[1.] Alexandru–Polifron CHIRIȚĂ, [1.]Andrei–Alexandru BENESCU, [1.]Adriana Mariana BORȘ, [1.]Ștefan–Mihai ȘEFU, [1.]Robert BLEJAN

THE IMPORTANCE OF REVERSE ENGINEERING AND 3D SCANNING IN REMANUFACTURING HYDRAULIC DRIVE SYSTEM COMPONENTS IN THE CIRCULAR ECONOMY CONTEXT

[1.] National Institute of Research & Development for Optoelectronics/INOE 2000, Subsidiary Hydraulics and Pneumatics Research Institute/IHP, Bucharest, ROMANIA

Abstract: Reverse engineering and 3D scanning are critical tools for remanufacturing components in the context of the circular economy. By disassembling and measuring existing components, companies can design and develop new parts replacing the old ones, parts that are compatible with the original equipment, either to repair faulty subassemblies, or to improve efficiency or functionality. 3D scanning captures all information needed to reproduce components, allowing them to be created using additive manufacturing processes. Combining these technologies reduces waste by maximizing the use of existing products, and it reduces the amount of new raw materials and energy required for remanufacturing as well. The circular economy encourages companies to embrace a sustainable approach by considering the entire product lifecycle. Adopting these principles leads to a more environmentally friendly business model, avoids waste, reduces material consumption, and creates new revenue streams for remanufactured products. The current paper shows a way of adapting the principle of reverse engineering and a particular way of involving 3D scanning and 3D printing for the remanufacturing of hydraulic system components by using additive manufacturing. The use of 3D scanning is necessary in the reverse engineering process especially for components with complex geometry; in the present paper, the geometry of such a component is created.
Keywords: reverse engineering, 3D scanning, 3D printing, MSLA, remanufacturing, circular economy

INTRODUCTION

In today's rapidly evolving industrial landscape, sustainability and resource efficiency have emerged as critical concerns. As the world faces challenges associated with limited natural resources and increasing waste, the circular economy has gained momentum as a promising solution to foster sustainable practices. Central to the circular economy is the concept of remanufacturing, a process that aims to extend the lifespan of products and reduce waste generation (Turner *et al.*, 2019). In this context, reverse engineering and 3D scanning play indispensable roles, providing innovative and efficient approaches to remanufacturing hydraulic drive system components.

The imperative to enhance sustainability practices in manufacturing has never been more pressing. Traditional linear manufacturing processes follow a "take, make, dispose" model – Figure 1 (Perr, 2020), which inevitably results in the depletion of resources and the accumulation of waste. In stark contrast, the circular economy represents a paradigm shift, envisioning a regenerative system where products are designed to be reused, repaired, and remanufactured (Sun *et al.*, 2022). This approach fosters a closed–loop system, wherein products' end–of–life becomes the beginning of a new production cycle, minimizing the environmental impact (Karimova *et al.*, 2022).

Remanufacturing, as a core pillar of the circular economy, aims to recover value from used products by restoring them to their original condition or better. One of the key challenges in remanufacturing is the need to recreate components that may have become obsolete or damaged over time. This is where reverse engineering steps in as a pivotal technique (Tian *et al.*, 2022).

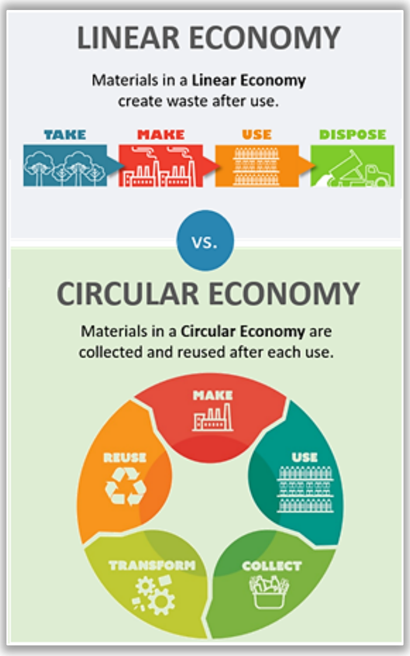

Figure 1. Linear vs circular economy

Reverse engineering involves the disassembly, analysis, and measurement of existing components to understand their design, materials, and functionality. By deconstructing a product, manufacturers gain valuable insights into its intricacies, facilitating the development of replacement parts that are both compatible and efficient (Atta, 2023). Consequently, this process not only extends the life of the product but also reduces the overall demand for new raw materials, thus contributing to resource conservation (European Commission, n.d.).

