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A methodology for the decentralised design and production of additive manufactured spare parts

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ABSTRACT

The production of spare parts using Additive Manufacturing (AM) is an emerging area that impacts the supply chain management. To give designers a way to proceed at the moment of redesign and produce a spare part using AM, this contribution presents a methodology for the design and manufacturing of digital spare parts using AM in decentralized facilities. The re-design of the spare parts is tackled by giving design considerations based on agile hardware development practices to improve the quality of the spare parts and reduce the lead time. Since this methodology is derived from different case studies of the military over two years, the approach is suited for the defence industry but can be adapted to other industries that operate reduced facilities abroad. Additionally, three different use cases following the methodology are presented. The weaknesses of the processes are highlighted and some recommendations for production engineers and designers are given.

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Additive manufacturing; spare parts; spare part supply chain; decentralised production; re-design; design for additive manufacturing

1. Introduction

During the lifetime of industrial equipment, many of their components have to be replaced in order to keep the asset in service. Therefore, these replacement parts or spare parts have to be supplied to the customer to perform the maintenance or repair operations needed. In addition, it is common that the spare part manufacturer or the Original Equipment Manufacturer (OEM) is established in a location far away from the end-user. As a consequence, to fulfil the customer needs, the Supply Chain (SC) could become very complex and reach several layers (Jacobs, 2011; Mentzer et al., 2001).

In warehouses, more than the half of the ordered spares are one-time requests (Schrauf & Berttram, 2016) and additionally, they are needed in non-discrete time intervals, which makes it difficult to predict. This is the reason why many inventories hold a massive number of spare parts, even for many years, since in some industries, customers keep the equipment in service for 2 or 3 decades at least.

During the last years, several studies about the impact of Industry 4.0 have analysed and classified the effects of the new technologies on the Supply Chain Management (SCM)

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(Hofmann & Rüsch, 2017; Oesterreich & Teuteberg, 2016; Pfohl et al., 2015; Richey et al., 2016). Among the Industry 4.0 enablers, is Additive Manufacturing (AM, also known as 3D Printing), a technology that has reached particular interest of the researchers on a way to improve and simplify the complexity of the modern SC for the challenge of Spare Parts (Li et al., 2017; Muir & Haddud, 2017). Actually, the production of spare parts is one of the many applications of this disrupting technology. In fact, AM can produce a broad variety of components and products in any place in the SC (Khajavi et al., 2014). Many companies have already implemented AM into their SC, like United Parcel Service (UPS®) which has around 20 3D Printing facilities in its distribution centres across the U.S. by early 2020, as *The UPS Store* mentions on its website for 3D Printing locations.

Several authors have analysed the benefit of integrating AM in the SC. They highlight the possibility of easy on-demand manufacturing and manufacturing in remote locations, while shortening the SC (Attaran, 2017; Liu et al., 2014; Montero et al., 2018; Oettmeier & Hofmann, 2016; Thomas, 2016). Additionally, Goldsby and Zinn (2016) stated that using AM for lowering costs brings opportunities for changes in inventory policies and warehouse management.

The military has expressed its interest in AM spare parts before many other industrial players. Several countries have already implemented experimental AM facilities in military bases around the world (Global Defence Technology, 2019; Judson, 2020; Louis et al., 2014; Suits, 2019). This leads to the situation that the deployed facilities need to create the 3D designs or ask to the OEMs for AM suitable 3D designs. Both tasks present many complications, to begin it is really expensive to deploy a team of design experts and, in addition, many OEMs do not give 3D designs away because they simply do not exist or are protected by confidentiality reasons. This situation exposes the first research gap. The lack of formal methods for the manufacturing of AM Spares in decentralized facilities.

On the other hand, AM has some manufacturing restrictions which can be circumvented by re-designing the 3D models to make them manufacturable. In addition, spare parts are originally designed to be manufactured by traditional methods and therefore most of the spare models have to be redesigned, which is a tedious task for designers. This is one of the biggest barriers for creating AM-spares. The authors have identified problems in the re-design and manufacturing stage, relying on the experience acquired during the last years in the AM design team which they belong to. They pointed out that the risks of having part reliability issues increase when working with divided teams in different locations. Thus, the second research gap is related to ensure the same part quality standards in reduced facilities away from the design headquarters. These research gaps lead to the following research questions:

RQ1: *How to produce spare parts with a centralized design team in deployed facilities?*

RQ2: *How to improve the design-manufacturing cycle in deployed facilities to deliver reliable AM spares to the customer?*

The study is organized in 5 sections. Following this introduction a systematic literature review is carried out to present the state-of-the-art AM methods used in this study, together with the AM spare parts production background. Afterwards, by using the concepts from the previous section, a methodology for the creation of spare parts in locations away from the engineering-design headquarters is presented. Directly after, use cases from the practical application of the methodology are shown and analysed. Finally, the last section summarizes the findings and highlights future research needs in the area.

2. State of the art

2.1. Additive manufacturing

Additive Manufacturing (AM) is defined by the ISO/ASTM 52900 standards as 'the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies' (DIN, 2017). The term *3D Printing* is used often as a synonym of AM, usually associated with machines for consumer use that are low end in price and/or overall capability. AM is applicable to different materials such as ceramics, metals and a large variety of polymers.

Since the 90s AM has been used for *Rapid Prototyping* (RP), *Rapid Manufacturing* (RM) and *Rapid Tooling* (RT) applications, although nowadays it is currently being established as an industrial manufacturing method. This technology is being adopted by sectors with rigid regulations, such as aerospace, automotive and medical, which demand AM to comply with standards. To tackle that situation, several organizations published and are developing AM standards (Monzon et al., 2019). The standard releases of the collaboration between ISO technical committee (DIN, 2017) are the most widely used.

