains the detailed specifications of how the qualification build of the component in question and relevant witness specimens for material testing shall be manufactured with additive manufacturing. Table 3 summarises the topics covered in the MPS. In addition to the general guidelines, a pre-manufacturing procedure specification (pMPS) was synthesised. A pMPS is a spreadsheet covering all the detailed parameters and conditions that a machine operator must follow and document when conducting an additive manufacturing build job, similar to a welding procedure specification (WPS).

Table 3. Summary of contents in the MPS.

General requirements	Pre-build operations	Build execution	Post-build operations	Appendices
Personnel training	Build file integrity	Initial layer	De-powdering	pMPS
Maintenance and calibration	Powder loading	Build startup	Part numbering	Machining drawings
Non-conformance of the L-PBF machine	Gas supply	Build monitoring	Visual inspection	
Cleaning	Platform placement	Build interruptions	Heat treatment	
Powder handling and storage			Removal of parts from platform	
			Removal of support structures	
			Removal of residual powder from parts	
			Machining	
			Surface treatments	

The testing plan describes the requirements, acceptance criteria and how the material and functional testing shall be conducted for the manufactured parts. Table 4 and Table 5 show a summary of the tests conducted for the manufactured specimens and for the feedstock powder. After the initial preparation, these documents were reviewed by a notified body and the manufacturing of the qualification build was conducted following the detailed specification described in the MPS and the build specimens tested according to the test plan.

Table 4. Summary of tests conducted for additively manufactured specimens in the case study.

Requirement	Test method	Standard	Specimen condition	Notes
Hardness	Vickers HV5	ISO 6507-1	Machined	
Tribology	Pin-on-flat	ASTM G133-05	Machined	Not conducted in DIVALIITO
Microstructure	Microscopy	-	As-delivered	
Porosity	Image analysis	-	As-delivered	
Impact toughness	Charpy V-notch	ISO 148-1	As-delivered, machined	
Tensile strength	Tensile testing	ISO 6892-1	Machined	
Chemical composition	OES	-	Not specified	
Functional test	Engine test	-	Machined	Not conducted in DIVALIITO

Table 5. Summary of tests conducted for powder feedstock powder in the case study.

Requirement	Test method	Standard	Specimen condition	Notes
Particle size	Laser diffraction	ISO 13320	As received, as exposed	
Morphology	Scanning electron microscopy	-	As received, as exposed	
Flowability	Hall flow	ISO 4490	As received, as exposed	
Packing density	Apparent and tap density	ASTM B212	As received, as exposed	
Chemical composition	OES		As received, as exposed	

The main goal of this study was to prepare the manufacturing procedure specification and test plan through a case study, as standardised guidance for how to prepare such documentation for additive manufacturing is not available, as opposed to, for example, welding (see *ISO 15609:1:2019 Specification and qualification of welding procedures for metallic materials – Welding procedure specification* and related standards*).* This approach towards qualification of additively manufactured spare parts is based on a detailed MPS and test plan. The component (valve seat ring) and witness specimens for material testing manufactured according to the MPS and tested according to the test plan, upon meeting or exceeding the set criteria, can be qualified (upon review by a relevant notified body) to be manufactured according to that specific MPS. Any essential change in the procedures or equipment as specified in the MPS shall require re-qualification.

In this case study, the main result was the development of the methodology, specifically the MPS and test plan documents and what they should include for additive manufacturing. The functional testing of the component in the intended operational environment was not conducted in the scope of this project and would be necessary for final qualification. Therefore, an official statement of qualification for the studied component was neither applied for nor issued.

6. Smart spare parts

In contrast to many conventional manufacturing methods as casting, AM enables different kinds of intelligent functionalities to be embedded into parts during the manufacturing phase. In the DIVALIITO project, the possibilities of embedding intelligence on parts were mapped (a literature survey), and several demonstrations were made.

6.1 Review and publication on embedded intelligence

The survey about smart spare parts found in literature and different sources online was carried out during the project and is planned to be published as a public VTT Research report (Vaajoki 2020). More detailed information can be seen in the publication, but a short summary is given here.

