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How additive manufacturing enables more sustainable end-user maintenance, repair and overhaul (MRO) strategies

Wessel W. Wits*, J. Roberto Reyes García, Juan M. Jauregui Becker

University of Twente, Faculty of Engineering Technology, P.O. Box 217, 7500 AE Enschede, Netherlands

* Corresponding author. Tel.: +31 53 489 2266; *E-mail address:* w.w.wits@utwente.nl

Abstract

This paper projects how Maintenance, Repair and Overhaul (MRO) strategies can be optimized to the specific needs of end-users using Additive Manufacturing (AM) technologies. AM can significantly reduce the design and production times for customized parts. This leads to key advantages for MRO strategies from the end-user perspective, as well as environmental and cost benefits. By enabling end-users to quickly adapt and manufacture spare parts themselves, the dependence on service providers, and parts and product manufacturers is disrupted. Therefore, end-users can better capitalize on their operational knowledge and experience. For MRO strategies, one standard process flow and four end-user optimized process flows are presented. All process flows are illustrated through an industrial case study example.

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Keywords: Additive manufacturing; 3D printing; Sustainable manufacturing; MRO strategies

1. Introduction

To lower its footprint, manufacturing technologies should try to utilize more renewable than non-renewable materials. Also, more efficient use of energy should result in lessening the stress on the environment [1]. Following recent trends in the development of manufacturing technologies, Additive Manufacturing (AM) is positioned as enabler to support more environmental sustainability in manufacturing.

In recent decades international outsourcing –especially to low-income countries– was seen as a cost-efficient method to increase competitiveness for production. However, next to doubts about the long-term impact on the environment, there are also serious concerns about the social and economic sustainability of outsourcing [2]. This trend is being reversed by shifting the focus from producing physical products to product service systems that are capable of fulfilling user needs while also reducing life-cycle costs and environmental impacts. The paradigm shift from product to integrated products and services creates innovation potential to increase sustainable competitiveness [3].

As customization is seen as a major component within high value manufacturing to provide competitive new products and services, AM is projected as key advanced manufacturing processes. In particular AM enables the production of high-value, complex, individually customized parts. Time-to-market can be reduced, as well as the cost of manufacturing. Similarly in the area of Maintenance, Repair and Overhaul (MRO), AM is seen as a potential game changer [4].

1.1. Additive Manufacturing (AM)

AM technologies encompass the set of relatively new production techniques in which products are produced by joining (adding) materials rather than subtracting (removing) them. Usually AM parts are produced layer by layer and the manufacturing process (a.k.a. 3D printing) starts from the 3D CAD model directly. In 2012, the ASTM International [5] categorized the AM processes into seven areas depending on the method of material fusion or solidification, namely:

1. Vat photopolymerisation
2. Material jetting

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3. Binder jetting
4. Material extrusion
5. Powder bed fusion
6. Sheet lamination
7. Directed energy deposition

Next to these seven distinct processes, there are in general three types of material that are utilized: (1) (photo)polymers, (2) metals and (3) ceramics [6].

For the MRO of machine parts, the most likely candidate process is powder bed fusion of metals; for instance, Selective Laser Melting (SLM) or Electron Beam Melting (EBM). For non-heavy-loaded parts, the most likely candidate is material extrusion of polymer; for instance, Fused Deposition Modeling (FDM). This distinction can be attributed to the Technology Readiness Level (TRL) of these processes. Polymer FDM is already at the production implementation phase (TRL 7-9), while metal SLM and EBM are at the technology proving and pre-production phases (TRL 3-7) [6].

1.2. Circular economy for sustainable manufacturing

The concept of a circular economy proposes a new pattern in which production, consumption and use are based on a circular flow of resources. For manufacturing and in particular MRO these circular flows generally involve: an end-user, a service provider, a product manufacturer, a part manufacturer and materials manufacturing [7]. Cascading loops, as shown in Figure 1, indicate the environmental impact and involvement of the different stakeholders from the end-user perspective.