In conjunction with reverse engineering, 3D scanning emerges as a cutting–edge technology that revolutionizes the remanufacturing landscape. 3D scanning enables the precise capture of a component's geometrical data, creating a digital replica of the object with remarkable accuracy (Kataev *et al.*, 2023). This digital representation serves as the foundation for employing additive manufacturing processes, commonly known as 3D printing, to recreate the component.

The integration of 3D scanning with additive manufacturing holds immense potential, particularly for components with complex geometry that may be challenging to reproduce using traditional manufacturing methods. By translating digital data into tangible components, manufacturers can effectively remanufacture hydraulic drive system parts with an unparalleled level of precision, reliability, and cost–effectiveness.

Through the convergence of reverse engineering and 3D scanning, remanufacturing processes become more streamlined and environmentally friendly. The reuse of existing components minimizes waste generation, while the incorporation of 3D scanning and additive manufacturing reduces the need for virgin raw materials, thereby lowering the ecological footprint of the remanufacturing process. As a result, companies embracing these innovative techniques position themselves as pioneers in adopting sustainable practices, while also unlocking new revenue streams through the sale of remanufactured products (Ma *et al.*, 2020).

In conclusion, the synergistic use of reverse engineering and 3D scanning represents a transformative approach in remanufacturing hydraulic drive system components within the context of the circular economy. By embracing these advanced technologies, companies can enhance their environmental stewardship (Stuart Chapin III *et al.*, 2010), optimize resource utilization, and ultimately foster a more sustainable and prosperous future for all.

In the following, part of the remanufacturing methodology for a flowmeter is presented, namely the production procedure for the damaged rotor of the flowmeter.

MATERIALS AND METHODS

In the initial stage of the remanufacturing process, the first crucial step towards creating a 3D model of the component involves the application of a matte spray onto the entire surface of the piece (Figure 2). This matte spray plays a pivotal role in enabling successful 3D scanning, as it effectively addresses the challenge posed by glossy surfaces that are difficult for the 3D scanner (with structured light) to capture accurately.

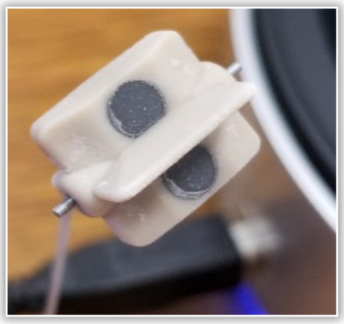

Figure 2. Part sprayed with matte spray

By applying the matte spray, all surfaces of the part become amenable to scanning, ensuring a comprehensive and precise digital representation of the component. The use of the matte spray not only streamlines the 3D scanning process but also enhances the overall remanufacturing endeavor in the circular economy context. By enabling accurate and comprehensive scans of existing components, manufacturers can effectively optimize their resources, minimize waste generation, and contribute to a more sustainable and environmentally responsible approach to manufacturing. The application of a matte spray on the scanned part plays a critical role in facilitating successful 3D scanning for remanufacturing purposes. This technique allows the 3D scanner to capture the entire geometry of the component, overcoming the limitations posed by glossy surfaces.

The process began by placing the part meticulously on the EinScan–SP V2 scanner table, ensuring it was stable and appropriately positioned for scanning. To ensure a comprehensive representation of the part's geometry, two distinct groups of scans were carried out with precision.

In the first scan, the piece was thoughtfully positioned horizontally on the scanning surface. This meticulous arrangement allowed the scanner to capture the intricate details of the part from one vantage point. As the scanning process unfolded, a multitude of data points were gathered, ultimately forming a dense and detailed cloud of 92,000 points. These points served as a digital footprint of the part's surface, effectively mapping its contours and features.

Moving on to the second scan, a deliberate shift of 180 degrees from the part's initial placement was executed. This strategic alteration in positioning ensured a comprehensive view of the part's surfaces from an entirely different perspective. As the scanning commenced once again, a second cloud of points materialized, recording the part's geometry from this new orientation.