The report describes the methods and possibilities of embedded intelligence in digital spare parts using additive manufacturing. Embedded intelligence can mean sensing elements added on the surface of the parts or elements added inside the parts. In the majority of the presented cases in this report, the elements have been added during the manufacturing process. Embedded intelligence can be used, e.g., in improving the communication, detection or condition monitoring of the digital spare parts simultaneously, having the sensors well protected from the environment. The used sensors and technologies should be selected depending on the phenomena intended for measurement. However, the application of sensors and manufacturing the components with functional sensors inside the parts is not always straightforward. Especially when embedding traditional electronics in metal AM components, the accumulated heat during the manufacturing process can destroy the sensing elements and special care needs to be taken in the design process, taking into account the possibilities and limitations. Typically, for plastic components, the embedding process is easier at lower temperatures. The process interruptions to enable the embedding of sensing elements can reduce the mechanical properties of the parts and should be investigated case by case.

6.2 Multi-material 3D printing and intelligent spare parts

A master's thesis (Lehtinen 2019) written during the project provides a brief review into multi-material 3D printing and intelligent spare parts (in Finnish). In the practical part, a commercial, open-source Bluetooth sensor (RuuviTag) was embedded into a 3D-printed part during manufacturing. The beacon emits environmental values and acceleration data which can provide information about the environment surrounding the part. This data can be viewed in real-time with a smartphone or logged for a longer time span. In this case, a Raspberry Pi 3 computer running on custom code was deployed to listen for the RuuviTag emitted values. The values were logged as CSV files for visualisation.

An imaginary scenario was executed for the part. The environment of the part was deliberately changed as discrete events to see how the sensor data and its response time would allow these events to be identified inversely from the data. The test provided an initial thought experiment on how the data could be used in creative ways. Some values, such as the signal strength for example, could be used to roughly estimate the amount of material in a warehouse, or as a presence sensor to indicate whether a person has entered a room. An acceleration sensor, with higher measurement frequency, could sense abnormalities in a process environment. For example, a pump elsewhere in the system could be failing. As the sensors and manufacturing methods improve, the possible application space will be expanded, yielding new business cases.

6.3 Additively manufactured self-sensing spare parts

Previous studies at the forefront of 3D printing have demonstrated the fundamental ability to additively manufacture smart spare parts by internally integrating or embedding passive Radio Frequency Identification (RFID) sensors within the parts during the manufacturing process (Akmal et al. 2018; Salmi et al. 2018). The concept constituted the necessary fundamentals of creating a smart spare part that included communication and identification within a reasonable range.

In the current project, the concept is extended to create additively manufactured parts that can dynamically sense their own properties such as mechanical stress and strain. The self-sensing capabilities are created by embedding conductive elements such as copper and continuous carbon fibre within the part during the production process (Figure 6). To this end, the self-sensing parts allow for the measurement of the electrical resistance of the embedded conductor as a function of the mechanical stress and strain, which is calibrated before the functional operation (Figure 7).

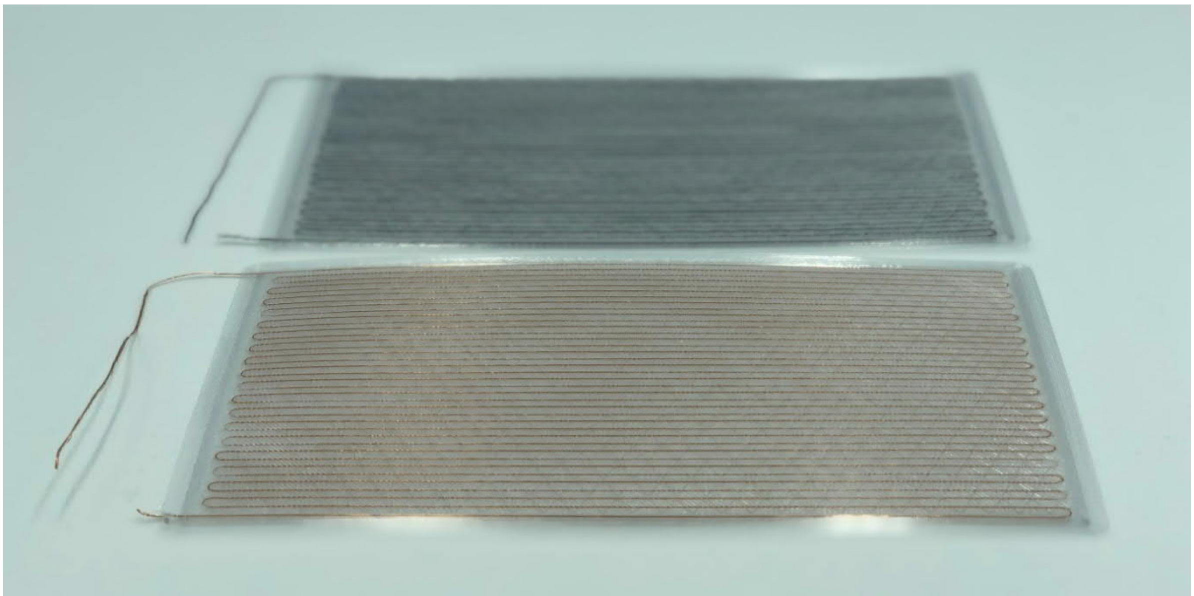

Figure 6. Additively manufactured self-sensing parts including copper (below) and continuous carbon fibre (above).

