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Algorithm for Applying 3D Printing in Prototype Realization in Accordance with Circular Production and the 6R Strategy: Case - Enclosure for Industrial Temperature Transmitter

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Algorithm for applying 3D printing in prototype realization in accordance with circular production and the 6R strategy: Case - enclosure for industrial temperature transmitter

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Abstract. In this paper, the implementation of additive manufacturing (AM) in circular production (CP) through implementation of the 6R strategy is investigated. The defined methodology allows designers to reconsider decisions, correct mistakes or make specific changes to the model in all phases of the design process, from initial drawings to finished product. CP enables the complete realization of the prototype with a particular focus on environmental protection and the additional use of recycled waste. The proposed algorithm is tested through the design and manufacturing of an enclosure of an industrial temperature transmitter. Some of the drawbacks of additive manufacturing such as mechanically damaged surface, surface roughness, and tearing of models on weak joints have been investigated and recommendations for mitigation are given.
The mechanical methods of product finishing are described in detail in the paper as well, and in order to check the prototype functionality, some tensile, thermal stress and drop tests were performed and results were analyzed and discussed. It was shown that large savings in time, cost and material can be achieved by implementing AM in the realization of a fully functional prototype while at the same being in line with the demands for CP and 6R.

Keywords: Circular production, 6R strategy, Additive manufacturing, FDM printing, Algorithm, Sustainable Development, Product Design, Enclosure

1 Introduction

The term product life cycle means: rapid product development, rapid changes/modifications to an existing product, rapid disassembly of the product and finally, reduction of the use of toxic substances [1]. For better competivness on the market enterprises need to increase their innovative activities and shorten the time to market, utilizing Additive Technology (AT) manufacturing.

When making any model/prototype with defined technical specifications, its geometry is considered first, i.e. the complexity of the product is examined. The implementation of AT creates additional value in realising complex geometry, which is not easy to realise with conventional processing methods. Therefore, the application of AT has multiple roles in parts reorganization, weight reduction, functional adjustment, parts reproduction and consideration of complete aesthetics [2]. AT is commonly used in prototyping but has found application in tool making, manufacturing of various parts as well as repair of damaged and replacement of worn parts [3].

According to research [4], the development of rapid prototypes with application of new technologies is a strategy for improving the enterprice business activities. When it comes to sustainable development of enterprises, application of AT means: improving use of resources, application of more efficient production systems, application of new production processes, application of new materials and adoption of new business models [5].

The use of additive manufacturing (AM) generates waste, but compared to conventional manufacturing (CM), this waste seems insignificant [6], see Figure 1.

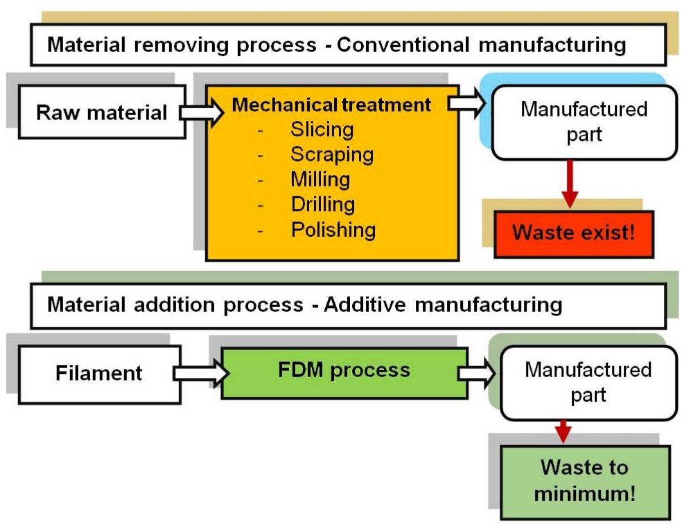


Fig. 1. Comparison of AM and CM [7]

AM has the following advantages over CM [7]:

- Efficient use of materials: AMs use materials efficiently because parts are made by addition, layer by layer rather than subtraction.
- Resource efficiency: AM does not require additional resources, including tools, auxiliary tools, accessories, and coolants.
- Flexible design: AM allows the production of parts with complex geometry and different mechanical properties.
- Flexible manufacturing: AM allows manufacturers to quickly change the design of the manufactured part without additional costs i.e. making new moulds.

AM operates on the principle of adding materials in layers [8], and the resulting waste mainly includes perfected or unfinished models due to poorly selected input parameters or unexpected shortcomings [9,10]. AM affects weight reduction, water, energy, and material use, all of which positively impact sustainability. Some AM techniques facilitate recycling and disposal of waste allow repair, processing and redesign of obsolete product [10]. AM uses less harmful ingredients, chemicals, cutting fluids, or hazardous compounds released by casting than CM when it comes to environmental protection.