With both sets of scans completed, the next crucial step was to merge the two point clouds. By superimposing and aligning the data points obtained from the first and second scans, a cohesive and unified representation of the entire part was achieved. This overlapping process aimed to fill any gaps or discrepancies present in either scan, resulting in a seamless and complete point cloud of the entire part's surface. Figure 3 highlights this process. Finally, leveraging the comprehensive point cloud data, the process culminated in the creation of an STL model of the part. The STL format is widely used for 3D printing and computer–aided design applications. The model accurately mirrored the physical part's geometry, making it a versatile and valuable digital representation for various engineering, manufacturing, and design endeavors. Overall, this meticulous and well–choreographed process of 3D scanning and STL model creation ensured a precise and detailed digital representation of the physical part, opening up a realm of possibilities for its utilization across diverse industries and applications.

Figure 3. The process of 3D scanning of the part and the cloud of points obtained

After generating the STL model through the 3D scanning process, the next step involved importing the model into the SolidWorks software, a powerful computer–assisted modeling (CAD) software widely used in engineering and design industries. SolidWorks offers a robust set of tools and features, enabling the creation and manipulation of complex 3D models with precision. Within SolidWorks, specific measurements and analyses were performed on the 3D model of the piece. By defining three points on two surfaces of the part, multiple planes were obtained. These planes served as references for various geometric analyses and measurements, especially in determining angles between surfaces that could be challenging to obtain using other conventional methods. CAD modeling technology within SolidWorks allowed the team to accurately measure the angles between different surfaces of the 3D model. This was particularly valuable for intricate and complex parts, where manual measurements might have been error–prone or time–consuming. With the aid of the software's advanced features, the team could efficiently analyze the model and ensure that the angles between surfaces conformed precisely to those of the physical part.

Once all the necessary measurements and analyses were completed, the 3D model of the part was now fully realized, including all visible surfaces with their accurate angles. This comprehensive model was then used as the basis for creating a new STL file, ensuring that the digital representation perfectly mirrored the physical part's geometry.

Figures 4 and 5 properly depicted and highlighted the key steps and processes involved in SolidWorks, including importing the STL model, defining reference points and planes, and measuring the angles between surfaces. These visual representations served as essential guides, aiding in understanding and documenting the intricate steps taken to ensure the accurate replication of the physical part through the 3D printing process.

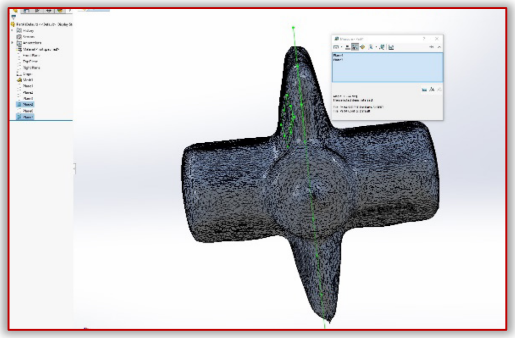

Figure 4. Determination of angles between the surfaces of the part

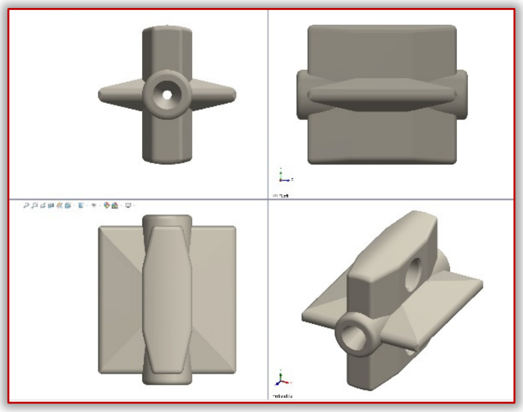

Figure 5. 3D model of the piece, from different angles, in the SolidWorks software

In Figure 6 one can see how the STL model fully reproduces the geometry of the part, made in the SolidWorks software.

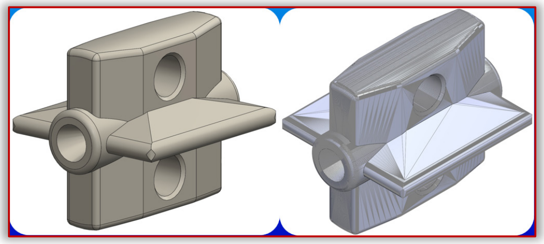

Figure 6. The model made in the SolidWorks software, on the left, and the STL model of the piece, on the right

The newly generated STL model, now aligned with the precise angles measured using SolidWorks, was ready to be further processed for 3D printing with PRUSA SL1S. It was imported into the PrusaSlice slicing software, a crucial component in the 3D printing workflow that converts the 3D model into a series of instructions for the printer to follow layer by layer.