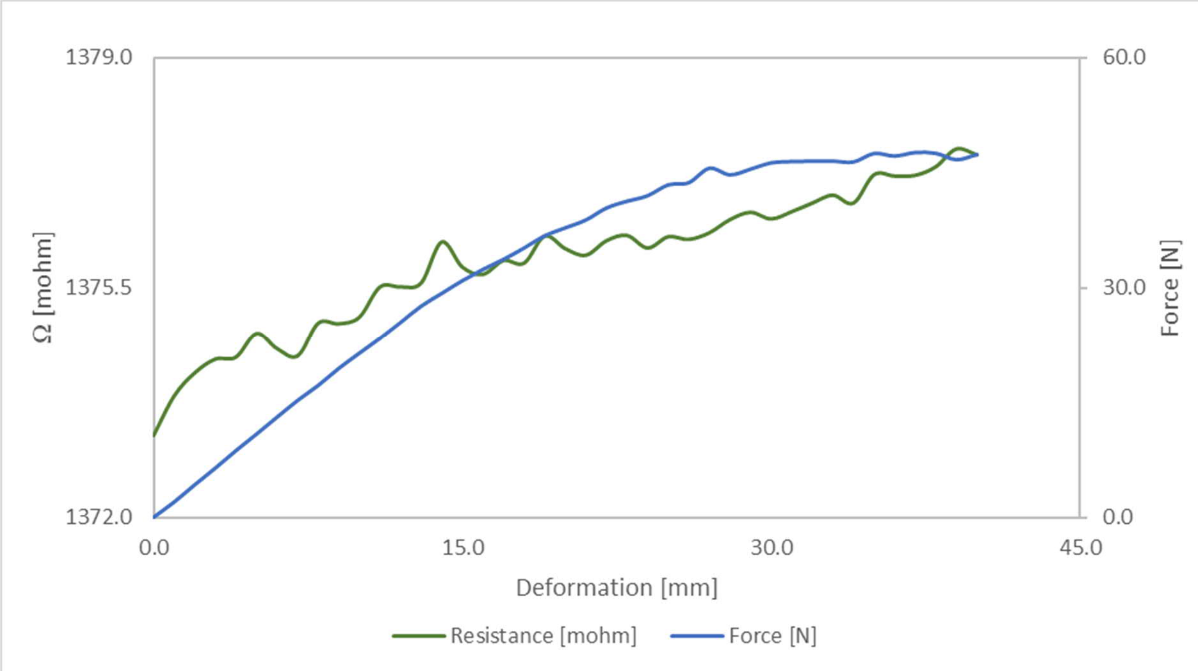

Figure 7. Change in resistance observed as a function of force and deformation.

This work, in combination with literature (Akmal et al. 2018; Salmi et al. 2018), also opens opportunities for integrating semi-passive and active sensors within spare parts that can now be powered through the conductive elements. The work develops a foundation onto which further self-sensing capabilities, i.e., temperature, proximity, damage, etc., can be tested for condition monitoring of the spare parts. In addition to self-sensing, the conductive elements can also act as an output transducer, e.g., to provide heat and magnetic flux, which opens up a vast amount of opportunities.

The results of this study will be submitted to a scientific journal for effective dissemination with the preliminary title 'Additive manufacturing of self-sensing parts through conductive elements' (Akmal et al. 2020).

6.4 Demonstration: the thermocouple part

A smart spare part demonstrator with embedded intelligence was realised at VTT during the project focusing on parts with temperature-measuring capability in demanding environments. The demonstrator was a metallic proof-of-concept part with embedded non-commercial thermocouple elements and was planned for use, e.g., in condition-based monitoring.

