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# New Trends and Developments of Additive Manufacturing in the Field of Hydraulic Drive Systems according to the Circular Economy Concept

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***Abstract:*** *Increasing the efficiency of hydraulic drive systems (HDSs) maintenance activities is a permanent concern at the global level as a result of the considerable expansion of their field of applicability. The maintenance of HDSs is part of the integrated management concept and it is a complex approach to specific activities in order to maintain HDSs performance. The development of additive manufacturing methods applicable for hydraulic components based on the principle of reverse engineering gives stability to functional characteristics and reliability in the context of the circular economy. The application of reliability-based maintenance (RBM) strategies requires the detection and exploitation of the maximum potential of HDSs operation. Through the 3D printing technology, which enables innovative performance and flexibility in on-demand production, there is the opportunity to remanufacture hydraulic components with complex geometry and specific characteristics. At the end of the article, examples of the application of additive manufacturing technologies and the adaptation of the reverse engineering principle in the field of hydraulic drive systems are presented.*

***Keywords:*** *Hydraulic drive systems, circular economy, additive manufacturing, 3D scanning*

## 1. Introduction

Additive manufacturing is one of the modern technologies that has introduced a new vision of industrial activity and perspective products. The use of additive manufacturing technology is advantageous for situations in which traditional manufacturing methods do not allow obtaining forms with complex geometries in a timely and cost-effective manner, the realization of a prototype or small series production, or in situations where the required raw materials are difficult or almost impossible to process. This method allows obtaining 3D models that can be used to create custom parts individually printed on high-performance rapid prototyping equipment. The obtained 3D model can be used as digital storage for the target part or for training in the virtual environment in various fields of activity. The 3D model resulting from the scan must be processed in such a way as to obtain the part in different layers, with different properties set for each of them in the virtual reality application. The final 3D model can be used to create a virtual reality application that allows the simulation of operations specific to the field for which the part was designed, using mathematical models to create profiles in polynomial form of reconstruction or parameterized modelling. The importance of the field of 3D scanning and printing continues to grow, so the multitude of tools and hardware methods for capturing the shape of real-world parts in three dimensions is constantly expanding. New software products for converting raw 3D data into usable digital format, such as computer-aided design (CAD) models, are being developed and implemented more rapidly by a growing number of developers and manufacturers in the field. Applications for 3D scanning have steadily expanded beyond its use for dimensional metrology in the aerospace, automotive, and power generation industries. Depending on the scanner and the nature of the project, the result of the scan is often a large number of very large files. Transforming these files into efficient formats for use can be one of the most challenging and time-consuming aspects of the project. Many projects require highly specialized software, intensive computing power, and operator skills, which can take years of development and significant cost. Laser, structured light and CT scanning instruments capture an impressive amount of data. These 3D digitizers devices often have a built-in software function used to transform scanned data into geometric features in real time. Special metadata processing software tools have been developed to bridge the gap between raw scan data and its end use, which have become integral to the use of scanners for both reverse engineering and dimensional inspection applications. The measuring instruments used for these industrial metrology applications are relatively complex and expensive. However, industrial customers have always been and still are the main source of funding for research and development of additive manufacturing (3D printing) technology. New tools such as laser and optical trackers, handheld arm (coordinated measuring machines) CMMs, and structured light scanners have helped engineers solve critical manufacturing problems, leading to increased demand and more research and development by scanner manufacturers. Parts so designed can be directly inspected, sometimes while still on a machine or in a tool fixture, using these advanced 3D measurement and analysis tools. 3D scanning technologies have seen dramatic improvement in speed, accuracy, portability and reliability. The speed and ability to go from CAD to print with close to zero set-up costs has revolutionized the market, through rapid part productions with excellent unit economy and small runs. For printing production parts, speed and price are important, but the features most often exploited are design freedom and ease of customization. In the aerospace and automotive industries, topology-optimized structures with a high strength-to-weight ratio are used for high-performance parts, and components that previously required assembly can be consolidated into a single part. In healthcare, customization is key, speed and versatility make it perfect for developing products made almost exclusively using 3D printing.

