Use of Reverse Engineering and Additive Printing in the Reconstruction of Gears

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INTRODUCTION

The traditional approach to design, manufacture and construction is beginning to go down in history. Currently existing innovative solutions supported by advanced computer systems significantly affect the engineering work process. First of all, they reduce production preparation time, ensure precision, which significantly affects the quality of products obtained. Currently, the market is ruled by the customer and the competition creates a pressure on lowering that price, production efficiency is critical for the company and its future. Dynamic changes, the specter of the crisis and the need to meet the client's individualized expectations are forcing entrepreneurs to look for new ways to achieve market advantage. The success of both production and service entrepreneurs is due to their willingness to introduce changes. These changes mainly consist in the implementation of innovative solutions to improve work efficiency, including the improvement of its organization, and in particular the improvement of material and information flows in production processes. An important issue in the case of industrial enterprises is the change in approach to maintenance and renovation (Kruczek, Żebrucki; 2012, Palka, Ciukaj; 2019).
The method of maintaining the movement of individual machines and devices depends on their characteristics, construction and purpose in the production process. Technologically advanced devices that are expensive to maintain and operate in automated production lines require a thoughtful and careful approach in understanding machine operation. This approach means the use of an appropriate operating strategy, because the failure of these machines usually results in downtime of entire production lines, and thus, huge financial losses. High maintenance costs, as well as the difficult economic situation, force entrepreneurs to intensively seek opportunities to reduce these costs (Wyleżoł: 2019, Fidali; 2018).
The current trend in maintenance is Rapid Prototyping technology. Its use is due to various reasons, most often it is the need to produce new elements retrofitting technical objects or to restore the damaged part of the operated object. This necessity results from the inability to purchase the damaged part due to the lack of availability on the market. Often these are objects without construction

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documentation, technical drawings or 3D models. The Rapid Prototyping technology enables changes to manufactured parts, their complete modification, and the implementation of unique tools, not mass-produced, and necessary for unforeseen repairs (Wyleżoł; 2019).

This technology involves creating three-dimensional physical objects, layer by layer, based on computer models. This process referred to is also, as additive technology.

Currently, there are many 3D printing methods depending mainly on the materials used for this purpose: resins, thermoplastics, powdered plastics, powdered metals, gypsum powder and foil, and even paper. The methods include for example: SLA, DLP, MJP, SLS, SLM.

The article characterizes methods and explains individual stages of engineering reconstruction. Basic concepts regarding the production and use of gears are also discussed. This is justified because of the need to know their parameters necessary to be used at the design stage. The ability to read the technical drawing, its interpretation and creation is an essential element of the reconstruction of each object. Finally, the next steps in the design and manufacture of gear transmissions were described and illustrated, both by measuring and spatial scan methods on the example of a selected gear. The work uses FDM (Fused Deposition Modelling) spatial manufacturing technology. The legitimacy of the subject of the thesis is also confirmed by the available literature on the subject, which is mostly devoted to the design of gearing, while it omits the issues related to the subject of reconstruction of these objects.

It is worth mentioning that 3D printing is one of the pillars of the fourth industrial revolution. Siemens, in cooperation with the Ministry of Entrepreneurship and Technology, examined the level of innovation of Polish manufacturing companies resulting from the implementation of these technologies. The report shows that respondents see opportunities for the development of their companies mainly in spatial manufacturing technology. Among the most frequently indicated benefits, there is the possibility of reducing the number of downtime caused by machinery and equipment failures. 3D printing is treated as part of a preventive maintenance strategy, in particular in situations of demand for unusual, hard-to-reach spare parts. In addition, respondents define 3 D printing technology as one of the easiest to implement as part of the concept of Industry 4.0 (Report by Smart Industry Polska; 2018).