The biggest advantage of AM over conventional manufacturing is the ability to create complex geometries, enabling designers to think of completely new shapes (Wang et al., 2016) and internal structures (Flores, 2019). This is precisely why the idea of *Design Freedom* is directly related to AM. Besides that, depending on the AM process and material, some restrictions apply to that freedom (Ponche et al., 2014), compelling the designers to comply with some rules in order to have successful AM parts.

The very high degree of design freedom, makes the design process to focus on improving the function of the parts rather than on the design for manufacturing aspects (Klahn et al., 2014). This can be a challenge for designers who are not used to these new AM technologies. The field of how to overcome the remaining restrictions, helping the designers to take advantage of AM at its full potential, is called *Design for AM* (DfAM) (Thompson et al., 2016). Several guidelines, recommendations and design rules on DfAM are available, from researchers (G. A. Adam & Zimmer, 2014; G. A. O. Adam & Zimmer, 2015; Gibson et al., 2010) and standards (DIN, 2018, 2019a, 2019b; VDI, 2015).

AM has capabilities to produce small batches of highly customized products with complex and lightweight designs, furthermore, it enables mass customization (Paoletti, 2017) when several AM systems operate at the same time. This is a great asset in modern scenarios where customers demands are highly variable (Oh & Behdad, 2019). Additionally, AM can be integrated to Cyber-Physical systems (Lee, 2008; Merdan et al., 2019), hence it is considered one of the key physical components of the fourth industrial revolution, namely *Industry 4.0* (Dilberoglu et al., 2017; Nardo et al., 2020; Sony, 2018). For some high-performance or specific applications, AM can also be combined with some other conventional manufacturing technologies, in order to accelerate the process, or to meet specific requirements such as dimensional accuracy and surface finish. This is known as *hybrid manufacturing* (MacDonald & Wicker, 2016), a field that expands the possibilities of AM in particular for high-end components. By following the DIN EN ISO/ASTM 52900 (DIN, 2017) and the VDI 3405 (VDI, 2014), there are 7 AM process categories: Binder Jetting (BJT), Directed Energy Deposition (DED), Material Extrusion (MEX), Material Jetting (MJT), Powder Bed Fusion (PBF), Sheet Lamination (SHL) and VAT Photopolymerization (VPP). In this article only PBF and MEX are used, thus they are described in detail in the following section.

2.1.1. Material extrusion

Material Extrusion (MEX) is an 'AM process in which material is selectively dispensed through a nozzle or orifice' (DIN, 2017). Fused Filament Fabrication (FFF) is a MEX process that uses thermoplastic filament as feedstock material. FFF was originally developed by Stratasys® in 1989, and patented in 1992 as Fused Deposition Modelling (FDM™) (Crump, 1992). In order to avoid legal implications, the RepRap® Project created the term FFF as a synonym of FDM™, under GNU General Public Licence (RepRap, 2019). Since FFF is legally unconstrained it is preferred by many industry players and researchers.

In FFF the filament (e.g., ABS, PLA, Nylon, Polycarbonate, etc.) is normally on a spool next to the printer. A feeder mechanism transports the filament to the extruder, in which the filament heats up and melts to be placed on the build platform through a nozzle, creating a layer. By placing new layers on top of the previous solidified ones, a new part is built. The nozzle follows a path determined by the slicing of the parts 3D Model data. Depending on the machine type and manufacturer, either the build platform or the nozzle moves in x-, y- and z-direction. Movement in the z-direction with an amount specified by the layer height is done after each layer is finished. The overall resolution of the produced part, as well as the printing time, depends on this layer height and the diameter of the nozzle. Some FFF systems use a second nozzle to place another thermoplastic, commonly soluble material, that acts as a support structure. A schematic of the process is shown in Figure 1.

The strength of the parts produced by FFF depends on the building direction, being weaker in the direction normal to the layers. This anisotropy hinders the use of this technology for demanding applications. In order to fill that gap, the extrusion of multi-materials is under intense research (Quan et al., 2015; Richter et al., 2015). Good examples are the integration of composites and carbon-fiber-reinforced filaments (Goh et al., 2019; Papon & Haque, 2019; Tekinalp et al., 2014).

Despite the lower mechanical properties and resolution of this process compared to other AM technologies, by 2019 FFF is the most popular AM process among desktop users (Wohlers Associates, 2019). This is because the cost of entry-level FFF systems and its operation are relatively low, simultaneously only very little maintenance is required and no high AM-expertise is necessary to operate them.

2.1.2. Powder bed fusion

Powder Bed Fusion (PBF) is an AM 'process in which thermal energy selectively fuses regions of a powder bed' (DIN, 2017). The powder material can be metal, polymer or ceramic. Within the scope of this contribution, only Laser PBF (L-PBF) is covered, which is a PBF process that uses a laser as an energy source. L-PBF systems are offered under different names depending on the manufacturer, e.g., Selective Laser Melting (SLM®) by SLM Solutions®, Direct Metal Laser Sintering (DMLS®) by EOS®, Selective Laser Sintering

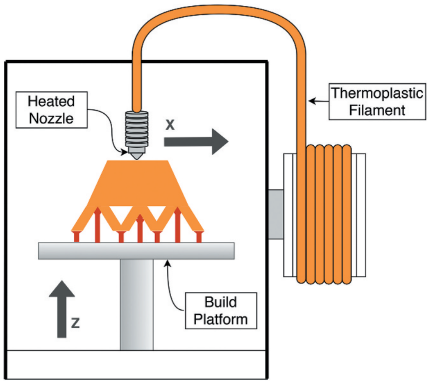

Figure 1. Schematic of a fused filament fabrication process.