## 2. Development of additive manufacturing technology in the field of HDSs

The concept of additive manufacturing is used in professional and specialized environments; with techniques to create objects by adding layer after layer of material, a wide range can be used, from plastic, organic fabrics, to metals, combinations, etc. 3D printers use molten material in the extruder which then solidifies, or metal powders fused by baking, liquid or UV polymerized resins, or annealing, etc. can be used. In additive manufacturing, laser sintering or laser melting, repairs and coating are possible even for components with the highest material requirements. Laser generative manufacturing processes developed to industrial standards quickly, flexibly and cost-effectively generate complex shapes and individual metal components layer by layer such as: laser fusion of metals (based on laser melting powder) and laser deposition of metals (laser welding charging). Generative manufacturing offers complete solutions that include machines, laser radiation sources and services developed for various products, which provides a clear competitive advantage. With the help of additive manufacturing, specific solutions, customized components can be implemented simply and flexibly, even in the case of series production. The high stability of complex structures, as well as the low weight of additive manufacturing components, make this technology particularly attractive for the field of lightweight materials construction, still challenging for the desired sophisticated components and geometries. 3D printing has been designed to accelerate the development of industrial products with rapid prototyping and UV light curing in various industries such as automotive, aerospace, healthcare and consumer goods. The self-replicating 3D printer launched has caused a surge in interest in this type of technology used for a wide range of more affordable forms of custom manufacturing. Today there are companies that manufacture printers and offer all kinds of services using 3D printing technology for almost any part geometry, this being one of the strengths of 3D printing. One of the limitations of 3D printing is that most parts are inherently anisotropic, or not fully dense, meaning they typically lack the material and mechanical properties of parts made using subtractive or formative techniques. Due to fluctuations in cooling or curing conditions, different prints of the same part are prone to slight variations, which limits consistency and repeatability. Control over every aspect of the process, through this method, makes it possible to produce incredibly precise parts with high repeatability. Most designs require computer-aided manufacturing (CAM) to draw custom toolpaths and efficient material removal, which adds setup time and cost. For most models, especially parts with a complex configuration, this production method, which allows for a complex design without significant material consumption, has proven to be the most cost-effective. As such, the 3D printing method does not have the limitations imposed by subtractive manufacturing where the cutting tool must be able to touch all surfaces to remove material, which greatly limits the complexity of the design. In the Subtractive Manufacturing process, a large amount of material is wasted by removal to produce the final geometry of the part, aspect which is insignificant in the case of the Additive Manufacturing method. Additive manufacturing enables innovative performance and unmatched flexibility in on-demand manufacturing without dedicated equipment or tools, across all industries, unlocking the design tools of engineering. 3D printing has thus triggered a change in the way products are designed for both small companies and industry giants. This is reflected in the engineering complexity of today's additive manufacturing products, and as this technology expands and matures, so does the industrial environment. 3D printing, in addition to allowing companies to quickly prototype ideas for parts or new products, contributes and to significantly reducing the costs related to the creation of products, minimizing the waste produced and the storage space required for the products obtained. The market penetration and success of this technology depends on technical-economic factors such as ease of use, the technology complexity, low operating costs, the evolution of the supply-demand market. The high efficiency in terms of energy consumption and the use in the prototyping phase of environment-friendly materials place the 3D additive manufacturing technology in the area of technologies that observe the principles of sustainable development, this aspect being a promoter of the implementation of the technology in modern engineering activities [1-3]. Among the 3D additive manufacturing technologies, FMD (Fused Material Deposition) rapid prototyping technology is the most widely used due to its simplicity and affordability. The technique adopted in this method consists in rigorous temperature control for melting the material and depositing it layer by layer, being used in modeling, prototyping, but also in production applications [4]. This accessible technology that uses a wide range of materials is also known in the specialized literature under other names: MEM (Melting Extrusion Modeling), thermoplastic extrusion TPE (Thermoplastic Extrusion), FFF (Fused Filament Fabrication) manufacturing by fused filament [5,6]. Depending on the materials used, the market needs and the complexity of the equipment, a series of 3D additive manufacturing technologies have been developed such as:

- SLA – Stereolithography;
- SLS – Selective Laser Sintering;
- SLM – Selective Laser Melting;
- DLP – Digital Light Processing;
- FDM – Fused Deposition Modeling;
- PJP – PolyJet Printing;
- 3DP – Three-dimensional inkjet printing;
- LOM – Laminated Object Manufacturing.