ENGINEERING RECONSTRUCTION

Rapid Prototyping is the definition of the method that it serves to used primarily for fast but precise and reproducible production of components using technologies incremental (Garbarczyk, Józefowicz, Rybarczyk; 2014). Models with a very complex shape can be made in a short time, compared to traditional methods of producing spatial objects. The high accuracy of mapping the geometric features of the models allows their use for structural, assembly and functional analyses. Figure 1 summarizes the pros and cons of this Rapid Prototyping technique (Mager , Moryson , Cellary et al.; 2011).

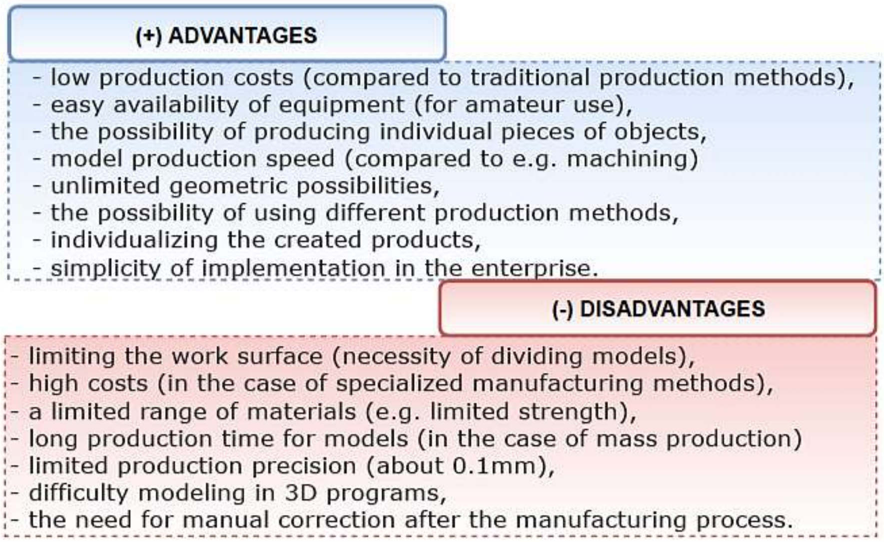

Fig. 1 Advantages and disadvantages of the Rapid Prototyping technique
Source: Own study based on (Mager , Moryson , Cellary et al.; 2011)

Rapid Prototyping technology is based on models made using Computer Aided Design CAD systems, which are the basis for CAM Computer Aided Manufacturing processes. One of the varieties of computer design is Reverse Engineering in the engineering sense, also known as Engineering Reconstruction.

In traditional CAD methods, creating a virtual model involves entering dimensions from existing technical documentation or creating technical documentation along with the resulting object model. The next step is to transform the virtual model into a real object.

Reverse Engineering method consists in transforming a real, existing object into its digital mapping. The 3D character is most often created through the scanning process, and this process is called digitization. In the era of existing technical solutions, manual measurements often appear to be insufficient, although they are still used in practice. Based on the reconstructed object it is possible to make technical documentation. The relationship between the described processes is presented in the diagram below (Fig. 2).

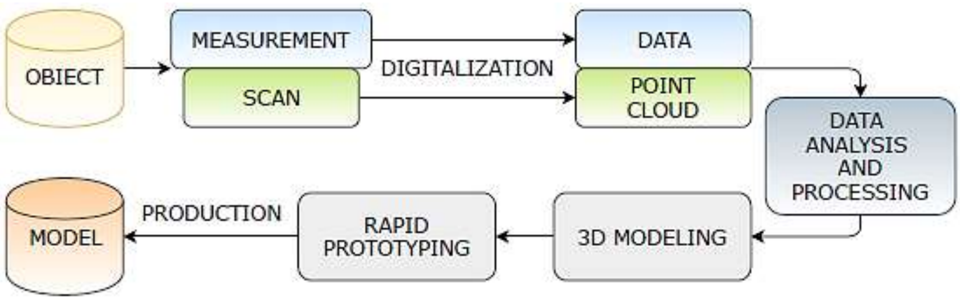

Fig. 2 Diagram of the procedure in engineering reconstruction
Source: Own study

The implementation of Reverse Engineering method provides the following conditions:

- interoperability – the ability to assess the compliance of the facility's cooperation with other system components that are used or designed to be manufactured for implementation,
- overview of the control object in terms of behavior and Hold swimming its geometrical dimensions,
- creating duplicates,
- building models for the purpose of numerical analyses of their work, strength and behavior of element, assemblies or entire objects,
- restoring or creating documentation of a device that does not have it or those documents have been damaged, lost, expired (Kachel, Kozakiewicz, Łącki et al; 2011).

GEAR

Today, despite the dynamic technological development, the general concept of mechanical devices has not changed. Gear is by far the most popular mechanism used in machines, electrical devices, bicycles, lathes, milling machines and even clocks. However, the industry also uses other types of gears that differ in design and the same method of operation, for example: worm gear, friction gear, belt transmission, reciprocating or chain.

A gear is a system whose task is to transfer torque by means of mutually cooperating, interlocking gear wheels. Due to the number of working wheels there are: single-stage gears in which one pair of wheels cooperate and multi-stage, in which cooperation in series with more wheels works in cooperation. In the second variant, we have the option of increasing the gear gradation by using a different number of teeth. Gears can also be divided due to the location of the meshing, mutual position of the axis of rotation and the type of transferred motion (Budzik, Cygnar, Janisz; 2009).

The use of gears is undoubtedly very wide, they are used in almost every industry. Apply in machines used in the engineering industry, mining, metallurgy, as well as in food industry and chemical industry. Their widespread use is primarily due to numerous advantages, which include: simple design, ease of implementation, compact construction, high efficiency, high reliability, high power transmission capability, and at the same time simplicity of operation.

Gear is the most frequently used element of machines and devices, which is used to change the torque, angular speed, as well as the direction and (in the case of gears with a conical profile) the torque transfer. And there are two types of structure and tooth contour: epicycloidal and involute. The first of these is used only in small gears of mechanisms that require special precision, such as, for example, a watch. For the study, the second type is selected, the wheel gear outline involute, used in most machines, industrial, automotive, machine tools and consumer devices. This type of outline enables smooth meshing of the gears.

Due to the need to know the design parameters of gears, Figure 3 shows the main dimensions of the gear.

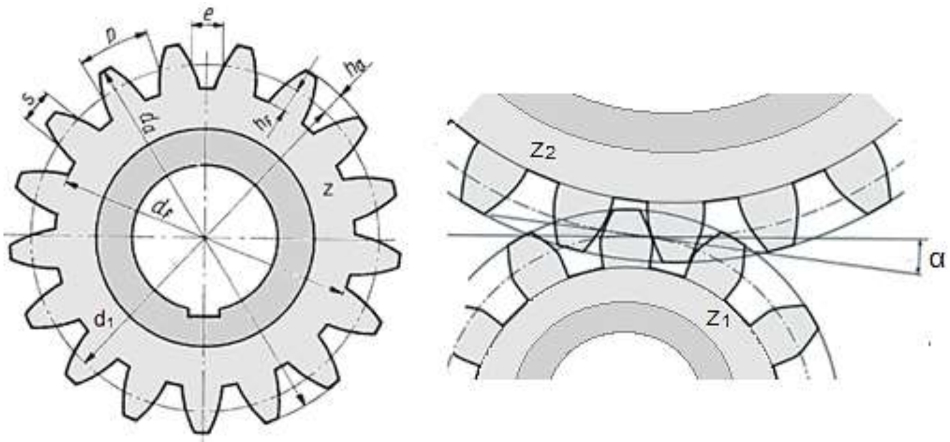

Fig. 3 The main geometrical parameters of the gear
Source: Own study based on (Rutkowski; 2000)

Description of markings:
d_1 - pitch diameter of the wheel,
d_f - gear foot diameter,
d_a - gear head diameter,
s - tooth thickness,
e - space width,
p - circural pitch,
h - tooth height,
h_a - head height,
h_f - feet height,
α - pressure angle,
z_1 - number of first wheel teeth,
z_2 - number of teeth of the second wheel.