(SLS®) by 3D Systems®. Although melting (fusing of fully molten particles) and sintering (fusing of partially molten particles) are different binding mechanisms between the powder particles (Mercelis & Kruth, 2006; Roberts, 2012). Both are considered PBF processes by the ISO/ASTM standards.

In the L-PBF process, the laser beam fuses powder particles together consolidating a layer. The beam is moved in the layer plane by a scanner device, which follows a path created in the slicing of the 3D model data. After a layer is complete, the powder platform is lowered down by a specific distance called layer height and a new powder layer is deposited on top. The process repeats layer-by-layer until the 3D object is done. In order to avoid oxidation, stabilize the melt pool and extract smoulder during manufacturing, an inert gas is constantly flowing through the build chamber. A schematic of the process is shown in Figure 2.

The solidification of layers and the high temperature gradients generate expansion and contraction of the material, leading to high residual stresses. This internal stress state

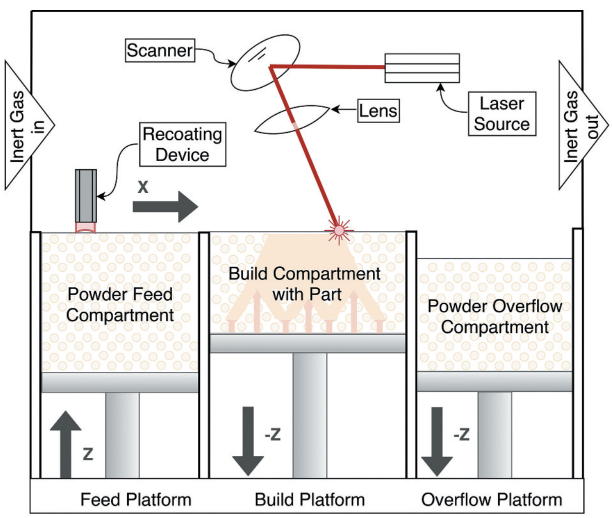

Figure 2. Schematic of a laser powder bed fusion process.

promotes undesired localized deformation and premature failures, especially in overhanging geometries where distortion is severe (Mercelis & Kruth, 2006). For preventing in-process failures, support structure is added, anchoring the part to the build plate and conducting the heat away from the part evenly (Cloots et al., 2013). Some L-PBF systems preheat the powder bed to lower the thermal gradient between loose powder and the fusing area and reduce the yield stress, so thermal deformations and residual stresses are diminished (Vrancken, 2016). The support structure is made out of the same material as the part and has to be mechanically removed by post-processing after manufacturing. Milling and wire electrical discharge machining are common practices for this purpose. Additionally, depending on the material used, heat treatments for stress relieving and part strengthening are applied. For parts with specific requirements, surface finishing and further machining might be applied.

2.2. Additive manufactured spares

AM is establishing itself as a Rapid Manufacturing technology rather than just a Rapid Prototyping solution. The application of AM for the production of functional spare parts is very recent and R&D is in an early stage (Bernard et al., 2019). Producing AM spare parts can be costly compared to traditional manufacturing methods, but the request-delivery time to the end-user can be significantly reduced, that is why it works for cases in which having to stop the service means a considerable loss for the company. There are a few successful examples of applications in the industry, like the locomotive bearing covers from the Deutsche Bahn (Stötzel, 2019), used for keeping the high-speed rail on service. Another example is the 3D printing centre of the Bundeswehr, which provides spares for the German military (Barth, 2019) enhancing the readiness of military equipment. In both examples, it is very difficult to calculate the enormous costs of the unavailability of the spares. In the first case, additionally to the cost of having a train stopped, exists the negative impact on the customer who might avoid the use of the service in the future. Finally, for the military it is impossible to calculate the costs of having an unaccomplished mission or the inconvenience of ceasing an operation overseas.

Normally, spares are produced with a previous industry mindset, i.e., with traditional manufacturing methods. However, producing an AM spare mostly involves a re-design stage, where the existing design has to be adapted in order to be re-manufactured by means of AM. This is due to the existence of geometrical features for manufacturing purpose that are no longer necessary or even challenging to produce with AM technologies. (Atzberger et al., 2018) summarizes the additive design-manufacturing of generic AM spare parts in a 3-phases process illustrated in Figure 3. When the process is done and all the related data of the spare is stored digitally, the part becomes a Digital Spare (DS) (Salmi et al., 2018). DS are transferable and are meant to be used according to need in AM systems conveniently located close to the end-user.

Several OEMs are looking in this direction. For example, in Germany within five years, 85 of the spare part suppliers are predicted to incorporate AM into their business (Geissbauer et al., 2017). A great exponent of advances in this area is the company Boeing, which holds a patented system that produces AM-spares on demand (Koreis, 2017). On the other hand, there are many legal uncertainties, especially in Europe, that

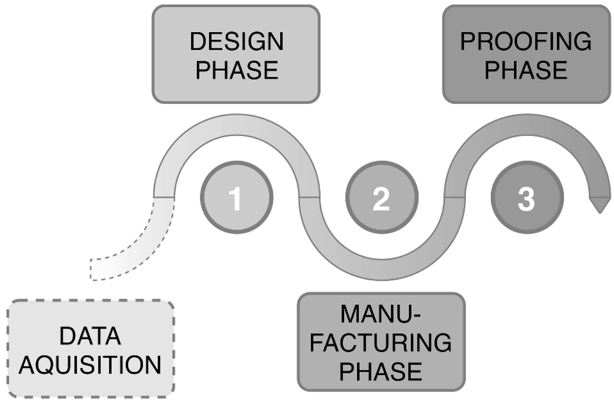

Figure 3. Simplified scheme of a generic spare part production adapted from Atzberger et al. (2018)

hinder the development of a sustainable DS market. Currently, there is no real agreement on the interpretation of the *repair* act in the European Union and it is not clear whether and to what extent purchasing a patented item and repair it or modify it is allowed (Ballardini et al., 2018). This gives place to a grey area that allows end-users to privately repair goods using AM under Intellectual Property Rights (IPR) while not infringing. Furthermore, in the case of legacy systems, the parts are likely to have their IPR expired due to their age, so there is no issue about the re-manufacturing.