For the accurate materialization of the 3D model, additive manufacturing technology involves passing a plastic filament through an extruder that heats it up to the melting point, then applying it uniformly (by extrusion) layer upon layer [7]. Controlled displacement of the extruder both horizontally and vertically is achieved by a numerical control mechanism specific to the printer. As it moves, the head deposits a thin thread of extruded plastic that upon cooling hardens immediately, sticking to the previous layer to form the desired 3D pattern. To prevent deformation of parts caused by sudden cooling of the plastic, the professional 3D printer includes a closed construction chamber, heated to a high temperature. The design stage in 3D additive manufacturing technology it’s a purely engineering stage, defining for the final product obtained [8]. With the help of a dedicated software application, the 3D model is designed and structured in layered cross-sections.
For simplicity, a 3D scan of complex surfaces with a suitable device can be used in obtaining a 3D model. This process transforms the object to be printed into a digital model, which is subjected to changes in size or configuration with the help of a specialized 3D design program, then it is analysed and prepared for the actual printing. To carry out a 3D scan, it is necessary to use a special equipment that works on the basis of a principle similar to that used by photo cameras (photogrammetric method). The difference between these devices is the use of a laser beam that is sent to the respective object and then reflected in a sensor, synthesizing this data into a digital model. Thus, with the help of the triangulation method, the equipment calculates the distance from

the scanner to the object from different angles, so that the scanner collects data about all the dimensions of the scanned object and can create the digital model, which can then be modified depending on the case.

For complex geometries or console models, FDM technology requires printing with support material that must later be removed manually. One of the materials used in applications is polyethylene terephthalate glycol modified (PETG). This is a type of hydrophobic filament, easy to use for 3D printing, characterized by a high degree of durability and impact resistance, with excellent thermoforming properties, flexibility and high chemical resistance, with high clarity and imperceptible odour. Also, this material has a low flammability rating and is approved in food contact applications. All these properties make PETG an excellent material that combines the advantages of PLA (polylactic acid) and ABS (acrylonitrile-butadiene-styrene) and recommends it for making protections, supports or casings for equipment in the medical or pharmaceutical industry, as well as in other applications. PLA is a biopolymer, a biodegradable material, considered to be ecological being made from renewable raw materials, such as corn starch or sugar cane. Apart from 3D printing, it is commonly used for packaging materials, plastic film, plastic cups and plastic water bottles. PLA is more fragile than ABS but has a higher surface hardness, being able to be cut, filled, sanded, painted, joined with the help of adhesives. ABS is a hard oil-based plastic material that can be used to create sturdy objects, electrical equipment, Lego pieces, etc. ABS filaments at the manufacturer's recommended temperature exhibit a superior bonding of the layers, ABS parts are more flexible, malleable than PLA parts and tend to bend rather than crack when under pressure.

A prototype obtained through 3D additive technology must identify with the CAD piece, (high fidelity prototype), and respect the dimensioning from the design stage [8]. The high degree of finishing of 3D printed products and mock-ups at the prototype level allows designers and engineers to carefully evaluate the proposed concepts, their implications, and make the best decisions in the shortest time, if changes are needed to launching a range of products on the market, based on the prototype used.

Additive manufacturing covers several techniques namely: 3D printing, rapid prototyping, digital manufacturing, layered manufacturing, additive manufacturing. The applications are therefore quite limitless, starting from rapid prototyping of production models, to product development for all types of industrial sectors (medical, aerospace, fashion, etc.). The concept of additive manufacturing is therefore, used in professional and specialized environments, with techniques to create objects by adding layer by layer of material, from plastic, organic fabrics, to metals, combinations, etc. 3D printers use material melted in the extruder which then solidifies, or metal powders fused by baking, liquids or UV polymerized resins, etc. can be used. 3D manufacturing is complex and efforts are made to optimize parameters such as: speed, geometric complexity, materials, mechanical properties, surface finish, tolerances and repeatability. Thus, additive manufacturing is the best choice, especially when speed is essential for small volumes and complex designs.