The division circle is divided into as many parts as there are teeth [z] in the circle. The scale determines the length of the segment, measured along the arc of the pitch circle. To the pitch circle, vertices and bases the following diameters are distinguished: pitch [d], apex [d_a] and base [d_f]. For two wheels [k_1, k_2] where the pitch diameters are marked as [d_1, d_2] they are the diameters of such wheels which, turning without slipping. It follows from the above that the gear ratio is equal to:

$$i = \frac{d_1}{d_2} = \frac{z_1}{z_2} \quad (1)$$

From the relationship (1) it follows that the ratio can also be written as the ratio of the number of gear teeth [z_1, z_2]. The part of the tooth that is below the pitch line is called the tooth's foot, while the part protruding above the tooth is the tooth's head. An important element of the tooth structure is the butt angle [α], which should be about 20°. The tooth pitch [p] can be calculated from the following formula:

$$p = \frac{\pi \cdot d}{z} \quad (2)$$

The tooth pitch is closely related to the meshing module [m], according to Polish standards it is a normalized size and can take the following values: 1; 1,125; 1.25; 1.14; 1.5; 1.75; 2; 2.25; 2.5; 2.75; 3; 3,5; 4; 4.5; 5; 5.5; 6; 7; 8; 9; 10; 11; 12; 14. It is possible to use other module values or when using automatic gear generators in a CAD type environment, it is necessary to select or specify a module. Its value can be calculated from the following formula:

$$m = \frac{p}{\pi} \quad (3)$$

Reconstruction of an exemplary object

Operating machinery and equipment causes their subassemblies, parts or components to wear out, which may ultimately lead to destruction. Damage to such a part may result in immediate shutdown of the given object from service, and this causes a stop, which in turn is the cause of losses. The easiest and fastest method of repair is to replace this element with a new one. The problem arises when the desired element is not available on the market, technical documentation is not available or the costs of obtaining a new element are too high. In this situation, Engineering Reconstruction is also called Reverse Engineering, which allows you to restore technical documentation and make a new product (Palka, Ciukaj; 2019, DIM-CAD, 2020).

The paper attempts to reconstruct an example gear wheel included in a gear using the Reverse Engineering method and 3D printing (FDM).

As mentioned earlier, the first step in the reconstruction is to digitize the reconstructed object. One way is to measure an object with simple tools. In the case of a gear, measurements can be made using an analog caliper. Then, based on the obtained values, you can start designing the 3D model, in this study you used the Fusion 360 program. We start designing by making a 2D sketch in the XY plane. The first step of the sketch is to enter the diameter of the circle and to lay out the guide lines. Then we draw a tooth using the options "arc", "line", "bounce", and then we arrange the selected number of teeth around the circumference of the circle. These stages of the project are presented in the figure below (Fig. 4).

The gear sketch created is replaced with a 3D model by using the "extrude" option. This tool allows you to give spatial dimensions and a smooth transition from a flat sketch to spatial models. In the same way we make a hole in the gear wheel and give its value as negative (Fig. 5).