The closest circular activity from the end-user perspective is maintenance in which (generally) no other stakeholders are involved. Further away, involving the service provider reuse/redistribution activities are located. The following loop of refurbish/remanufacture involves the product manufacturer as well. Next, as an end-of-life activity, recycling also involves part manufacturers. Finally, if these circular activities are not (economically) feasible, energy recovery and landfill remain. Obviously, from an environmental perspective this leakage should be minimized.

What Figure 1 tries to illustrate is that smaller loops (i.e. more activities closer to the end-user) are better in lowering the environmental impact and therefore increase sustainable manufacturing. For instance, the reuse or remanufacture of a mechanical part is preferred to recycling that part or even worse using virgin material.

With the ability to produce highly customized parts directly from 3D CAD files, AM has the ability to strengthen the position of the end-user and further increase eco-efficient approaches. It essentially allows an end-user to try and bypass the service provider and product & part manufacturer altogether, enabling a loop at the smallest level.

Already in communities of technophile tinkerers such developments are widely shared through internet by operating from so-called ‘fab labs’ (fabrication laboratories). Here, digital 3D design and new modes of automated production are combined in open spaces for experimentation [8].

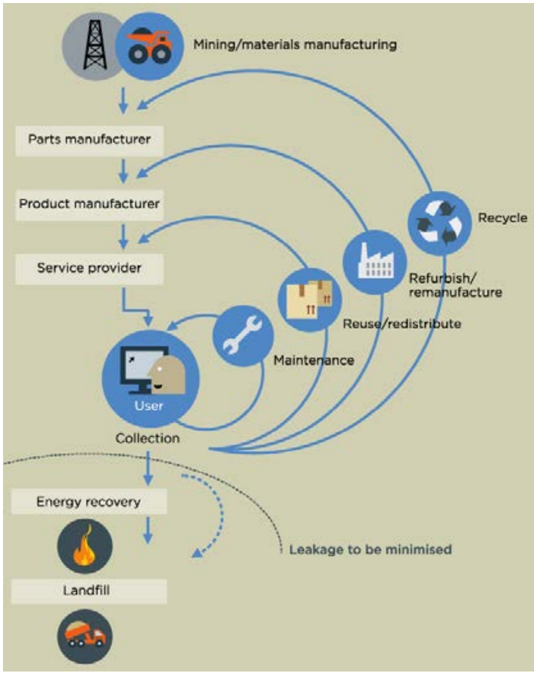

Fig. 1. Concept of circular economy for sustainable manufacturing; edited from Towards the circular economy by Ellen Macarthur Foundation [7].

1.3. More sustainable MRO strategies

Product-in-use and operational knowledge (production statistics) are well-known by the end-user; however, product and part fabrication knowledge usually not so much. Therefore to guarantee the uptime of manufacturing systems it is quite common to buy equipment including a service contract through a service provider, following the reuse/redistribute loop in Figure 1. Due to the fabrication knowledge barrier and service contracting, repair and overhaul operations are usually addressed from the Original Equipment Manufacturer (OEM) perspective, and not by the buyer and end-user of OEM equipment.

With the establishment of AM as a disruptive technology that opens up a field of possibilities, these barriers are significantly lowered. Parts can be produced from the 3D CAD file directly without having experienced fabrication knowledge. Moreover, if a digital file format is not available, a part can simply be digitized through 3D scanning of the original part. This is especially interesting for MRO activities.

AM enables the rapid development of sustainable products and is already increasingly used to produce lightweight components to save materials and costs. Thus saving a considerable amount of material, energy and cost for the production of one-off or small volume products [9], precisely the niche in which MRO activities operate.

One area where AM is already an established MRO activity is the laser cladding of high-volume aerospace, automotive, marine, rail or general engineering components, where excessive wear has occurred [10]. Laser cladding can also be used to add material if a one-off high value component has been accidentally over-machined.

1.4. End-user optimized MRO strategies

This paper presents new approaches that discuss end-user MRO strategies using AM technologies that are more effective in the short run and more sustainable in the long run. A key decision in practicing MRO is to determine to what extent a new product can be built from remanufactured parts versus new parts [11]. This decision is ultimately in the hands of the end-user.