## 3. Reverse engineering principle applied to additive manufacturing of HDSs

The concept of reverse engineering involves working principles of a device, system or software program by analyzing its structure, function and operations. This process is applied to increase production under conditions of high product competition, thus avoiding the effort encountered in the original design. Reverse engineering originates from the analysis of various devices and systems especially for commercial or military use in order to make a new similar device or system that does not copy anything from the original. Reverse engineering is also useful for estimating the costs of the elements that make the device work. The concept of reverse engineering was approached before the development of new modern technologies, being used to copy devices or information obtained by capture in espionage operations. Hackers use this technology to remove the copy protection of software programs (cracking). Reverse engineering in programming is a technique used to analyze software to recreate and strengthen the program being applied in multiple fields: industry, electronics, software, chemical engineering, biology, etc. The reverse technique is used whenever one wants to understand the inner workings of software. The goal is to make design decisions for finished products with minimal information or knowledge of the procedures involved in initial production. Reverse engineering is used to create three-dimensional virtual models of existing parts and subassemblies, thus bringing physical geometry into the digital environment. As reverse (reconstruction) engineering is useful to analyze the functionality of products, to analyze sub-components, it can be used to complete some documents, specifically for parts designed before the development of CAD programs. The compatible reverse engineering program can interpret the measured data and generate the 3D point cloud network [9]. Measured data, usually represented as point clouds, do not contain topological information and so are often processed as triangular network (STL) files, then modeled into a usable format, a set of surfaces - Non-uniform rational B-spline (NURBS) surfaces - or a CAD solid model. Data can be transferred to a computer screen, but the overall process is much more complex. Some companies use the reverse technique when they do not yet have similar products to create their own products. The elements that allowed the development of this process consist of three-dimensional measurement systems for palpating the surface to be scanned, permanently accompanied by an information/data processing software. This information represents digital input data for processing with CAD-type software (for the integral design of products and direct obtaining of the driving programs necessary for the manufacturing system) or CAM (computer-aided manufacturing) as driving/management equipment/ of various machines and tools. To create a fully parameterized model, an advanced CAD package, for example CATIA (Computer Aided Three-Dimensional Interactive Application) or Solidworks, is usually used to achieve the final result. There are also inherent fidelity losses that occur during the technological process of reverse engineering due to the measuring equipment but also the characteristics of the part (dimensions, tolerance, visibility, density, speed, etc.). The program can be easily interfaced with third-party programs such as Polyworks, Geomagic, and Rapidform. Network generation is very fast, the key is an innovative algorithm developed to allow fast and accurate processing with fewer points, which speeds up the network generation process. The elements that allowed the development of this concept are three-dimensional measuring machines for scanning the surface, constantly assisted by a software for processing information and digital data to obtain high-performance results in terms of simulation and modeling of the desired components.

Another reason for applying the concept of reverse engineering is to compress the time required for product development to meet the competitive demands of the market. The process involves measuring an object, then reconstructing it as a 3D model. Approaching the problem from another point of view, one can observe the rapidity of the method of reconstruction of a product that no longer has the original documentation for various reasons, whether it is destroyed, incomplete, whether it is inadequate to the new technological requirements, etc. The use of reverse engineering allows a 3D product or model to be quickly transformed into a digital form, then reshaped and prepared for rapid prototyping or even rapid manufacturing. The combination of scans performed for different profiles, directions, angles and depths, in a unitary whole of great finesse and good resolution is the most recommended application in the field of reverse engineering. Once the object exists in the database, the same features can be easily called upon, even improved by correlating with other newly received/acquired information in a multitude of files that complete the complexity of the process. The 3D data in the form of a cloud of points from the database are then transmitted through information acquisition tools in an organized, orderly system, corresponding to the real geometric position of the scanned surface, compared to a previously established reference point. The data (a multitude of points) are processed mathematically, geometrically, logically, naturally and conventionally to create a virtual image of determined surfaces. The correspondence between real and virtual will be all the greater, the greater their number, an aspect that can also affect the accuracy of the final image of the product. The combination of errors due to device, software or operator in the processing steps can be fixed by a detailed analysis and filling the appropriate sections in a rigorous manner. The analysis results can also be influenced by the variation of the method used for 3D printing, the material used, the temperature of the 3D printing environment, the sensitivity of the electronic and mechanical system. Considering the average accuracy values of the modeling process, one notices that the average accuracy rate decreases gradually as the value of the scale factor decreases. This method is based on solid and surface features [10-14] of given parts, snapping adjacent surfaces, forming radii and chamfers, and performing geometric constraints on the part.