Figure 7 provides a visual representation of the final stages of the post–processing of the 3D model of the piece. After generating the 3D model of the part using SolidWorks and converting it into an STL file, the model was imported into the slicer software. The slicer software plays a crucial role in translating the 3D model into a format that the 3D printer can understand and execute.

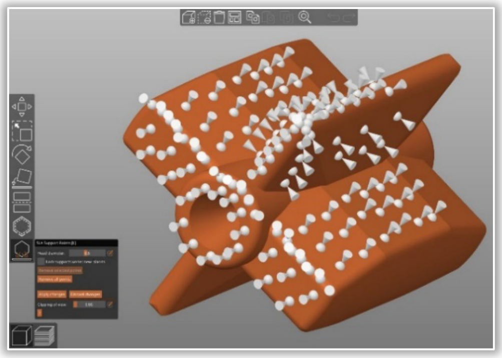

Figure 7. Manual application of the support layers

Within the slicer, the 3D model was processed, and various printing parameters were set, such as layer height (0.05 mm), print speed (2 seconds / layer), and infill density (100%). The slicer divided the 3D model into numerous horizontal layers, generating a set of instructions that the 3D printer would follow to create the physical object layer by layer.

In preparation for printing, additional support structures were applied to the 3D model. These support structures are temporary elements added to the design to provide stability and prevent overhangs or unsupported sections from collapsing during the printing process. (Figure 8)

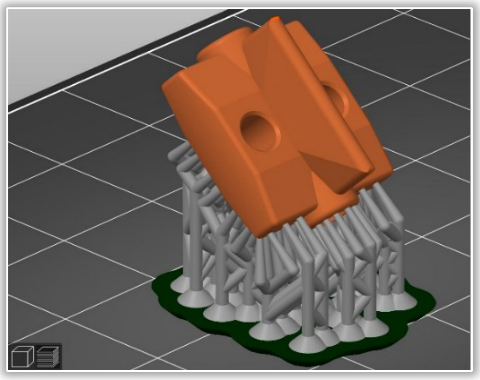

Figure 8. The support of the piece (in gray colour)

Typically, the slicer software automatically generates support structures based on the part's geometry and the chosen printing settings. However, in some cases, manual intervention is required to optimize the support structures so that the first layers of the piece are successful or add custom supports to specific areas of the part.

Figure 9 shows how the first layer of the piece is printed on the support. By carefully adding supports, the part's stability during printing was greatly enhanced, ensuring that it retained its intended shape and accuracy throughout the printing process. The support structures could be removed easily after printing was complete, leaving the final 3D printed part in its desired shape without any residual supporting material.

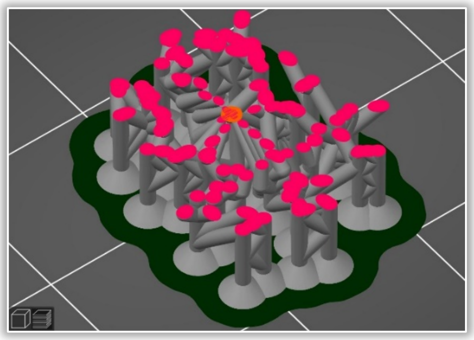

Figure 9. The first layer of the piece

Figure 10 highlights the print parameters of the piece. The piece contains 517 layers, each layer having a thickness of 0.05 mm. These layers represent the total layers, which also include the layers of the part support. The entire printing time is 40 minutes, the piece having a height of 25.85 mm. In all additive manufacturing technologies, proper setting of the initial parameters is critical for the success of the fabrication process; similar work was accomplished by the main author in a previous research (Chirita *et al.*, 2021).

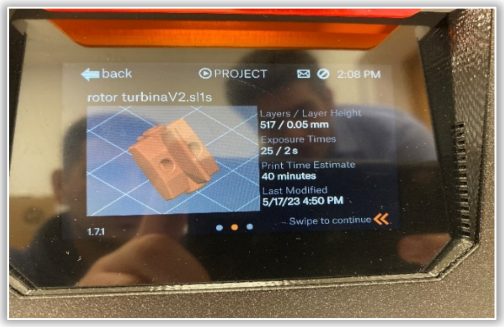

Figure 10. 3D printing parameters of the part

Figure 11 depicts the latter stages of post–processing for the 3D printed part. The 3D printer used in the laboratory utilizes MSLA technology, a form of resin–based 3D printing that employs ultraviolet (UV) light to cure the resin layer by layer, resulting in high precision and detailed prints.