Chapter 2 describes the general process flow for MRO strategies that allow end-users to shorten the circular loops (i.e. be more sustainable) and optimize equipment parts and equipment usage (i.e. be more profitable). The focus of this research is on the utilization of material extrusion of polymer. This was the most suitable AM technology with respect to the industrial case study that will be discussed in Chapter 3.

2. MRO process flow

Two main process flows are presented as the base of five potential strategies that allow end-users to shorten the circular economy loop and to optimize equipment parts and usage. By following these strategies, end-users take advantage of AM within the MRO area to restore/remanufacture standard components or replace a broken/failed part with a newly printed one. Furthermore, AM also enables end-users to optimize a part according to their specific needs by modifying the digital CAD model before manufacturing. Moreover, by modifying the CAD model, end-users can quickly redesign existing parts to use them in new applications.

2.1. Standard process flow

The standard flow is the first strategy that enables the end-user to get involved in MRO activities when using AM. As illustrated in Figure 2, following a three-step procedure: (1) get the CAD file, (2) 3D print the part and (3) replace the part, end-users are able to repair/restore some specific machine components themselves. Hence, they are making the circular economy loop smaller and are also optimizing the process by reducing the time to manufacture and restoring the equipment.

To carry out the Step 1 of the standard flow, three possible ways are possible. The CAD file to-be-printed can be obtained: (1) through the OEM, (2) through a digital repository or (3) generated by the end-user. A description of each possible way is discussed in the following sections.

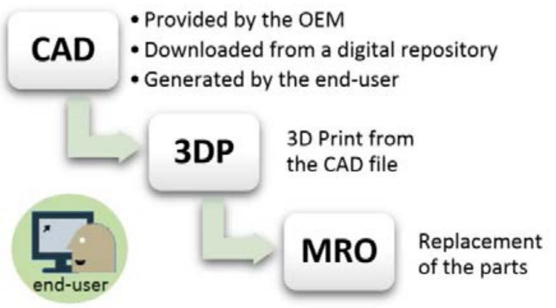

Fig. 2. Standard MRO process flow for additive manufacturing.

2.1.1. CAD file provided by the OEM

The first option to get the CAD file is by requesting it from the OEM. In fact, OEMs are increasingly willing to share part files, as a method to increase their market share. In some cases, for instance when the OEM is in a far location from the end-user, it is easier and faster to send a digital file than to send a physical spare part. Once the end-user has the original part CAD file, it can confidently print the part and then replace it into the equipment.

2.1.2. CAD file downloaded from a digital repository

When the CAD file corresponds to a standardized part, it is well possible to find it in a digital repository. Websites such as www.tracepartsonline.net, www.b2b.partcommunity.com or www.3dcontentcentral.com offer a wide content of 3D CAD models from some of the most popular parts suppliers in the mechanical, electrical, pneumatic and hydraulic industries. Moreover, some industrial automation companies such as Festo, SMC and Bosch-Rexroth also provide CAD models of most of their products on their official websites. Again, after downloading the part just needs to be printed and then replaced into the equipment.

2.1.3. CAD file generated by the end-user

The third possibility to get the CAD file is by generating the CAD model by the end-user's own means. When a 3D file is not available it is always possible to generate one. Based on the physical part to-be-replaced or from a 2D drawing, end-users can use CAD software to generate a 3D model of the desired part. Another and probably more efficient way to generate the 3D file is by 3D scanning the original part.

2.2. End-user optimized process flow

Derived from the standard flow, a more optimized process flow, as illustrated in Figure 3, enables four more strategies to consider when AM is used for MRO activities. These new strategies include one additional step, which is the design optimization of the part that is going to be printed.