These types of processes are gradually developing, and their variety increases with the development of technology. The choice of the part modeling strategy (mechanical or non-mechanical) is important, because the fewer elements used in the modeling process, the smaller the file size will be, and the smoothness of the part will be ensured. For complex surfaces, the measurements taken are not standardized and combinations of a limited number of hardware and software equipment can be used. Laser scanning and coordinate measurement are dimensional inspection processes widely used in industry for small-sized components or for large-sized components with high precision. The synergy between 3D measurements and scans and the advanced use of CAD/CAM/CAE software packages contribute significantly to engineering achievements in industries and fields such as automotive, aerospace, biomedical, renewable energies, but also to the introduction and foundation of digital reconstruction and reconstruction methodologies. In this context, the method of the principle of reverse engineering consists of complex and interdisciplinary applications developed within programs and projects of excellence for the creation, optimization and capitalization of digital technologies, to facilitate the manufacture of products and the development of intelligent solutions compatible with the requirements of the current economic and social environment. The specialized literature [15-17] provides details on some achievements and practical contributions, new methods and techniques in different fields of activity, contributing to the development of collaboration with innovative companies from industries with high economic potential. These trans-disciplinary developments of the virtual environment bring significant scientific advantages in areas of specialization such as industrial equipment design and simulation, reverse engineering in various interdisciplinary fields such as medicine, archeology, metrology, etc., allowing specific results to be obtained.
One of the problems with successful results was the integration of high-resolution 3D scanned models directly into virtual reality applications. Due to their complexity and the fact that the parts are made of composite material, their manufacturing is computerized, starting with the stage of designing the parts, designing the molds and making them from various materials. Measuring complex surfaces is a difficult task, in some cases sampling of the inspected surface is necessary to obtain global information about its geometry.
Dimensional and symmetry verification methods are applied in the case of parts with complex surfaces to determine geometric and symmetry deviations such as: measurement in points, in plan using 2D scanned profiles, or globally using 3D scanned surfaces. The method of checking geometric deviations and symmetry in additive manufacturing for landmarks with complex surfaces provides a three-dimensional image, developed and analyzed by measurement procedures with translation of the reference system so that the system can be materialized using surfaces and elements from the inspected landmark. After aligning the CAD model and the real one, a segmentation of the landmark to be measured is made into areas of interest. Depending on the size of these areas of interest, a representative number of points to be scanned in that area as well as the scanning strategy are determined. The nominal values extracted from the CAD model are compared to the touched coordinates by calculating the deviation on all 3 axes, and the deviation of the points is presented as a color map. The results obtained by coordinate measurements are more accurate than those obtained by using for point acquisition scanners. The methodology used to determine the initial surface area of a part involves the use of scanning with trajectories parallel to the equator to obtain sets of data in the form of concentric circles used to plot circularity diagrams. This diagram can be drawn automatically using the measuring machine software. Thus, the deviation from the local circularity (positive or negative) can be highlighted and all the points that do not fall within the tolerance limit can be removed with the help of a software such as CAD, MATLAB, etc.
The CAD software used in the methods that apply the principle of reverse engineering generally have functions that allow the automatic generation, directly from the point cloud of geometric elements (cylinder, plane, cone, sphere) without introducing additional sources of error. After scanning, the coordinates of the points are exported for each circle separately and processed to eliminate the points outside the nominal radius. The remaining points are imported generating the worn surface sphere, an area that provides a high density of points and is highlighted by a color map. The method allows the objective establishment of the points that can be used to reconstruct

the initial surface based on roughness diagrams, being a mathematically documented tool implemented in software that can be used to reconstruct certain surfaces or areas of interest.
The amount of work associated with this method is quite high because establishing the diameter and shape of the initial surface is laborious, but it provides a fairly good accuracy compared to other methodologies presented in the specialized literature.