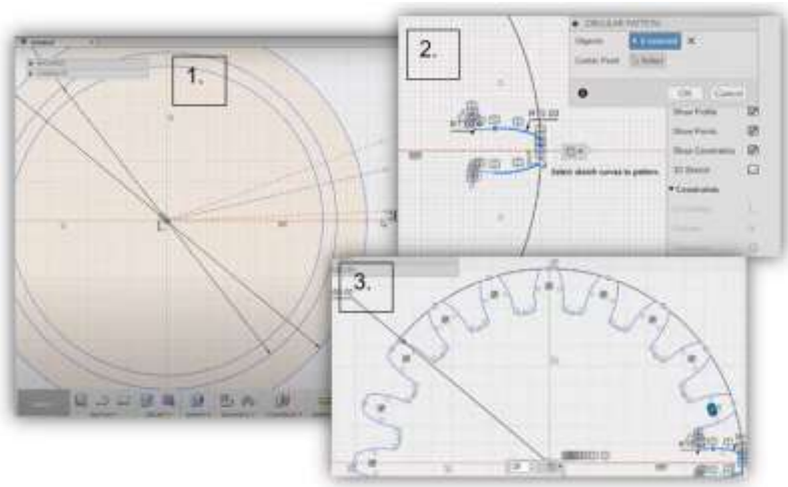

Fig. 4 Next steps for gear design

Source: Own study based on (Mufasu CAD)

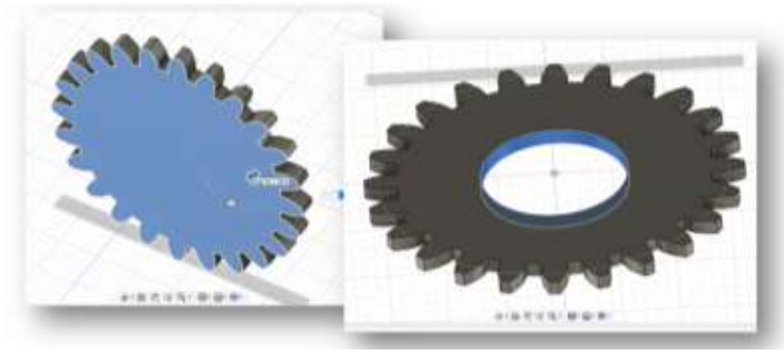

Fig. 5 Conversion of a flat sketch into a 3D model

Source: Own study

The second way to design an example object is to use a gear generator. The presented example uses the SpurGear generator, which is one of the plug- ins of the Fusion 360 program. This tool allows you to automatically generate a wheel based on the given parameters (Fig. 6).

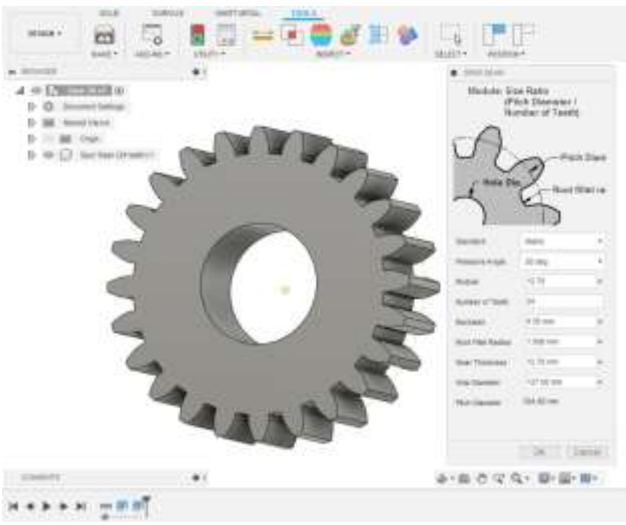

Fig. 6 Gear design through the SurpGear generator

Source: Own study

The program automatically proposes standardized values, however the application allows free selection of parameters, which gives the possibility of creating non-standard parts. The use of this tool definitely simplifies and speeds up the work, however, manual design seems more precise due to the specificity of the object.
The second way to digitize the desired object is to transform the measurement points to form a gear model based on the 3D scanning method. Based on the first and second scan samples, significant differences were found in the structure of the real and modelled object. A quick analysis of the obtained point cloud is the basis for the conclusion that the adoption of automatically obtained geometry of gear teeth does not give unambiguous results of gear accuracy assessment. The obtained point cloud should be processed in the CAD environment so that the shape of the object allows it to be filled. A closed object and a uniform structure ensure greater accuracy in the manufacture of the final product (Fig. 7).