Overall, the fabrication of AM spares has a great impact on three main areas: legacy systems, inventories and emergency repairs. Those are explained in detail in the following subsections.

2.2.1. Legacy systems

In some industries, the machinery that is still in use dates back a few decades, mainly because that equipment is not giving extra revenue from machine improvements. Often these machines are no longer in production, the manufacturer or the tooling does not exist anymore or even the documentation is lost. These facts are characteristic for legacy systems, which makes obtaining the spares really difficult for an eventual repair since neither the spare nor the tooling is available. As a result, the repairs are expensive or in the worst case not possible to perform.

The re-manufacturing of a spare is then considered when for any reason the spare is not available on the market, or if it is uneconomical or time-consuming to acquire new replacement machinery. This opens a window for AM, due to its ability to rapidly create any sort of shapes in small batches, it becomes a valuable instrument for those situations where tooling is a limitation. Typical examples of this are cast, injected, or stamped spare parts.

2.2.2. Inventories

From the engineering viewpoint, maintenance is one key element to the management of any physical asset (Moubray, 1997). To comply with maintenance requirements, some spares have to be available in stock and depending on the spare characteristics and criticality, different inventory policies are applied (Tiacci & Saetta, 2011). Criticality is rated by the impact on the whole system based on the failure of a part and is one of the main characteristics of the spare parts in the inventory. Other characteristics are specifity, demand, value and repair efficiency as well as some physical properties like weight and volume.

The inventory policy determines the size of the repository, and depending on the variety of parts that a supplier offers, large warehouses are necessary. In current logistic systems, critical parts have to be kept in stock. This is only economically viable for more generic parts that are used by more than just one customer. Therefore user-specific parts need to be held in stock by the customers themselves (Huiskonen, 2001). For the rest of the spares, they are requested from the manufacturer according to need, leading to waiting times conditioned by the geographic location and manufacturers capability.

The objective of an inventory management system is to maximize the service level whilst minimizing inventory investment and administrative costs (Huiskonen, 2001). This is done by either reducing time for transport, increasing availability of spares or increasing the flexibility to customer needs. All of this can be improved by using AM since it introduces the possibility of locating the manufacturing means close to the customer within a reduced space. With the right IT-infrastructure, having a Digital Spares system enables AM-spares supply on demand.

2.2.3. Emergency repairs

Most of the inventory policies contemplate local safety stocks for parts with high criticality, i.e. parts that are needed right away in case of a failure. The same policy is used with custom parts as they are spares which are, in the eventual case of an unexpected failure, not available from vendors right away. If needed, they have to be requested. This may take time as custom spares need to be manufactured separately in small quantities or even as an individual part.

AM is a great asset for those emergency repair operations since it can supply spares quickly in almost every location, a long as raw materials and electric power are provided. This leads to the opportunity to perform fast repairs through the use of provisional AM spares, produced just for the short-term to keep the system functioning until the original spare arrives. The latter is an interesting application for the military since many times equipment is deployed in locations where no spares are in stock. Moreover, If the quality of the AM spare is good enough there is no further necessity to replace it for the original, making the AM spare valid for the long-term run. In this way, machinery can be kept in operation during a mission and immediate repairs are enabled in critical situations.

3. Methodology

In this section a methodology for the production of AM spares in a decentralized way is presented in two parts. In first place is the model explaining how to tackle the manufacturing process of a generic spare part in reduced facilities, geographically away from the manufacturer headquarters. The second part details a way to re-design parts for creating a digital spare, which is the crucial element in the production of spare parts through AM. Overall, it consists of five consecutive phases carried out in two different facilities and is graphically summarized using the Business Process Model and Notation (BPMN) language.

The presented methodology is developed from experience and analysis of several case studies from the 3D Printing Center at the Research Institute for Materials, Fuels and Lubricants and the University of the Bundeswehr Munich. It is based on the creation of prototypes and design iterations, following Agile Hardware Development principles. Furthermore, it is engineered for aiding a maintenance or repair operation in a system which can have a broken, worn or missing spare part, in locations where standard logistics cannot deliver in time. This Methodology is not only applicable to the military but can as well be adapted to many other different industries.

3.1. Decentralized additive manufactured spares production methodology

In order to carry out the production of AM spare parts, a set of consecutive phases has to be pursued, following the 3-phases agile spare production process model of (Atzberger et al., 2018), shown in Figure 3. This is proven to work for the AM spare production in several layers of the SC (Mokasdar, 2012; Sirichakwal & Conner, 2016). In contrast, for the case of minimizing the SC or facing any of the situations presented in Sections 2.2.1–2.2.3, it is more feasible to produce the spares in situ, i.e. straight in the operation area.

It is common for the military to operate in areas of poor infrastructure or restricted access, where it is hard to keep the risk of an SC disruption due to external factors low. In addition, those territories are normally far away from the manufacturer of the spares. As an example, many military installations are located overseas while using equipment manufactured in different countries around the world. In this approach, these territories are called *remote locations*.