2 FDM procedure

Fused Deposition Modeling (FDM) is an AM process developed by Advanced Ceramics Research (ACR) in Tucson, Arizona [11]. This process has been significantly improved at Stratasys, Minnesota, USA. FDM provides effortless design of devices, low maintenance costs, increased security, and very affordable highly complex model/prototype manufacturing in a wide range of colours and materials, which is one of the main reasons for the widespread acceptance and application of this procedure [6,12,13].

Disadvantages when using FDM devices are: increased surface roughness due to layer lines on the model surface where the shape and contour of the part can be seen, insufficient strength in the vertical layer printing direction, need for additional design and supporting construction, need for coating and additional shaping, large printing time required and somewhat expensive filament material. [14,15].

2.1 Model making methodology

The methodology of making a model/prototype using the FDM procedure (or 3D printing) is in the following steps [16,17]:

1. Realization of the 3D CAD model. The model is realized using some CAD software package (i.e. Catia, Solid Edge, Solid Works, Inventor Fusion, Pro/ENGINEER, FreeCad etc.). This step allows changes to be made to the model before it is put into manufacturing, thus improving communication with the customer;
2. The 3D model is imported as *stl. or similar file in a specialized slicing software (i.e. Ultimaker Cura, Skeinforge, Slic3r, Simplify etc.), with which the printing parameters can be adjusted [18]. The 3D Systems *stl. (often refered as standard triangle or standard tessellation language) file format has become somewhat a standard for describing the geometry of CAD models for AM [19]. With this file format the CAD geometry is transformed in an unstructured triangulated surface with a ASCII or binary representation. Advantages of *stl. files are reflected in the fact that most CAD application software supports it, while the disadvantages are reflected mostly in the loss of printing resolution, [20].
3. Preparation for printing in a slicing software. Here, the free slicing software Ultimaker Cura which supports various file formats such as *stl., *3mf. and *obj., and provides large number of options for printing parameters setup

(temperatures, infill patterns, support generation, bed adhesion etc.) and model manipulation (rotation, translation, scaling, mesh fixes etc.) was used [21].

4. Most 3D printer postprocessors use G code i.e. the *gcod extension. The G code is a standard format used for CAM that describes the tool path (nozzles in the FDM procedure), i.e.: 1) the movement of the print head in the x, y and z directions, 2) the amount of extruded material and 3) the speed of movement of the head. During this step, *gcod is loaded into the printer and thus, the model/prototype is ready for manufacturing. Most conventional FDM printers use the horizontal technique to print a 3D object, layer by layer [22];
5. In the last step, the 3D model is realized. There is also the removal of excess material and model cleaning, subsequent (additional) processing and testing of the finished product [23,24].

The paper [25] presents a block diagram by which a 3D CAD model is transformed into a finished/fabricated physical object (prototype), see Figure 2.

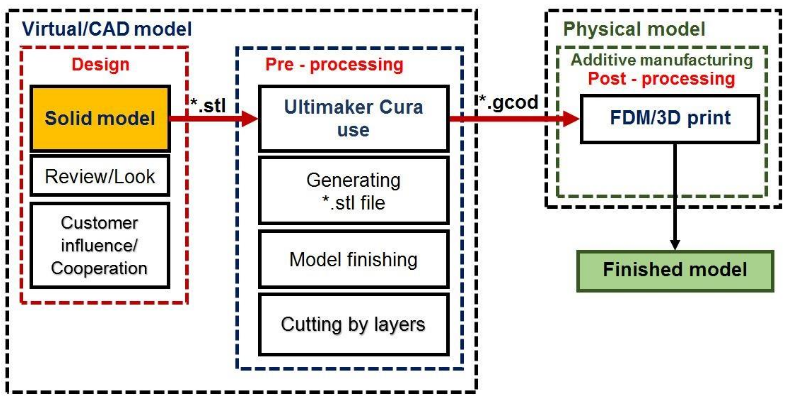


Fig. 2. Block diagram of the virtual into the finished physical model realization

Therefore, applying the FDM procedure requires advanced technical knowledge in preparing, setting parameters, and making a model/prototype [26].