Once the printing process is complete, the part remains coated in uncured resin, which needs to be removed to reveal the final, fully cured part. To accomplish this, the printed piece is placed in a container filled with isopropyl alcohol (IPA). The IPA works as a solvent to dissolve and wash away the excess uncured resin from the surface of the part. To further ensure the thorough removal of any remaining uncured resin the part undergoes additional cleaning using an ultrasonic cleaner (Figure 12). The ultrasonic cleaner utilizes high–frequency sound waves to create tiny, rapid bubbles in the IPA. As these bubbles collapse near the surface of the 3D printed part, they agitate and dislodge any remaining resin, leaving the part clean and free of unwanted residue.

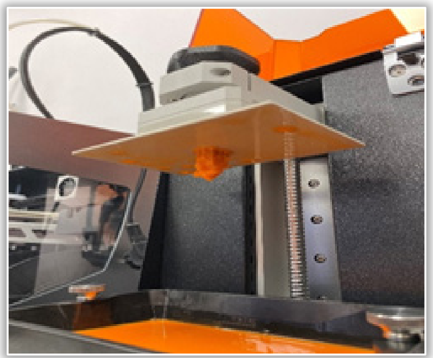

Figure 11. The piece at the end of the 3D printing process

Figure 12. Cleaning of the part in ultrasonic bath with IPA

Once the cleaning process is completed, the 3D printed part is removed from the ultrasonic cleaner, now fully cleaned. At this stage, the part may still exhibit some level of flexibility or brittleness. To enhance its mechanical strength, the part is inserted into a curing device (Prusa Curing and Washing Machine (CW1S)). This device, which is a post–processing station with UV chamber, exposes the part to additional UV light for a specific period. The UV light further cures the resin and ensures its complete hardening, resulting in a final part with improved mechanical properties and durability (Figure 13).

Figure 13. The part at the end of the curing process

RESULTS AND DISCUSSIONS

The culmination of the 3D scanning, 3D modeling, and 3D printing processes, as well as the meticulous post–processing steps, is the functional part presented in Figure 14. This final result showcases a high–quality 3D printed part, free from defects and accurately representing the original physical piece.

The successful completion of these intricate processes ensures that the 3D printed part possesses the necessary geometrical precision and mechanical integrity to seamlessly fit into the intended device. The part's dimensions, angles, and intricate details have been faithfully reproduced, guaranteeing its proper functionality and optimal performance within specified parameters.

The absence of defects in the final 3D printed part indicates the effectiveness of the entire workflow, from the initial scanning to the post–processing procedures. The meticulous alignment of multiple scans, proper support generation, and thorough cleaning of the part during post–processing have all contributed to achieving a flawless and reliable end product.

By adhering to these comprehensive procedures, the 3D printed part fulfills its designated functions entirely. Its accuracy and structural integrity enable smooth interaction with other components within the device, ensuring seamless operation and reliable performance in real–world applications.

The successful completion of this project highlights the potential and versatility of 3D scanning, modeling, and printing technologies. The ability to accurately reproduce complex parts using advanced CAD modeling techniques and 3D printing with MSLA technology showcases the power of additive manufacturing in various industries, such as engineering, medicine, and design.

Figure 14 serves as a visual representation of the triumph of the entire process, depicting the functional 3D printed part in all its detail and complexity. This result stands as a testament to the team's dedication, expertise, and the effectiveness of integrating cutting–edge technologies to create functional parts with outstanding precision and reliability.

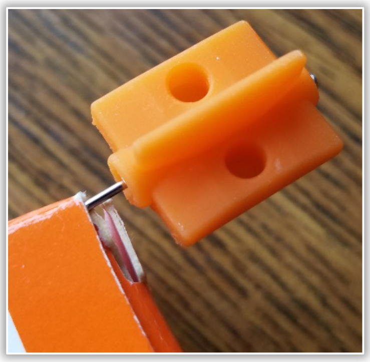

Figure 14. The final result of the entire process – the fully functional flowmeter rotor

CONCLUSION

The presented remanufacturing methodology for flowmeter rotor production showcases the effectiveness of integrating reverse engineering, 3D scanning, and additive manufacturing in the circular economy context. By adopting these advanced techniques, companies can prolong the lifespan of critical components, reduce waste, and contribute to a more sustainable industrial ecosystem. Remanufacturing not only conserves resources but also presents a cost–effective and environmentally responsible solution for ensuring the continued efficiency and reliability of flowmeters in various industrial processes.