Fig. 7 3D scanning of the reconstructed object
Source: Own study

At the final stage of modelling, it is worth remembering to prepare technical documentation, including projections, cross-sections, scale and comments necessary for the production of the object.
The key element of reproduction is the manufacture of the final product. For this purpose, the design of the 3D model was exported to the STL format. STL files are a conventional form of commands to be performed by a 3D printer, at the same time it is a compatible file format with a CAD environment and dedicated software for the printer. This software enables giving detailed printing parameters. Among the available options, the material from which the product will be made is selected, in this case it is Z-ULTRAT filament. This material is based is on the material artificial and ensures an adequately high quality and durability models, so this can be used for a variety of functional prototypes, components or finished consumer products. In addition, according to the manufacturer's assurances, this material is easily subjected to chemical and

mechanical treatments, it allows the printing of models with physical properties similar to products produced using injection molds (Zortrax). Figure 8a presents the availability of advanced printing options that determine the strength and quality of the manufactured item, they relate to the filling of the object: the structure and density given in percent and the precision given in tenths of a millimeter. Figure 8b presents the options determining the method of production. In order to ensure the smoothness of the object's surface, it is most often made on a thin platform, and in the production of geometrically complex objects it is worth using supports supporting the model during its manufacture. An important element for the strength of the element is the dispersion of the seam. The seam is the point where the application of a new layer of material begins and ends, at the same time the place is most often exposed to cracks.

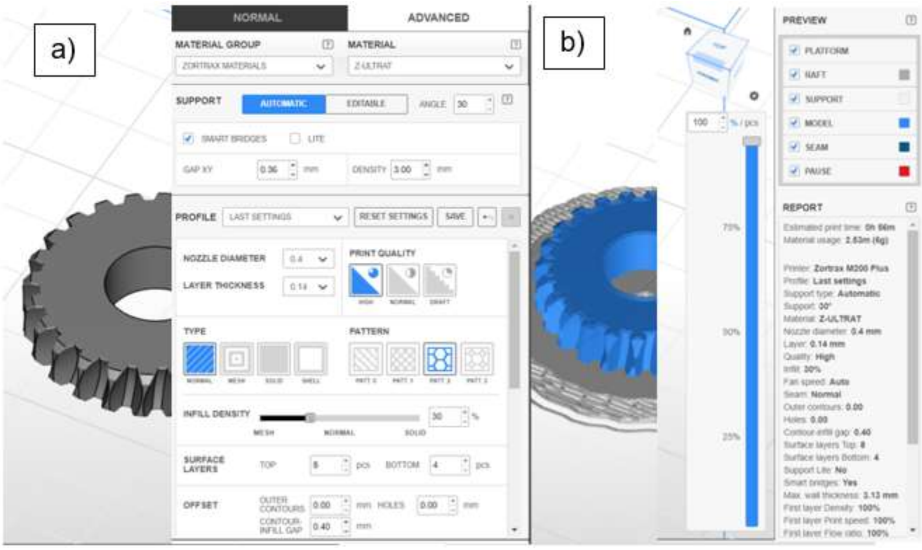

Fig. 8 3D printing options settings

Source: Own study

The final view of the settings informs the user about the material consumption and the duration of the object production process. In the studied case, the gear printing process took 56 minutes and material consumption was 6 grams.
The final stage of reconstruction is the manufacturing process itself, as shown in Fig. 9.