To tackle the production of AM spares in remote locations an improved process model is presented, consisting of five different phases and two different physical locations (referred here as facilities) carrying them out. The first and the last two phases are to be done in the operation area by the deployed facilities while the others are fulfilled by the local facilities. The five phases model is illustrated in Figure 4, following the Business Process Modelling and Notation (BPMN) language (Fischer et al. 2012). Since this methodology is suited for the military use case, the end-user is the same actor as the manufacturer and supplier, but internally, the actor requesting the spare (also referred as *source*) can be considered the customer as in the case of customer-driven manufacturing (Wikner and Bäckstrand 2018).

3.1.1. Facilities description

3.1.1.1. Local facilities. Local facilities have high AM specialization, big teams and laboratories with many equipment, plenty of IT-resources and human resources with high expertise. Here are the responsible for executing the main design tasks and keeping the know-how. Major technical aspects are discussed here as well. Capabilities for the development of process parameters are available and detailed testing and proofing of AM parts is being conducted. In this study, they are also referred to as headquarters.

3.1.1.2. Deployed facilities. Deployed facilities have a low to medium AM specialization, reduced team size and only the necessary equipment for producing AM spares. They hold a good expertise in dimensional data acquisition. Here are the responsible operators for 3D scans and measurements of worn parts and the AM machines which produce the spares.

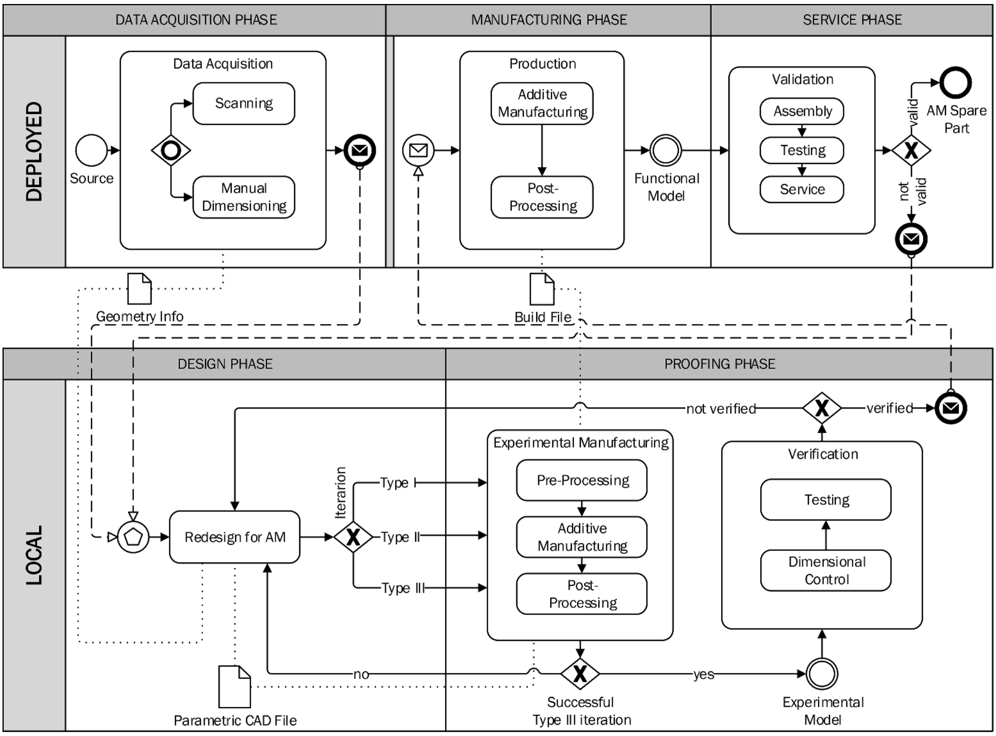

Figure 4. Process model of a deployed AM spare part production.

3.1.2. Phases description

3.1.2.1. Data acquisition phase. This phase is carried out in the deployed facilities. The process starts with the request of the spare by the end-user to replace a broken, worn or missing part. This old part is the *source* for the data acquisition sub-process, where the spare's geometry data and requirements are collected. 3D scanning, photographing and manual dimensioning are practices performed by the deployed operators, in order to generate the deliverable. The latter is a set of digital files containing the geometry information and material properties. Normally this consists of a 3D point-cloud and a text file with additional information. The deliverable is displayed in Figure 4 as *Geometry Info*. In the case that the OEM provides the technical documentation of the spare, this is the deliverable and is used as a template in the Design Phase. Consequently, the Data Acquisition is omitted.

3.1.1.2. Design phase. This phase is carried out in the local facilities. Here all the design-related tasks are performed. The data transferred from the previous phase is interpreted and the new 3D model is created. This 3D model differs from the original since it is parameterised, adapted and optimised to be produced by AM. For this reason the process is called re-design. The re-design for AM is a broad and integrative process and is therefore expanded separately in Section 3.2.

The deliverable is the parametric CAD file of the re-designed spare. In addition, this methodology uses the production of prototypes to enrich the spare design. They are called type I, II or III prototypes, the higher the type number, the higher the grade of maturity of the spare. The latter increases with the number of re-design and experimental manufacturing iterations. This is explained in detail in Section 3.2.2.

3.1.1.3. Proofing phase. The proofing phase consists of two processes, carried out in the local facilities. The first process is the experimental manufacturing. Here the 3D model data, represented by the *Parametric CAD File* in Figure 4, is pre-processed. After that, the spare is manufactured using an AM system and post-processing operations are performed. This set of operations changes accordingly to the used AM method. Depending on the maturity of the prototype, the used AM method varies. MEX is used for type I and II polymer prototypes and metal L-PBF for type III.