## 4. Maintenance efficiency concerns for Hydraulic Drive Systems (HDSs)

Systematic analysis of production costs reflects the qualitative level of activity in the context of integrated maintenance management. Maintenance responds to mixed, very complex objectives such as: ensuring the security and reliability of the system, eliminating or reducing the risks in its operation, the stability of the functional characteristics in the life cycle of the system, the continuity of the activities of this system, economic survival and competitiveness, by controlling the expenses related to the system used. The development of maintenance procedures and the application of predictive, preventive and corrective programs of technological systems and equipment is one of the essential activities with an impact on the efficiency of HDSs, being correlated with the adaptation and optimization of the plan for re-engineering the hydraulic system. It is necessary to create a clear plan for prevention and current maintenance in order to satisfy the designed functional parameters, which allow the realization of the technology in safe and precise conditions. Improving the production integrity and the technological systems quality are specific maintenance aspects in the hydraulic drive systems that find their practical solution through the correct diagnosis of the defects that appear, depending on the observed effect. In-depth knowledge of maintenance and repair techniques, in accordance with the application of European Union directives and international standards in the field, leads to the development of industrial activity, the realization of the largest possible productions, of the best quality and with the lowest possible costs. As such, these elements can determine a certain orientation of company management and machinery and equipment experts towards the development of defining measures for HDSs. The development and increasing complexity of industrial systems has led to the modernization and updating of maintenance techniques and policies. Depending on the costs related to spare parts and materials, respectively the losses due to downtime for repairs, different maintenance policies have been developed that consist of interventions on machines that have accidentally stopped working, due to wear and tear or the appearance of malfunctions. Detecting, locating and remediating the malfunction in order to restore the normal operation of the system are actions taken to ensure the optimal operation of the installed systems. The only way in which the owners of the installed technological systems have maximum benefits in their operation is to ensure maintenance with qualified and approved personnel. The use of technology connected to powerful data analysis systems makes it possible to monitor identified problems, and downtime periods / intervals can be planned according to your own schedule. Of course, part of the problem is access to a whole series of sensors, which allow a correct observation of the phenomena, but this method of intelligent maintenance is actually another way of thinking, to anticipate potential failures and trigger actions suitable to prevent or reduce the impact of these defects on the operations performed. This type of advanced technology makes it easier to predict when problems will occur. One possible approach could be to identify equipment with high failure potential as well as costly effect of unwanted interruption: e.g., pumps, compressors, motors. By implementing real-time monitoring systems, interventions on the operating status of these components can be reduced.
The monitoring can also be extended to the other equipment with a low impact of failure, reaching in the end that the whole process enjoys the possibility of anticipating operational problems, this aspect leading to increased safety over the entire technological system. Applying temperature, pressure and vibration sensors to these engines makes it easier to alert the maintenance team in case of failure. Another aspect of maintenance consists in scheduling periodic inspections based on certain sensory information, even if the system is functional. The frequency of these scheduled inspections must be considered. Technologies for testing these systems during operation and modeling algorithms that take into account the following: vibration data, measured temperatures, determination of dissolved compounds in oil, insulation resistances, partial discharges, SF6 pressure, oil level, etc., are very important, which may lead to the reduction of the number of

inspections, or even to their elimination. Thus, depending on the necessary information obtained, the adoption of the new technology can be done. Proactive maintenance emphasizes the idea of routine detection and correction of the primary causes that lead to equipment failures, which are generally the following: abnormal noise generated by cavitation or air ingress into the oil - aerations that can lead to foaming of the hydraulic oil, the high fluid temperature and too slow operation of the system [18]. The set of technical-organizational activities ensures the achievement of maximum performance for the asset considered (equipment, installation, etc.) through the approach way based on the concept of maintenance for restoring a technical system to a specific state of operation that allows it to fulfill its functions in the future. From the point of view of the strategy of the maintenance activity, the aim is to accumulate experience in the field and obtain a high efficiency for establishing the budget, quantifying the need for specific maintenance and repair expenses, necessary for the smooth development of the production process.
The strategy of diversifying the actions carried out involves the provision of specific maintenance activities in order to reduce some funds allocated depending on the impact in order to ensure maximum reliability in the key points of the production system. The principles of limiting the study and the economy of actions are mainly used, with advantages related to the technical and technological level.

## 5. Reliability of HDSs in the circular economy context

In order to ensure good reliability of complex systems, rigorous verification measures are adopted in the technology development phase and in the execution stage of the essential mechanisms that ensure dimensional accuracy, geometric shape as well as compliance with assembly conditions, appropriate heat treatment and maintenance norms. Another measure to increase the reliability of HDSs consists in the monitoring and preventive replacement of subassemblies with reduced reliability or oversizing some of these elements with low reliability. In such situations, the optimization of repair and maintenance technologies is required. The correct operation of the hydraulic mechanisms is conditioned by the maintenance of the drive circuits and the verification of the execution of the links between the elements according to the drive scheme. The maintenance of HDSs is a combination of all the technical, administrative and managerial actions that are taken during a life cycle of an equipment/ machine/ part/ subassembly with the aim of maintaining or restoring its ability to perform the desired function. In this sense, the maintenance of HDSs includes activities of measurement, performance control, testing, fault detection, repair, adjustment, replacement of elements or subassemblies, and service. Therefore, service or repair activity are parts of a complex maintenance and monitoring action, given that they already exist in industrial practice with wide applications in hydraulic drives. These actions ensure the continuity of activities for as long as possible without interruptions that can cause a significant decrease in productivity, with the natural consequence of reducing the consumption of raw materials and supplies. This process (Fig. 1.) minimizes the waste of raw materials that are limited and, in some cases, are already exhausted or on the verge of extinction.