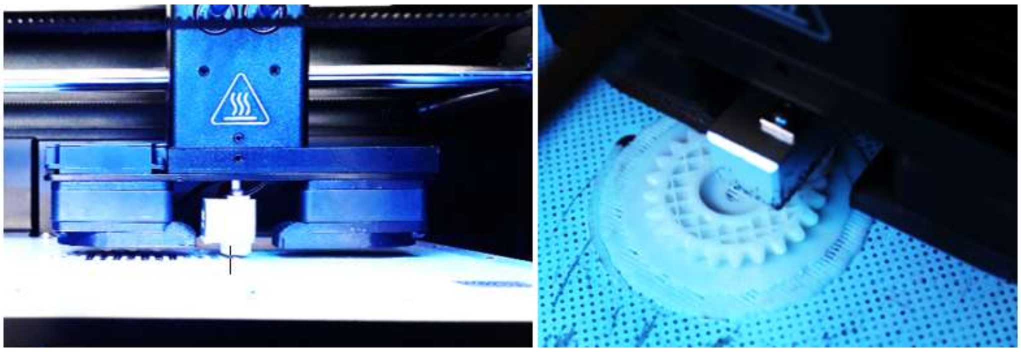

Fig. 9 Production of the final product

Source: Own study

CONCLUSION

The purpose of the article was to apply Reverse Engineering and 3D printing in the reconstruction of gears. In the implementation of the intended goal a simple caliper measuring tool and a laser scanner designed for automatic reconstruction of the object's geometry were used. Data analysis and processing was performed in the Fusion 360 program, which turned out to be multifunctional, both for 2D and 3D design, automatic gear generation and creation of technical documentation. At the last stage, software dedicated to the 3D printer used has been used, which enabled production parameters to be set. With the current difficult market situation, the approach to the issue of maintenance is of great importance for the future of enterprises. The slightest failure generates a stop and this usually causes costs and losses. These costs can be much higher if the failure relates to a spare part that is not available on the market. The inability to repair a damaged machine creates a need that the Reverse Engineering method responds to.

Engineering reconstruction can take place in various ways, IT tools for modelling or developing technical documentation are also numerous. The quality of the final element is associated with the use of appropriate methods, software, hardware and material. And their diversity allows for the appropriate selection of solutions for the selected element, taking into account many factors - the level of geometric complexity, the essence of aesthetic values, the function of fulfilling by the element.

In addition, 3D printing eliminates the need to start the entire production line, making it ideal for the production of a single individual item. It reduces costs, time and effort that has to be put into the traditional production process. In addition, it does not differ in precision or quality of manufactured objects from traditional methods.

Having a digital version of a real element also allows you to make improvements to it without generating additional costs. These improvements can be associated with changes in the object's geometry or the choice of alternative, better material. Undoubtedly, the technique presented is a new approach to the reconstruction of existing elements and is part of the idea of industry 4.0.

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Abstract: Despite the very rapid technological development, the general concept of mechanical devices has not changed. Still, the most common element of these devices are gears, whose range of use is very wide. There are both technological and historical considerations for the reconstruction of gears and other elements. In particular, this applies to spare parts for technical facilities that are not available on the market or service costs are too high. Contemporary reconstruction is called Reverse Engineering, which offers tools that allow transformation of an existing object through a virtual model into the final real product. Modern production engineering is based on innovative CAD – Computer Aided Designed design methods and computer-aided manufacturing technologies, CAM – Computer Aided Manufacturing. The rapid development of 3D CAD systems has led to the development of solutions to obtain the designed object, already at the development stage. Such a solution is the Rapid Prototyping method, designed for fast, precise and repeatable production of machine components. Widespread use and growing interest in the use of additive printing influenced the development of this technology. The purpose of the article is to present the practical application of the Reverse Engineering method and 3D printing in the reconstruction of gears. The object of research is the real gear, which has been reconstructed using Reverse Engineering and 3D printing. The article presents the basic assumptions of the methods used and the methodology for conducting reconstruction work. FDM (Fused Deposition Modeling) technology was used for the research. The results obtained are a real example of the practical application of the presented methods. At the same time, they create great opportunities for their wider use.

Keywords: 3D printing, Reverse Engineering, design, gears, reconstruction