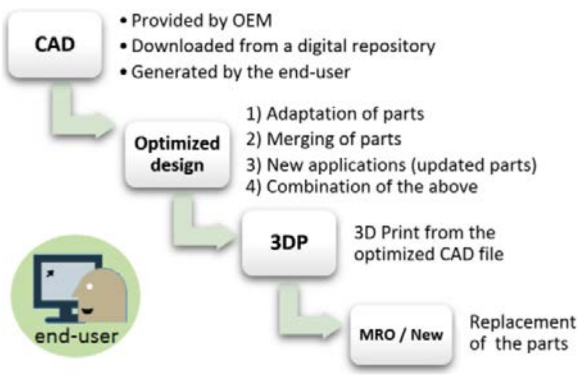

Fig. 3. Optimized flow for AM to enable end-users optimization strategies.

As stated before, one of the advantages of AM is the possibility of editing the 3D model before printing. The redesign optimization can be focused on four different goals that are discussed in the following sections.

2.2.1. Adaptation of parts to end-user needs

The first optimization goal consists of the adaptation of the desired part to specific end-user needs. For instance, if the size of the part needs be increased (or decreased) to better fit into the main component or assembly; or if the shape of the part needs to be changed to benefit the handling/assembly of the component, this can quickly be done by modifying the 3D file before printing without the intervention of actors other than the end-user.

2.2.2. Merging parts to avoid unnecessary assemblies

The second optimization goal is the possibility to merge two or more parts into one. This strategy, which consists of merging parts from 3D models, avoids useless or unnecessary assemblies.

In practice, it is common to manufacture couplings or adapters to join parts from different suppliers, or to join standard parts to end-users' tools/accessories. When feasible, using 3D CAD software to merge CAD models into one final CAD model and then print it as one part, can save manufacturing time and materials. Also, assembly resources such as fasteners, screws and weld are minimized.

2.2.3. Update parts for new applications

The third strategy consists of the modification of existing parts oriented towards new applications of the same main component. The original part will be the base of the new part and the design begins from the 3D file of the original part. For instance, a single groove pulley used in an automatic transmission system could be the base to design a hand wheel with handle to operate manually in a slower application.

2.2.4. Combination of the aforementioned strategies

Finally, the last strategy presented in this paper has to do with the combination of the aforementioned strategies. As can be inferred, the application of each strategy is not exclusive to the others and a huge advantage can be obtained by combining them. For instance, after adapting a part to specific end-user needs, it can also be merged to another and even more parts. End-users can take advantage of this newly merged part to use it as the base to design a new part usable for a different application. The industrial case study example presented in the next chapter will showcase a perfect example of how this strategy can be addressed in practice.

3. Industrial case study example

The aforementioned strategies are now exemplified by an industrial case study centered on the maintenance given to a machine for flap discs production used in the abrasive manufacturing industry. Figure 4 shows the pick-up and drop cylinder of this machine.

The maintenance of this machine is carried out by the end-user and not by the OEM. The manufacturer of the machine, as well as other industrial suppliers, only provide some spare parts to the end-user.

Fig. 4. Flap discs manufacturing machine.

One of the main components for the MRO activities is the restoration/reparation of the pneumatic cylinder shown in detail in Figure 5. This cylinder is used in the last station of the machine to pick-up and drop the final product onto the stacking disc magazine.

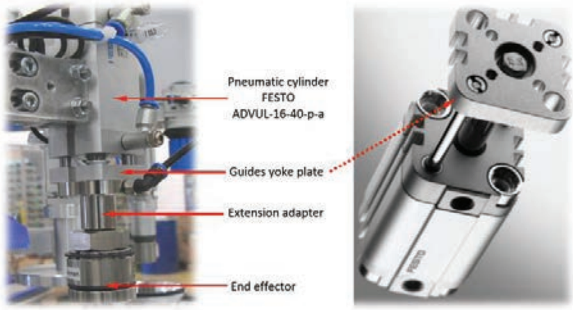

Fig. 5. Pneumatic cylinder used to pick-up and drop the final product.

As shown in Figure 5, attached to the cylinder's guides yoke plate, there is a metal extension adapter required to join the cylinder to the end effector. The replacement of this yoke plate and the extension adapter is used to showcase the application of the proposed end-user MRO strategies.