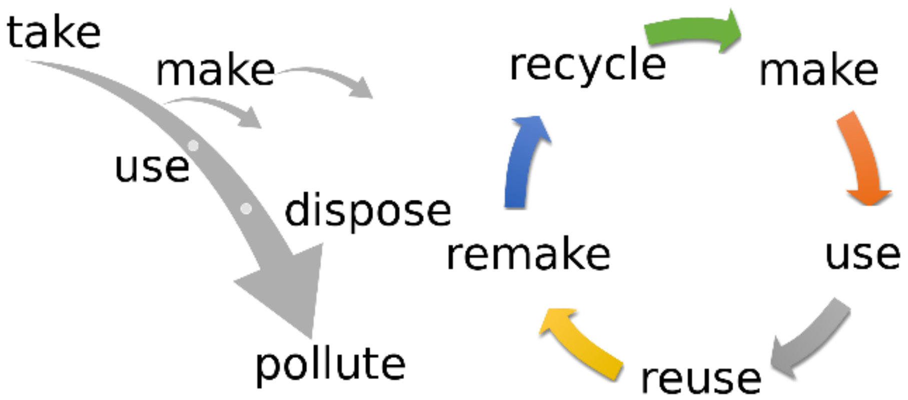


**Fig. 1.** An illustration showing the difference between the take-make-dispose linear economy approach, and the circular economy approach [19]

In this sense, action plans and measures are adopted at the European level for the transition to the circular economy (Fig. 2.), a transitional method for the correct management of technological waste. In the field of hydraulic drives, maintenance and manufacturing elements are items that can be included in the working methodologies of the Circular Economy concept. These aspects that should become principles of life for humanity aim reusing waste as a raw material, using objects with a long life instead of disposable ones, minimizing packaging, etc. As such, the circular economy represents a model of production and consumption that involves all stages, from design to consumption and then to recycling, ultimately resulting in only a reduced amount of waste comparable to the raw material and initial materials used. This new concept helps the economy as a result of the reduced consumption of new materials and raw materials and creates a new closed loop system that allows the reuse of existing products in a circuit from design to exhaustion. Approaching the circular economy concept aims at the impetuous need to move to a system that favours the recovery of waste materials and products, instead of favouring their destruction. Thus, a close connection between the concept of sustainable development and that of the circular economy is highlighted, supported by arguments regarding existing international trends about some ways of aligning with the requirements of technical and scientific research in the field of HDSs.