For the demonstrator, L-PBF was used to create the body of the part and Direct Write Thermal Spraying (DWTS) for the manufacturing of the thermocouple elements, required dielectrics and fill layers. The challenge of the structure is the heat accumulating during the L-PBF process, which can make the internal structures defective. The DWTS process enables additive manufacturing of multimaterial patterns in 3D without pre-masking and it can be used to manufacture, e.g., electrical structures, sensors, conductors and antennas which can be more robust than the commercial alternatives. The body of the demonstrator was manufactured from 316L stainless steel starting with a bottom half with varying groove shapes. The DWTS thermocouple elements and dielectrics were sprayed on the grooves (Figure 8), after which the upper half of the L-PBF was printed on top. The final structure then had the layers of 1) the L-PBF block (316L), 2) the DWTS dielectric (Al_2O_3), 3) the DWTS conductor (alumel or chromel, depending on the leg), 4) the DWTS dielectric (Al_2O_3), 5) the DWTS metallic fill (Ni5Al) and 6) the L-PBF block (316L). The layer thickness of the DWTS conductor was varied to get the structure thin enough for fast temperature change response but thick enough to withstand the heat during manufacturing.

After the manufacturing steps, the functionality and temperature response of the thermocouple elements were measured (Figure 9). Three elements with approximate thickness of 44 µm, 74 µm and 117 µm were all found functional and the temperature response for the elements were measured to be 29.5°C/s, 19.5°C/s and 10.0°C/s, respectively. The proof-of-concept demonstrator was found to be successful but additional development is needed in order to improve the DWTS thermocouple spraying for more complex structures and make the DWTS elements more pressure-proof so that the method can really be used in demanding, robust environments.

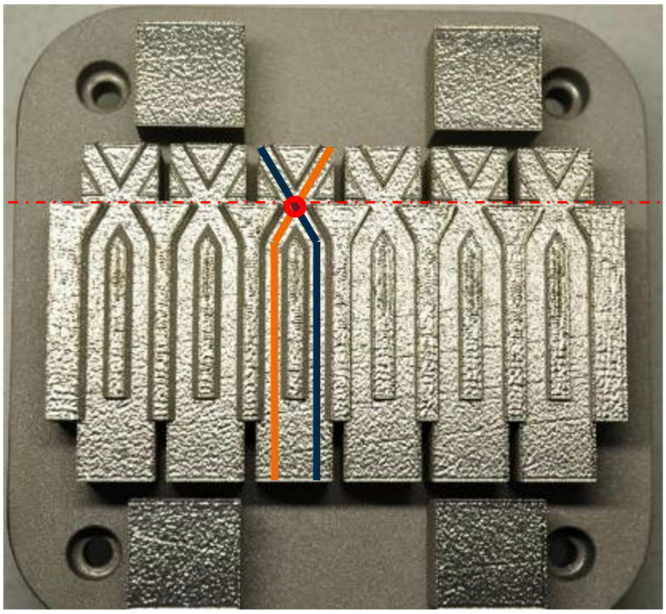

Figure 8. Schematic example of DWTS thermocouple legs of dissimilar materials and their crossing point as the planned temperature measurement spot on top of the lower half of the L-PBF.

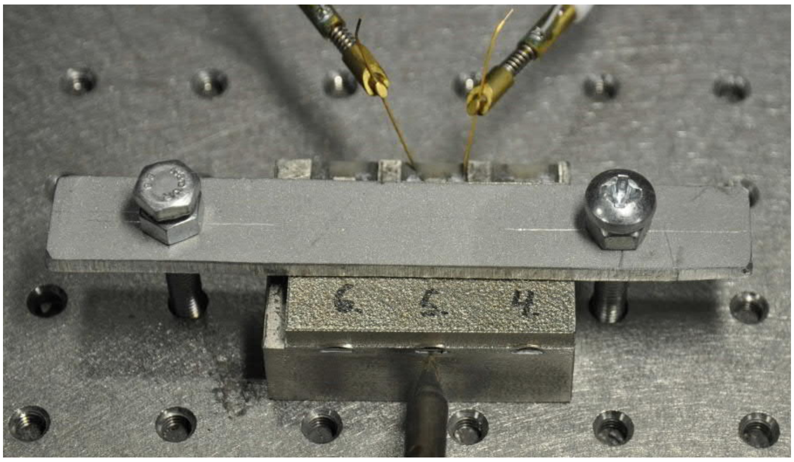

Figure 9. Successfully manufactured thermocouple demonstrator part with three temperature-measuring spots (#5 being heated and measured).