The dimensions of the 3D printed part are the same as those of the initial part. Using 3D scanning, additive manufacturing and adapting the principle of reverse engineering, the rotor of a flowmeter was remanufactured. Without these technologies, the flowmeter would have been considered a waste, and would have been thrown in the trash. By remanufacturing its rotor, the flowmeter was returned to nominal operating parameters, reusing the other components of the flowmeter, according to the principle of the circular economy.

Acknowledgements

This work was carried out through the Core Program within the National Research Development and Innovation Plan 2022–2027, carried out with the support of the Romanian Ministry of Research, Innovation and Digitalization (MCID), project no. PN 23 05. The research was financially supported by a project funded by MCID through Programme 1 – Development of the national research & development system, Sub–programme 1.2–Institutional performance–Projects financing the R&D&I excellence, Financial Agreement no. 18PFE/30.12.2021.

References

[1] Atta, N.: Remanufacturing Towards Circularity in the Construction Sector: The Role of Digital Technologies, 493–503. In: Arbizzani, E., et al.: Technological Imagination in the Green and Digital Transition. CONF.ITECH 2022. The Urban Book Series, Cham, Springer, 2023.
[2] Chirita, A.–P.; Sovaiala, G.; Barbu, V.; Blejan, M. and Pavel, I.: Determining the optimal printing conditions for the production of a Fertigation Pump Prototype with FDM Technology, Materiale Plastice, 58(2), 140–149, 2021.
[3] European Commission: Internal Market, Industry, Entrepreneurship and SMEs. Critical Raw Materials Act. https://single–market–economy.ec.europa.eu/sectors/raw–materials/areas–specific–interest/critical–raw–materials/critical–raw–materials–act_en, n.d.
[4] Karimova, G.–S. and LeMay, S. A.: Consumer Social Responsibility (CnSR) in the Circular Economy of Global Value Chains: What Does It Mean, and Why Does It Matter?, International Journal of Circular Economy and Waste Management, 2(1), 1–19, 2022.
[5] Kataev, Yu.V.; Goncharova, Yu.A.; Sviridov, A.S. and Tuzhilin, S.P.: Application of 3D Printing and 3D Scanning Technologies in the Manufacture and Repair of Agricultural Machinery, Machinery and Equipment for Rural Area, 34–38, 2023.
[6] Ma, P.; Gong, Y. and Mirchandani, P.: Trade–in for remanufactured products: Pricing with double reference effects, International Journal of Production Economics, 230, 107800, 2020.
[7] Perr, J.: Hi–Cone. Consumption, sustainability, and the circular economy: Hi–cone, August 13, 2020. https://hi–cone.com/2020/08/the–total–cost–of–consumption/.
[8] Stuart Chapin III, F.; Carpenter, S.; Kofinas, G.; Folke, C.; Abel, N.; Clark, W.; Olsson, P.; Stafford Smith, M.; Walker, B.; Young, O.; Berkes, F.; Biggs, R.; Grove, M.; Naylor, R.; Pinkerton, E.; Steffen, W. and Swanson, F.: Ecosystem Stewardship: Sustainability Strategies for a Rapidly Changing Planet, Trends in Ecology & Evolution, 25(4), 241–249, 2010.
[9] Sun, H.; Zheng, H.; Sun, X. and Li, W.: Customized Investment Decisions for New and Remanufactured Products Supply Chain Based on 3D Printing Technology, Sustainability, 14(5), 2502, 2022.
[10] Tian, Y.; Wang, X.; Li, J.; Yang, J. and Liu, Y.: Rapid Manufacturing of Turbine Blades Based on Reverse Engineering and 3D Printing Technology, CISC 2022: Proceedings of 2022 Chinese Intelligent Systems Conference, 540–553, 2022.
[11] Turner, C.; Moreno, M.; Mondini, L.; Salonitis, K.; Charnley, F.; Tiwari, A. and Hutabarat, W.: Sustainable Production in a Circular Economy: A Business Model for Re–Distributed Manufacturing, Sustainability, 11(16), 4291, 2019.

ISSN: 2067-3809