2.2 Input preparation and control of FDM procedure

The FDM process is fairly easy to maintain and control. In this regard, this paper provides several guidelines for quality printer operation and quality model making:

- Before starting up the printer, check all screw connections to make sure that the adjusting screws on the pulleys are tight. Check belt tension/looseness. The guides should be lubricated to allow unobstructed movement on the axles;
- Pay attention to the choice of type and quality of the filament. Poorly selected filament does not give high-quality prints. Since the filament is hygroscopic (absorbs water from the atmosphere), storing it in a dry place without dust and moisture is essential. Storing filament in a "desiccator" (container with a

moisture absorber) is recommended and if necessary the filament can be dryed in an oven prior to use;

- Ensure that filament goes fluidly into the extruder, as well as ensure its proper flow during the printing process;
- The plate should always be free of dust and added adhesives. If there are issues with bed adhesion leading to warping and part detachment during prints, thin layer of adhesive (glue) can be applied on the work surface;
- The plate should be levelled to obtain a perfect formation of the first layer. In this case, levelling means that the nozzle's movement remains parallel to the printing surface. Poor levelling can cause bending on the bottom layers or cause the print to separate from the work surface;
- Correct temperature values for the nozzles and the work surface (bed plate) should be set. These values are determined depending on the print material and size. Incorrect nozzle temperature can lead to poor layer adhesion or part deformation as well as nozzle clogging. Incorrect bed plate temperature can lead to warping of the lower layers and/or separation during printing. Some materials such as ABS have large thermal expansions and require enclosure for quality prints;
- During printing the extruder abruptly changes direction. First, it gradually slows down and then accelerates again in a new direction. If printing speed is to high the inertia force can be significant and can cause vibrations that will be manifested in the quality of the print (this is especially emphasized in printers where the entire extruder including the motor moves during printing). Reducing printing speed also reduces the flow and pressure of the molten filament through the nozzle, i.e. the accumulation of material in the nozzle is prevented, and uniform printing is obtained during printing. It however means longer print times.
- In order to prevent bridging (thin lines of material extruded during travel) extruder retraction is used. The optimal retraction speed and distance can be found by trial and error.

2.3 Printing and modelling technology

The FDM process involves melting the thermoplastic material through a heated nozzle. The filament is fed from the coil of material (1) to the extruder (2). The extruder is transported to the guide (4) via a stepper motor (with a pair of gears) (3). Further, filament moves through the heater (5) and exits through the nozzle (6) as a molten material in a string form (7), after which it touches the active plate (8) and sticks to it. Finally, the material is cooled and solidified as a finished piece/model (9) (Figure 3b) and 3c)). Standard filament diameters of 1.75 mm and 3 mm are most often used, while nozzle diameter ranges from 0.1 mm to 1 mm. The heater's maximum temperature usually reaches 280 °C (dependant on the type of material).

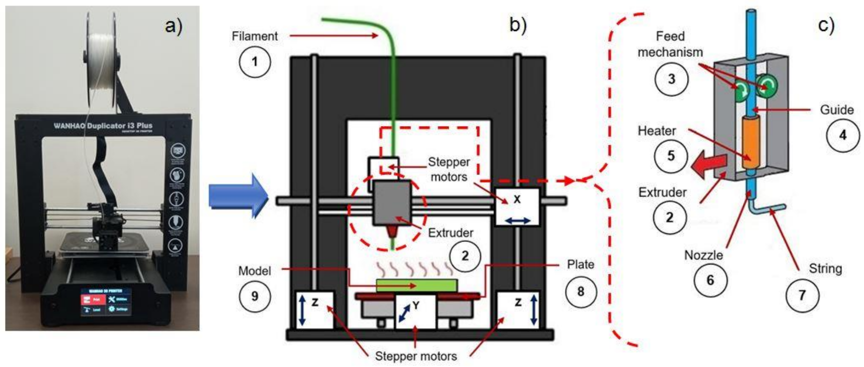


Fig. 3. 3D printer elements, type Wanhao Duplicator, i3 Plus

The extruder (2) is an essential part of a 3D printer (see Figure 3c). It consists of two interconnected parts:

- The hot part contains a nozzle and heater. The heater is mainly made of copper, but aluminium is also more and more present.
- Cold part or mechanism that cools and drives the hot part of the extruder. A toothed mechanism drives the filament to the extruder; see Figures 3a and 3b.

This part allows cooling and prevents further heat dissipation from the hot part using fans and coolers. When the first layer is formed in the XY plane, the extruder is moved by a specific value of the layer height in the z-axis, followed by the formation of the next layer in the XY plane, and the procedure is repeated until the finished model of the desired height [27-29], see Figure 4.