7. Conclusions

Digital spare parts will revolutionise the aftermarket business of companies in the short-term future. The drivers for digital spare parts with the highest potential are the rapid and cost-efficient manufacturing of individual parts or small batches, the integration of intelligence into the parts and the manufacturing of optimised parts. Digitalisation of the spare parts is especially suited for situations of unexpected breakdowns of a plant or a production process, long delivery times of spares due to conventional serial production processes as well as for parts of old machines. In addition, digital spare parts will enable digital stocks and warehouses, shorter supply chains, distributed manufacturing, more efficient material usage, reduced number of parts by integrating assemblies, crowdsourcing opportunities for 3D models, proactive maintenance and monitoring through smart parts, IoT and digital twins, and protecting IPR of the parts through digital identification. During the peak of the global lockdown surrounding the covid-19 pandemic, additive manufacturing has been used as a form of bridge manufacturing when global supply chains have been broken and delivery times have been months, and many of solutions were made with open source and crowdsourcing principles (Salmi et al. 2020).

Based on our findings, the following issues should be taken into account in further research and implementation of digital spare parts:

- Additive manufacturing can be a solution for spares when availability and delivery times are long – especially under abnormal circumstances.
- The major barriers for digital spare parts are the quality of additively manufactured parts, the lack of expertise in AM and the importance of data availability.
- For identification of 3D printable parts from larger spare part groups, analytics tools, platforms and services are needed, and actually those have recently been developed/are under development.
- All steps related to the order-delivery process should be efficiently communicated and the history of the communication stored for ensuring, e.g., efficient version management and quality control. Web-based tools could be developed and potentially connected to customers' databases in the future.
- Online decision support systems for AM business case identification can help students and industrial professionals understand the basic principles of AM and to obtain activity-based cost and lead time estimates.
- The availability of materials for additive manufacturing is limited, therefore quite often substitute materials have to be used. In the case of metal alloys, AM may produce different microstructure than other manufacturing methods such as casting or moulding, which has to be taken into account in post-processing, especially in the selection of heat treatment procedures.
- 3D-printed polyamide parts are not suitable for extended outdoor exposure without a UV-resistant surface treatment. The inherent part properties could be enhanced via material research and addition of photostabilisers.
- Establishing different reverse engineering methodologies, based on the type and availability of input data, can aid designers and engineers in the production of spare parts in a time-critical and quality-controlled manner.
- Embedding conductive elements within 3D-printed spare parts can enable self-sensing capabilities that can be measured as a function of desired properties for condition monitoring.
- Parts with embedded intelligence can provide valuable information, not only about their own state, but also about the state of the environment and other components in a system. Creative ways to utilise the data can generate new business cases.

References

Ait-Mansour, I., Kretzschmar, N., Chekurov, S., Salmi, M., & Rech, J. (2020). Design-dependent shrinkage compensation modeling and mechanical property targeting of metal FFF. Progress in Additive Manufacturing, 1–7.

Akmal, J. S., Salmi, M., Mäkitie, A., Björkstrand, R., and Partanen, J. (2018). Implementation of Industrial Additive Manufacturing: Intelligent Implants and Drug Delivery Systems. Journal of Functional Biomaterials, 9(3), 41. https://doi.org/10.3390/jfb9030041.

Akmal, J. S., et al. (2020). Additive manufacturing of self-sensing parts through conductive elements. To be submitted.

Ambadipudi, A., Brotschi, A., Forsgren, M., Kervazo, F., Lavandier, H. and Xing, J. (2017). Industrial aftermarket services: Growing the core. https://www.mckinsey.com/industries/advanced-electronics/our-insights/industrial-aftermarket-services-growing-the-core.

BCC Research, Global Markets for 3D printing (2019). Copyrighted Material, All rights reserved.

Chatham, C.A., Long, T.E., Williams, C.B. (2019). A Review of the Process Physics and Material Screening Methods for Polymer Powder Bed Fusion Additive Manufacturing. Progress in Polymer Science. 93, 68–95.

Chekurov, S., & Salmi, M. (2017). Additive manufacturing in offsite repair of consumer electronics. Physics Procedia, 89, 23–30.

Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I., Jussila, A. (2018). The perceived value of additively manufactured digital spare parts in industry: an empirical investigation. Int J Prod Econ 2018; 205:87–97.

Chekurov, S., (2019). Industrial Opportunities of Additive Manufacturing - Workflow planning and decision making of additively manufactured end-use components. Doctoral dissertation. Available: http://urn.fi/URN:ISBN:978-952-60-8430-5

Chekurov, S., Salmi, M., Verboeket, V., Puttonen, T., Riipinen, T., Vaajoki, A. (2020). Assessing industrial barriers of additively manufactured digital spare part implementation: a cross-organizational focus group study. In review.