The pneumatic cylinder is a standard component manufactured by Festo. For the development of this particular case study, the 3D file of the cylinder as well as the yoke plate were obtained from the supplier website. Figure 6 shows the website from where the 3D file was downloaded.

As mentioned for this case study, polymer FDM was chosen as the appropriate AM technology. All part were printed using an Ultimaker[2] machine. This 3D printer has a heated bed and a nozzle to print 2.85mm filament wire. The specific material used was polylactic acid (PLA), a strong and hard (but brittle) biodegradable thermoplastic. Printing was done at 210°C with a print speed of 50mm/s. The printer bed was heated to 60°C. The vendor specified layer resolution is up to 20 microns.

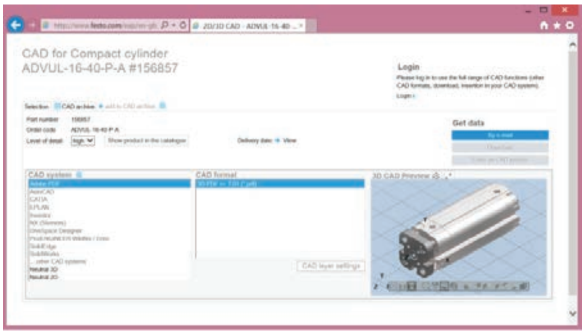

Fig. 6. Festo website to download the cylinder and yoke plate CAD files.

3.1. Conventional and standard AM process flow

Conventionally, MRO technicians restore the cylinder by replacing the guides, bushings, seals and the yoke plate. To replace the latter, they would manufacture a steel spare part, as shown in Figure 7(a), according to the dimensions of the original part. This spare part was redesigned by the MRO engineers according to this particular usage (e.g. the sensor slots were eliminated from the design). The differences between the shape of the original part in Figure 7(a) and the steel redesigned part shown in Figure 7(b) can also be observed.

Fig. 7. (a) Original aluminum yoke plate; (b) Adapted steel yoke plate.

In order to implement a more sustainable process within the MRO activities, as well as saving time and money, end-users can use AM to manufacture the yoke plate spare part. The first and fastest option for the end-users is to use the standard process flow strategy of Section 2.1. So, after downloading the 3D file from the supplier website, the end-user only needs to 3D print it and replace it. An example of such 3D printed spare part is shown in Figure 8(a) which can be easily installed on the cylinder as shown in Figure 8(b).

In this case the download and design times are negligible. As the print process planning is fully automated based on the 3D CAD file, this time is also negligible. The production of the part took about 20 min. with a material usage of about 3 g.

Fig. 8. (a) 3D printed yoke plate; (b) yoke plate installed on the cylinder.

3.2. End-user optimized process flow

Another option for end-users is to adapt the desired spare part according to the strategies of Section 2.2. In this case, the adaptations to the design were done to the 3D file downloaded from the Festo website. The changes made consisted in removing the unnecessary holes and sensors' slots from the yoke plate. Another change was the modification of the holes in the corners that are used for the screws to attach the extension adapter. Instead of cylindrical holes, the design of the new yoke plate includes two countersink holes so the used flat-head screws fit perfectly on the yoke plate. The adapted and then 3D printed part is shown in Figure 9.

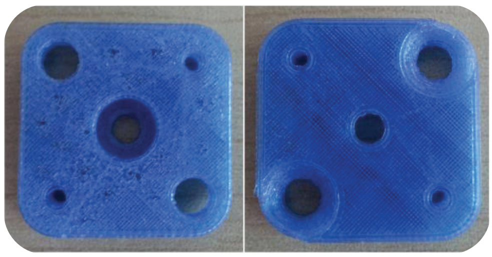

Fig. 9. Adapted and 3D printed yoke plate (front and back view).

As the design is based on the original model, the design time was about 15 min. The production of the part is a bit faster at 16 min. The material usage remains unchanged at about 3 g.