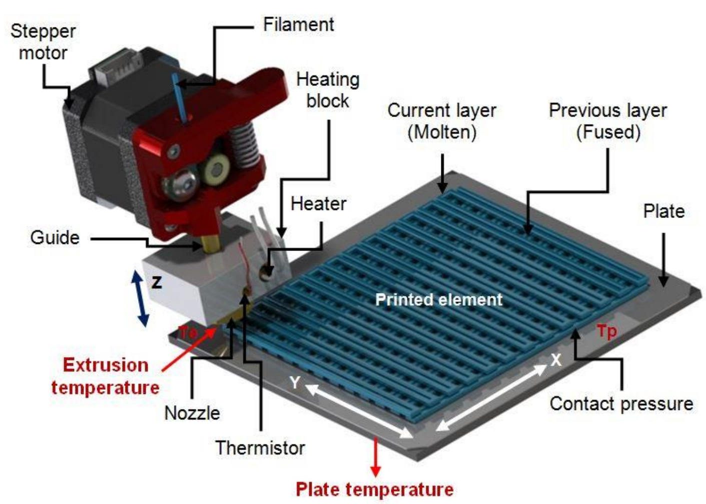


Fig. 4. View of extruders and model making by layers

The nozzle is constantly in contact with the printer and in contact with the material, see Figure 4. During the 3D printing process, there is a risk of the nozzle colliding with the formed model [30]. Clogging of the nozzle often occurs due to

1. mixing of material,
2. hardening of molten material on the walls of the channel and external structure,
3. material drying that eventually becomes brittle and breaks before entering the printer head [31].

Since printing height or layer thickness attributes most to the surface quality of the printed part, smaller values are better, however this means increase in print time. The Wanhao Duplicator i3 printer (Figure 3a) is a low end 3D printer and offers minimum layer height of 0.1 mm which is good enough for most purposes.

The accuracy of dimensions, the quality of the layer bonding and the final mechanical properties of the model depend on the flow rate and the temperature of the molten filament [32,33]. Nozzle temperature (T_N) and plate temperature (T_P) play a significant role in forming layers, see Figure 4. T_P temperature is directly related to the type of material and is always much lower than the nozzle temperature. For ex. PLA has a glass transition temperature of 57 ï 63 °C and a melting point of around 160 - 180 °C (depending on the manufacturer) so it is usually printed with temperatures larger than 200 °C. More on the different types of printers can be found in [34].

The operating temperature of the build plate depends on the used material as well. For PLA material, the recommended PLA temperature ranges from 50 °C to 60 °C, and for ABS from 70 °C to 80 °C. If higher temperatures than the mentioned ones are set, the previously formed layer may dissolve, which eventually leads to inaccuracies in the dimensions of the realized model. Also, the cooling can be non-linear, and in the end, a model of incorrect dimensions and irregular shapes is obtained. Therefore, the temperature difference between the nozzle and the model should be as slight as possible, and the cooling process should take place slowly and gradually [35].

The build plate (8) is also an essential part of a 3D printer. The build plate is made of aluminium and heats evenly, and the molten material from the nozzle is applied to it. The role of T_P on the work surface is to prevent sudden cooling of objects and materials collection. However, to better adhere the material to the surface (quality joint), polyamide tape, glass or steel plate, and various coatings are often used as accessories. In order to facilitate the removal of the model from the work surface, flexible magnetic Teflon surfaces are increasingly being used.

3 Printing materials

AM uses nylon, various resins, elastomers and thermoplastic materials [36]. Non-toxic thermoplastic materials (polymers) such as PLA and PET are most commonly used in the FDM process. These materials have a low melting point and require less energy when heating the nozzle and work surface [9].

PLA (Polylactic Acid) is a biodegradable, thermoplastic material obtained 100% from renewable sources such as beets, potatoes, corn [37]. It has a relatively low melting point, 150-162 °C [38], which requires less printing energy and does not emit toxic gases into the environment [39]. Unfortunately, this material is hygroscopic and not resistant to high temperatures [40].

ABS (Acrylonitrile Butadiene Styrene) is an amorphous polymer characterized by the following parameters: excellent mechanical properties, resistance to elevated temperatures and impact resistance [41,42]. In the AM model, ABS is a petroleum-based thermoplastic material. Unfortunately, the vapours released during the melting of ABS release harmful gases to human health and the entire environment, so it is necessary to provide filtration and an isolated (closed) work system with as little human presence as possible [43].