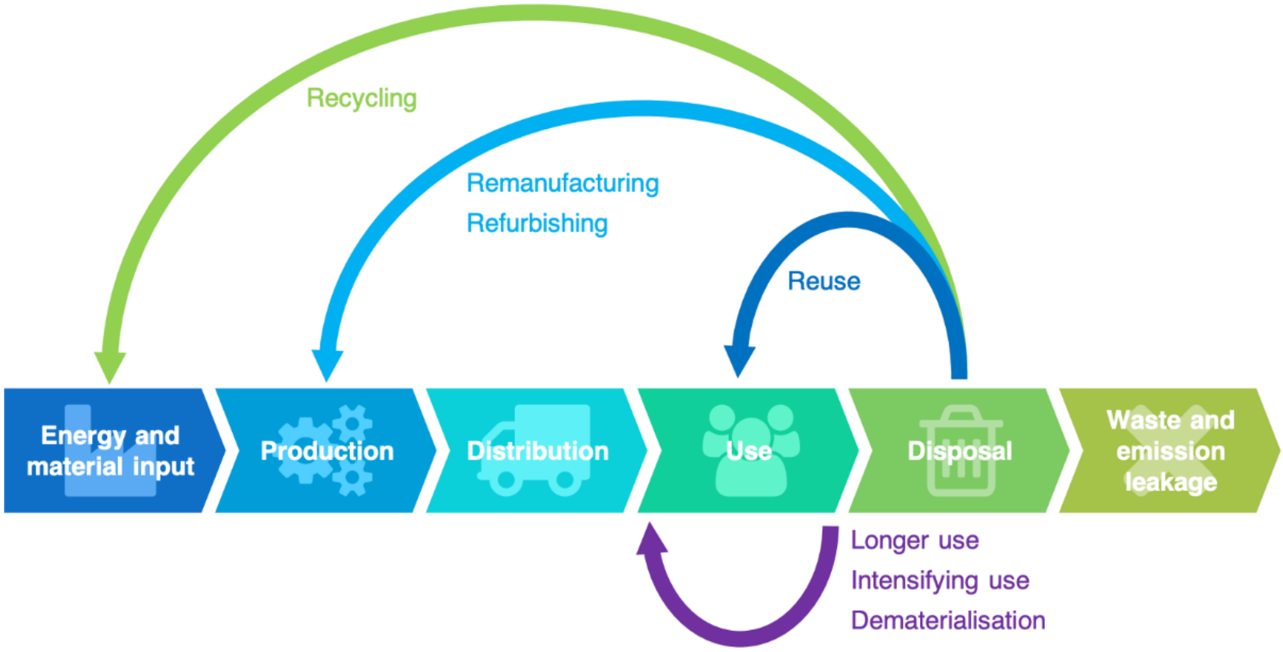


**Fig. 2.** An illustration of the circular economy concept [20]

## 6. Conclusions

In this article, the authors have explored the new trends and developments of additive manufacturing in the field of hydraulic drive systems (HDSs) according to the circular economy concept. The maintenance of HDSs is crucial for ensuring their efficient operation, especially considering the expanding range of applications for these systems. By adopting an integrated management concept and employing a complex approach to maintenance activities, the performance of HDSs can be effectively maintained.
The field of hydraulic drive systems (HDSs) has witnessed significant advancements and developments in recent years, driven by the need to enhance maintenance activities and embrace the principles of the circular economy. The integration of additive manufacturing methods and 3D scanning technologies has opened up new possibilities for improving the efficiency, reliability, and sustainability of HDSs.
Additive manufacturing, also known as 3D printing, has emerged as a transformative technology in the field of hydraulic components production. Its ability to enable on-demand production, innovative

performance, and flexibility has paved the way for the remanufacturing of hydraulic components with complex geometries and specific characteristics. This allows for the revitalization of worn-out or obsolete components, reducing waste and supporting the circular economy principles. Throughout the article, the authors have presented various examples of the application of additive manufacturing technologies and the adaptation of the reverse engineering principle in the field of hydraulic drive systems. These examples highlight the practical implementation of 3D scanning and additive manufacturing techniques for remanufacturing hydraulic components, such as pumps, valves, and cylinders, with enhanced performance and extended lifespan. The utilization of additive manufacturing methods in the production of hydraulic components based on the principles of reverse engineering offers stability to functional characteristics and enhances reliability within the context of the circular economy. Additive manufacturing, also known as 3D printing, provides innovative performance and flexibility in on-demand production, enabling the remanufacturing of hydraulic components with complex geometries and specific characteristics. This technology opens up new opportunities for optimizing the maintenance and lifecycle of HDSs.

Reliability-based maintenance (RBM) strategies play a crucial role in maximizing the potential of HDSs operation. By implementing RBM, it becomes possible to detect and exploit the maximum capabilities of hydraulic drive systems, ensuring their continuous and efficient performance. Additive manufacturing serves as a valuable tool in RBM strategies, offering the ability to quickly produce replacement parts or customized components when needed, reducing downtime and costs associated with traditional manufacturing and supply chains.

The integration of additive manufacturing methods into the maintenance practices of hydraulic drive systems brings numerous benefits, including reduced lead times, increased customization possibilities, improved resource efficiency, and minimized waste generation. By embracing these new trends and developments, industries can enhance the sustainability and circularity of their hydraulic drive systems, contributing to a more efficient and environmentally friendly approach to manufacturing and maintenance.

The principle of reverse engineering plays a crucial role in the adaptation of additive manufacturing technologies for HDSs. By utilizing 3D scanning techniques, the existing components can be accurately captured and converted into digital models. These models serve as a basis for the production of new components through additive manufacturing, ensuring stability in functional characteristics and reliability.

Overall, the combination of additive manufacturing, 3D scanning, and the circular economy concept presents a promising future for the field of hydraulic drive systems. By leveraging these technologies and principles, it is possible to achieve sustainable and efficient maintenance practices, leading to enhanced performance and reduced environmental footprint in the hydraulic industry. As the field of additive manufacturing continues to evolve, further research and development are needed to explore the full potential of this technology in the context of hydraulic drive systems. Continued collaboration between academia, industry, and policymakers is crucial to address the challenges and seize the opportunities offered by additive manufacturing, circular economy concepts, and the integration of advanced maintenance strategies.

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