Colombo, E. (2019). Methods to reverse engineer spare parts. Master's thesis. Available: http://urn.fi/URN:NBN:fi:aalto-201906234063

Feldman, D. (2002). Polymer Weathering: Photo-Oxidation. Journal of Polymers and the Environment, 10(4), 163–173.

Gallagher, T., Mitchke, M.D., Rogers, M.D., (2005). Profiting from spare parts. The McKinsey Quarterly.

Khajavi, S. H., Partanen, J. and Holmström, J. (2014). Additive Manufacturing in the Spare Parts Supply Chain. Computers in Industry. Vol. 65, no. 1, s. 50–63.

Kretzschmar, N., Chekurov, S., Salmi, M., & Tuomi, J. (2018). Evaluating the readiness level of additively manufactured digital spare parts: an industrial perspective. Applied Sciences, 8(10), 1837.

Kretzschmar, N. (2020). Assessment of additively manufactured end-use components - Current state and incremental improvements in design, materials, and decision making. Doctoral dissertation. Available: http://urn.fi/URN:ISBN:978-952-60-8939-3.

Lehtinen, J. (2019). Monimateriaalitulostus ja älykkäät digitaaliset varaosat. Master's thesis (In Finnish). Available: http://urn.fi/URN:NBN:fi:aalto-201908254866.

Puttonen, T. (2020). Evaluation of Metal Lattice Structures with X-Ray Micro-Computed Tomography: Dimensional Accuracy and Manufacturability. Accepted and to be published as part of the proceedings, ASME IMECE 2020 virtual conference, 15 – 18 November.

Puttonen, T. (2021a). Accelerated weathering and mechanical properties of additively manufactured and conventional plastics. Journal article in preparation.

Puttonen, T. et al. (2021b). The effect of lattice geometry and unit cell size on corrosion of selective laser melted 316L stainless steel. Journal article in preparation.

Reijonen, J. (2017). Identifying 3D-printable Spare Parts for a Digitalized Supply Chain. Proceedings of the 2nd Annual SMACC Research Seminar 2017. Tampere University of Technology, p. 37–40.

Reijonen, J., Björkstrand, R., Riipinen, T., Que., Z., Metsä-Kortelainen, S., Salmi, M. (2020). Cross-testing laser powder bed fusion production machines and powders for distributed manufacturing - variability in mechanical properties of 316L stainless steel with stress-relieving, solution annealing or hot isostatic pressing, Journal article in preparation.

Riipinen, T. (2020). Heat treatment of AM alloys. VTT Report, VTT-R-00899-20.

Salmi, M., Ituarte, I. F., Chekurov, S., & Huotilainen, E. (2016). Effect of build orientation in 3D printing production for material extrusion, material jetting, binder jetting, sheet object lamination, vat photopolymerisation, and powder bed fusion. International Journal of Collaborative Enterprise, 5(3-4), 218–231.

Salmi, M., Partanen, J., Tuomi, J., Chekurov, S., Björkstrand, R., Huotilainen, E., Kukko, K., Kretzschmar, N., Akmal, J., Jalava, K., Koivisto, S., Vartiainen, M. / Metsä-Kortelainen, S., Puukko, P., Jussila, A., Riipinen, T., Reijonen, J., Tanner, H., Mikkola, M. (2018). Digital spare parts. Available: http://urn.fi/URN:ISBN:978-952-60-3746-2.

Salmi, M., Akmal, J. S., Pei, E., Wolff, J., Jaribion, A., & Khajavi, S. H. (2020). 3D Printing in COVID-19: Productivity Estimation of the Most Promising Open Source Solutions in Emergency Situations. Applied Sciences, 10(11), 4004.

Sander, G., Tan, J., Balan, P., Gharbi, O., Feenstra, D.R., Singer, L., Thomas, S., Kelly, R.G., Scully, J.R., Birbilis, N. (2018). Corrosion of Additively Manufactured Alloys: A Review, CORROSION. 74, 1318–1350.

Singh, B., Sharma, N. (2008). Mechanistic Implications of Plastic Degradation. Polymer Degradation and Stability, 93(3), 561–584.

Vaajoki, A. (2020). Smart spare parts methods and possibilities. VTT Report, VTT-R-01037-20.