When a type III prototype is manufactured without any issues during the process, the resulting part is called *Experimental Model*. If the print job was successful, the development continues with the verification process. Here the dimensions and tolerances are checked, mostly through 3D scanning. For some specific features, manual measurements are necessary. Inspections for keyholes and cracks are also performed as those are the main concern in order to avoid premature failures. For high-performance parts, mechanical destructive tests are performed. When the testing results are not satisfactory or it is not possible to get a successful print job, the data is sent back to the previous phase for a new re-design iteration.

Once verification is done, a manufacturing job is sent to the deployed facilities. The deliverable is the *Build File*, which includes the pre-processed data with machine parameters and some extra specifications for post-processing operations.

3.1.1.4. Manufacturing phase. When the proofing phase is completed, a notification is sent to the deployed facilities, where the manufacturing phase starts. The same *Build File* as used in the experimental manufacturing process is transferred to the production process. Therefore no pre-processing is necessary. The Additive Manufacturing of the spare and its post-processing is carried out in this phase, in order to produce the deliverable Functional Model. The manufacturing environmental conditions are emulated from the ones in the proofing phase, to ensure the same part properties.

3.1.1.5. Service phase. This is the last phase in the deployed facilities. The *Functional Model* goes into the validation process, the spare is integrated in the destination system at the assembly sub-process and then the correct functionality of the spare is tested. If it passes the testing, it is ready to be released into service. Not passing the tests would require an extra iteration in the design phase, which at this point might have a very high cost.

3.1.3. Resources distribution

The methodology contemplates two different kinds of facilities carrying out the tasks, as explained in Section 3.1.1. They differ not only in size, technological resources and specialization but also in the operators' expertise. The local team with high expertise in AM design, manufacturing and testing creates the digital spare. On the other hand, the deployed team just needs enough knowledge to replicate the development from its counterpart but needs high expertise in data acquisition.

With an eye on saving cost by keeping only the necessary resources in the deployed facilities, it is recommended to have only one deployed expert as a team leader. The expert should have a very high specialization in data acquisition and standard knowledge about AM and testing, since the most knowledge demanding task in the remote location is the creation of the *Geometry Info* deliverable.

By taking into account these considerations, Table 1 is formulated. The level of expertise recommended for the operators in each phase is shown. The expertise is expressed in three knowledge levels, one dot means basic, two dots means high and three means very high knowledge. Black dots are indicators for mandatory knowledge and white for optional.

3.2. Re-design and additive manufacturing of spares

As mentioned in Section 2.2, spares have to be specifically designed to be produced by AM in order to have a higher rate of manufacturing success. The re-design process used in this methodology is iterative and incremental. The first iteration uses the acquired data and requirements as input. After the process, the designers deliver the first prototype. Subsequent prototypes are then created based on the feedback from the proofing phase, leading to new iterations.

Prototypes are named differently according to their grade of design richness. The higher the grade, the more mature is the prototype. Because this methodology is meant for the production of metallic AM spares using the L-PBF method, three specific types of prototypes are introduced. They are described in Section 3.2.2, using the model of Montero et al. (2019) as a basis and following the concepts behind the Adapted Media Richness Theory from T. S. Schmidt et al. (2017). The creation of prototypes is performed by following a Features Classification Template, which is expanded in the following subsection.

3.2.1. Features classification

Re-designing a spare to be produced via AM is considered as the creation of a new part in this methodology. For the purpose of having relevant parameters and its constrains under control, the CAD designs are created from scratch following a template. This template is a list or table containing the classified geometrical characteristics, called features. The latter is conceived by the interpretation of the 3D acquired data from the first phase. Therefore, aiming for a simplified model with only the necessary features

Table 1. Expertise level.

	Knowledge			
Phase Operators	Data Acquisition	AM Design	AM Manuf.	AM Testing
Data Acquisition	●●○	○	○	–
Design	●●○	●●●	○	● ○
Proofing	–	○	●●●	●●●
Manufacturing	–	○	●●	○
Service	–	–	–	●●○
Deployed Expert	●●●	● ○	●●○	●●○

(Montero et al., 2020), the classification of geometrical features is done by analysing the *Geometry Info* deliverable as follows:

3.2.1.1. Level I features. Level I features are features that compromise the technical functionalities and the performance of the spare part, as well as essential features that determine the functions of the part as a component in an assembly. Examples are fixation points, holes, pads and relevant distances, any shape that might place another component, bushings or bearing holds. Furthermore, any feature that is considered of high relevance for the specific part or component fits in this group as well.

3.2.1.2. Level II features. Level II features, on the other hand, are features which have no impact on the expected function of the component, but affect the handling or manipulation by the user, or the ease of assembly in a component group. Examples are assembly marks, guides, grips, printed instructions, fillets or chamfers on sharp edges.

3.2.1.3. Level III features. Furthermore level III features are inherent to the former manufacturing method, i.e., features that are on the part exclusively for manufacturing reasons. An example are draft angles used in cast parts, cast defect or marks, bending marks and die marks. In this group are also the features that are merely cosmetic and add no functional value to the part. They include branding marks, logos or watermarks, printed codes and ornaments.

3.2.2. Iterations and prototypes

In product development, prototypes help designers to get an overview of the final part and notice errors in the early stages of the design process (T. Schmidt, 2019). In this methodology, the creation of a prototype for the only purpose of enriching the spare part design is called design iteration. In each iteration, features are added to the spare 3D model. At the end of the process, the spare will have all level I features and only the considered necessary level II features. Level III features are neglected in the re-design for AM process.

In the early iterations, the prototypes produced in the re-design process contain basic features, i.e. the most important of the level I features. These prototypes are used to check elemental functionalities and make the necessary corrections before the first production attempt is made. Since they are preferred to be manufactured rapidly in a cheaper way, polymeric materials are used through the MEX method. Depending on the scale, in which they are manufactured, they are named differently. Prototypes of type I are spares in reduced scale and type II are spares in full scale. The same designation is used for the design iterations in which they are produced. Overall, type I prototypes help the designers to visualize the spare and identify improvements in an easier way than with a digital 3D model. Type II prototypes are used to check, if they fit in the assembly and to verify the correct design of challenging features. Type II prototypes contain all the level I features and the elemental features of level II.