The second optimization strategy that the end-user can implement is to improve the MRO activities by merging the yoke plate to the extension adapter. This allows for manufacturing only one part instead of two. In this case, the end-user has two options, the first one is to directly merge the two parts by taking both original 3D models, joining the parts and then print it as one part, see Figure 10(a).

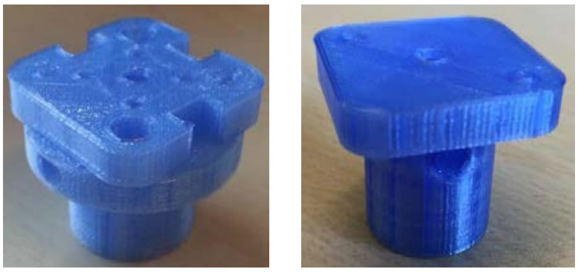

Fig. 10. (a) Merged original parts; (b) Adapted & merged parts.

The second option, leading to the next optimization strategy, is to combine the merging strategy and the adaptation strategy. Doing so, the end-user can take advantage of the adapted yoke plate and merge it to an also adjusted extension adapter in order to get a more appropriate part. This part is shown in Figure 10(b). As shown, the countersink holes used before to attach the extension adapter to the yoke plate are removed, also the shape of the adapter was changed because now it is not necessary to have a bigger diameter in the top of the adapter since the parts are already merged.

In both cases the design time is still roughly 15 min. The production time for the merged part is 44 min. with a material usage of 7 g. For the merged and adapted part this was 31 min. and 5 g, respectively.

Finally, to describe the final strategy oriented towards new applications, let us assume that the end-user wants to use the same pneumatic cylinder to pick-up and drop small and rounded bowls. To do so, and because of the shape and characteristics of the material, the end-user needs an end effector capable of picking-up the bowls using a vacuum. To fulfill such requirements and having as a base the yoke plate 3D model, the MRO engineers had to design the part shown in Figure 11(a). As can be inferred, it would be quite difficult to manufacture such part using conventional machining methods, but with the use of AM the task becomes very feasible. The 3D printed part is shown in Figure 11(b).

The design time for this part was about 30 min. Next to the original files, also some Design for AM knowledge rules were utilized (e.g. minimizing overhang). Hence, a bit more design experience was required. Production time and material usage are about 90 min. and 12 g. All in all, it is just a matter of a few hours to get a part that is ready to be installed onto the pneumatic cylinder.

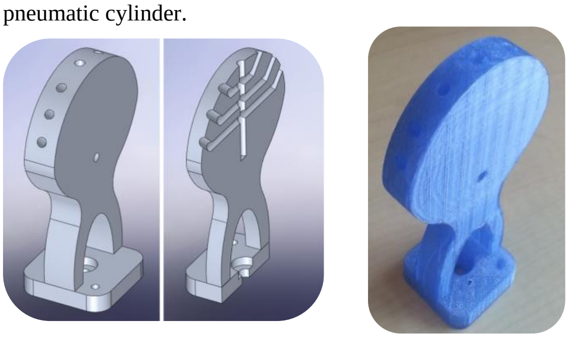

Fig. 11. (a) Redesigned 3D CAD and (b) printed part for a new application.

4. Conclusions

The quickness of the MRO activities can make the difference between achieving the desired objective of a system. In this sense, AM brings precious advantages to the end-users for the MRO activities. Besides the manufacturing benefits, AM allows end-users to have a feasible and more sustainable alternative when maintaining, repairing, overhauling or replacing components and spare parts.

On the one hand, the time spent on downloading a 3D model file from the internet, 3D printing the spare part and replacing it could be far faster than waiting for the spare part from the supplier or even manufacturing such part by means of in-house conventional methods. On the other hand, the easiness of merging parts enable MRO technicians to save time and resources when replacing some components due to the elimination of unnecessary assembly steps.

Also, the opportunity to redesign a component or spare part without the intervention of the OEM or any other external supplier gives the end-users the freedom to use their own knowledge and experience to improve the MRO performance when dealing with standard components. Moreover, the possibility of 3D printing very complex or unusual parts, empowers end-users to deploy new applications without the need of buying new components or machines.

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