The type III prototype is fully functional and is manufactured in metal with the L-PBF method. They have all the level I features and the necessary level II features. This becomes the experimental model that is verified in the proofing phase. Type III iterations involve experimental manufacturing and verification processes. Therefore, they are expensive to perform but bring a big increment of knowledge to the design team. The chance of having more than one type III iteration is low, whereas the goal of the design team is to minimize them. Together with the type I and II iterations, they are performed in the local facilities.

The last iteration, type IV, occurs when issues or manufacturing failures of the AM-spare arise in the deployed facilities. Since the production process is planned to be a replication of the experimental manufacturing process, all the parameters are already controlled, and the *Build File* is checked beforehand. Therefore, the chance of having a type IV iteration is really low, but when it occurs, it leaves a considerable knowledge increment that must be documented. This is more likely to happen in the early stages of team development. Factors as ensuring the build environment conditions of the local facilities and material shipping, make this iteration type the most expensive to perform. A summary of the detailed iteration types is shown in Table 2.

4. Practical application

Following the methodology of Section 3, several AM spares have been re-designed. In this study, just a few cases are reported, because of confidentiality reasons. With the objective of highlighting the benefits of using the proposed methodology, 4 different AM spare re-designs are presented. In the first place, two spare parts are re-designed with successful results. Then, two other spares exposing issues due to improper implementation are analysed. All the parts appearing in this section belong to legacy systems, whose OEMs do not produce the spare parts anymore.

The presented spare parts are requests from the 3D printing centre at the Bundeswehr Research Institute for Materials, Fuels and Lubricants (WIWeB). The used material is the aluminium-based alloy AlSi10Mg in a SLM Solutions® 280 L-PBF machine. The presented methodology has been tested with different AM systems and different materials, delivering similar results.

The software used in the Data Acquisition phase is Polyworks® Inspector™ which outputs a point cloud file. In the Design phase, Autodesk® Inventor® is used for the creation of the parametric CAD files. For the pre-processing subprocess in the Proofing Phase, Materialise Magics® is used, giving as an output the machine file containing machine manufacturing parameters, part geometry and support structure. For the overall file management, tracking of changes and design increments, Atlassian Jira® is implemented.

4.1. Successful implementation

The two spares of Figure 5 (a,b) were 3D-scanned and sent to the design team as a coordinated point cloud file. The re-design process took three type II iterations and an approximate design

Table 2. Variants of iterations.

Iteration	Material	Prototype scale	Experience acquired	Cost	Manuf. time
TYPE I	Polymer (FFF)	2:1	•	$	•
TYPE II	Polymer (FFF)	1:1	• •	$	• •
TYPE III	Metal (L-PBF)	1:1	• • •	$$$	• • •
TYPE IV	Metal (L-PBF)	1:1	• • •	$$$$	• • •

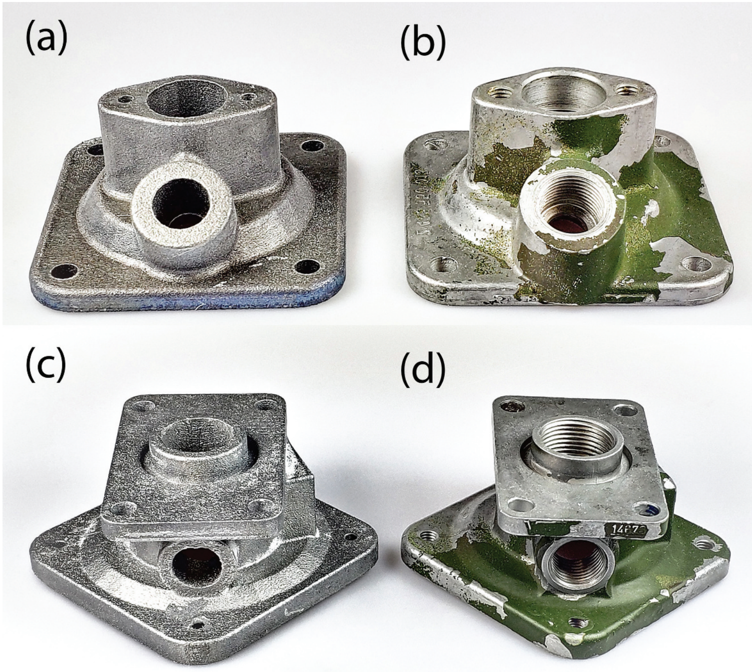

Figure 5. Reverse engineered and L-PBF printed metal spare parts (a) and (c) in *as printed* condition (a, c) compared to the original part (b, d).

time of six hours in total for both spares, carried out in two workdays, because of the prototyping time, which is not included. The proofing phase took three workdays, taking into account that the experimental manufacturing duration was around 28 hours.

Originally the parts were manufactured by aluminium casting. As it can bee seen in Figure 5 features like the identification casting numbers are not reproduced. Those are clear examples of level III features. Some other important features, like the inner threads, are to be done as post-processing operations. They are not displayed in the picture, because the parts are shown in as-built condition, just extracted from the AM machine after removing the support structure. Both parts were accepted for service.

4.2. Unsuccessful implementation

Undesired results have been experienced when the methodology was not applied rigorously. In Figure 6 (a) failed *Functional Model* can be observed, next to the original spare part. This was a mistake of the proofing phase, which transferred the 3D CAD data instead of the *Build File* to the deployed facilities. As a consequence, the manufacturing phase did their own *Build File* with standard parameters. The result was a *Build File* with poor polygonisation, that was unnoticed until after the manufacturing by the deployed personal. In the picture, a non-continuous edge on all the round features can be seen. Therefore the lack of shape quality was evident after the manufacturing. Finally, the part could not get into service, leading to a type IV iteration.

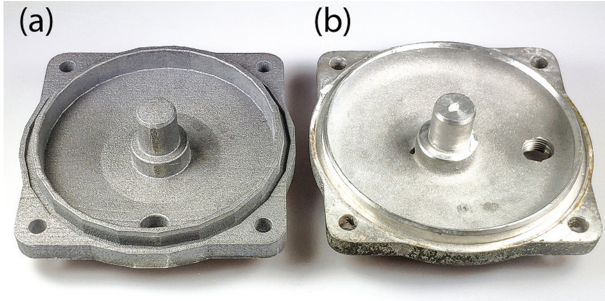

Figure 6. Insufficient resolution of the STL-File for the printed spare (a) compared to the original (b).

This result is not an isolated case in this AM design team. Many other part quality issues due to the same causes had been identified. This contradicts one element of the AM SC model presented by (Li et al., 2017), in which the supplier responsibility is to deliver STL-files (triangulated 3D models) to the manufacturer. In order to avoid such problems, this methodology suggests transferring *Build Files* instead of 3D models.

In Figure 7 another failed *Functional Model* is shown. In this case, the manufacturing had no methodology behind it. The part was 3D scanned and consecutively produced. The result was unsatisfactory since the AM spare had the same issues as the original worn part. Modifications are unfeasible since there are no parameters to modify in a 3D point cloud file. Only smoothing and subtractive tasks can be performed. The defective functionality could not be repaired and the part was rejected for service.

5. Conclusion and further research

This contribution shows a decentralized way to re-design and re-manufacture spare parts by using AM. Several spare parts have been re-designed for AM by the design team in which the authors participate actively, and delivered to a manufacturing team in a separated reduced facility. From the learning of many trial and error use cases over the last two years, a Methodology for the production of Spare Parts through Additive Manufacturing is presented and tested, with the aim of improving the quality of the

Figure 7. Spare directly printed from scan (a) compared to the original part (b).

spares and as consequence the AM spare acceptance rate. By applying the presented methodology a few case studies were reported, showing the benefits of a rigorous application of the developed process scheme. The reported parts belong to legacy systems in operation by the German Federal Armed Forces.

The use of decentralized facilities for the production of spare parts is a complicated task when there are re-design activities involved since high DfAM expertise is needed. Since DfAM is a volatile field that evolves rapidly, it becomes unfeasible to have up-to-date experts deployed. The solution of having a headquarter holding high design expertise that delivers the digital spares, based on the data collected by the deployed team, was designed and works for the case of the defence sector, but can be broadened to further industries. It is considered fundamental to have at least one expert deployed in the remote location, with high dependability and knowledge on 3D data acquisition. This is one of the costly components of the scheme.

Most of the spare parts are designed to be manufactured via traditional manufacturing methods, so they have to be re-designed in order to be AM spares. The use of prototypes with different levels of richness during the re-design stage is momentousness for reaching quality and functional spare parts in a shorter design cycle. Furthermore, it leaves a knowledge increment to the design team, which will reduce the number of prototypes needed for a successful AM job in the future. It is also really important, to create the manufacturing files in the headquarter for two reasons. At first, it is a way to ensure that the data used in the deployed facility matches exactly the local facilities, reducing possible addition of noise in file translation across platforms. Secondly, to unify the data and be able to send all the manufacturing related parameters in a single file. Thereby it is also possible to speed up the data transfer between the facilities.

The application of this methodology for producing spare parts could be considered expensive for generic consumer parts, but for specific applications, where the budget is not a limitation such as the military use in remote locations, it is justified by the increase on the service level. The logistics associated costs still playing a role, since raw materials and AM equipment have to be transported. Additionally, there are as well costs associated to the data management infrastructure, which is significant at the beginning of the operations. The main advantages of using this approach are the possibility of aiding emergency-repairs and keep outdated machinery running, in places where standard SCs can be easily disrupted or operate under uncertainty (Angkiriwang et al., 2014; Mahmoodi, 2019). The use of AM for the spare parts production simplifies the layers of the SC and diminishes warehousing, which is expensive, labour-intensive and fraught with potential errors (Schrauf & Berttram, 2016). The cases presented in this study are a confirmation that AM contributes to a faster, more efficient and more resilient SC. The main duties of the SC in the presented scheme are reduced to keep the supply of raw materials and to eventually distribute the spares to the final user in the operation area. Overall, the presented approach is proven to fulfil customer requirements and has shown to be effective when the demand is critical enough.

As future research, an extension and further testing of the methodology is expected, especially in the civil field. Since the enhancing of DfAM by using Hardware Agile Development principles is starting to get attention, a deeper understanding in this area would improve the dynamics in the Design Phase. Data management and cyber-security of sensitive data is also an issue to tackle by researchers since the digital spares have to be stored in an structured way and have to be available for access anytime in different locations.

Additionally, more research in the area of Geometrical Data Acquisition is needed, since new guidelines could simplify the first phase of the methodology and deployed experts would be no longer necessary, simplifying the phase and reducing the overall cost. A good example of advances in this direction is the work of the United States National Institute of Aviation Research (NIAR), which aims to create Digital Twins of the UH-60 L Black Hawk helicopter by using 3D scanning (Simunaci, 2020). Moreover, the use of machine learning (Wuest et al., 2016) could positively impact the geometrical features classification process and even automate the features recognition for the AM spare parts re-design.

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