Nylon is a biocompatible material that, with its properties, best matches ABS in the model-making process. The most common use of this material is in the medicine, textile and aviation industries [44]. Compared to PLA and ABS, nylon shows better chemical resistance, higher tensile strength and modulus of elasticity (tensile strength 28.5 MPa and modulus of elasticity 1807 MPa), and realized models on FDM printer are characterized by lightweight and excellent flexibility [27,45]. No harmful splashes occur during the model making.

4 Circular production and 6R strategy

According to [46] Circular Production (CP) includes:

- improving process automation;
- redesigning products;
- improving the quality of redesigned products based on 3D printing and reducing the cost of process elements;
- reducing the use of natural resources and reducing environmental pollution.

According to [47], the application of circular production is possible in cases where organizations have well-considered and analyzed the product's complete life.

The 6R strategy is crucial in ensuring multiple product life cycles characterized by a closed-loop [48]. These closed loops allow for greater efficiency in the flow of materials, components, energy and water during successive product life cycles [49].

Enterprises in the process of sustainable development should implement the 6R strategy. This strategy includes 1.) Reduction of waste material to a minimum (Reduction); 2.) Reuse of waste material or used product (Reuse); 3.) Recycling, 4.) Regeneration of raw materials, materials and energy from waste that cannot be reduced, reused, or recycled (Recovery) [50], 5) Product redesign, areas of business or complete business process (Redesign) [51] and 6) Reproduction that includes disassembly, cleaning, measuring and testing of parts, as well as disposal of correct / repaired parts in the warehouse (Remanufacturing) [52].

The purpose of recycling is to reuse the material or elements of the used product. In general, a product can be composed of old and new elements. In the reproduction process, Jiang et al. [53] defined three main phases of reproduction: decision making, process planning, and technology planning. Also, by applying reproduction, the authors [54] pointed out that it is possible to save up to 85% on the product's weight, i.e. 80% less energy is needed for product manufacturing. Also, the material costs of reproduction amount to only 40% of the total costs compared to 70% of the total costs of selling new products [55]. Unfortunately, designers are increasingly wary of recycled components, as such components may have variable quality characteristics [56].

5 Circular production and additive manufacturing

In the CM process, losses in the form of veneers, poorly made pieces, broken tools, etc., occur at the outlet next to the finished product. The algorithm for the application of CP through the 6R strategy in the company's sustainable development provides feedback between the seller and the buyer. The buyer appears as a supplier, i.e. he appears in the role of the seller of used products, which is an important segment in the application of the 6R strategy in the sustainable development of the company [57]. Also, the customer becomes a strategic partner of the enterprise because it reduces the accumulation of raw materials and losses in the sale of new products. On the other hand, recycling used products have become an environmentally friendly component that allows enterprises to target markets where customers cannot buy a new product or have products that are not serviceable.

Also, according to [58], lean management (LM) is ideal in upgrading the CP algorithm. LM is a set of procedures and principles used in industrial processes to find and eliminate useless activities [59], and AM enables this. The authors of this study, on the example of small and medium enterprises (SMEs) in Serbia, showed that ẹnterprises lack a system that ensures that the customer receives a quality product on time, due to lack of production optimization and limited resources. At the same time, standard procedures are insufficiently applied in enterprises.

This paper aims to introduce an algorithm for the application of CP over 6R strategy in the sustainable development of enterprises. The strategy allows defective and outdated products/parts to be used in the modification or production of new elements/parts [30], see Figure 5. Literary sources [60,61] served as a starting idea for developing the initial algorithm.

The presented algorithm enables waste reduction, recyclation of worn-out parts and redesign and use of used/repaired products for several life cycles. AM is seen as the basis of CP and serves as a complement to CM. Reproduction potentially helps many developing economies. Product reuse and processing are becoming more intensive, while processed or modified parts or whole products are cheaper than newly produced products. In this sense, if a quick repair or modification of an element of the product is required, AM provides quick responses and solutions.

According to the algorithm, the product can be composed of entirely new, repaired or modified elements (see Figure 5). If the product is purchased from the customer/consumer, it must be controlled; whether it works (e.g. if it is in use) or does not work (out of use or technologically obsolete!). The first question in the algorithm is: Is the product within the warranty period? (1). If the product is within the warranty period (YES), the product is serviced correctly. The servicing process involves disassembling the product, cleaning the surfaces of the components, analyzing the correctness or malfunction of the disassembled components, repairing or possibly replacing them with new [52]. Correct elements/assemblies are stored in the finished parts warehouse. In the process of disassembly of correct and defective devices (out of warranty period - NO answer), defective parts are present, along with specific technological procedures of processing and finishing (redesign of the mentioned product is also considered here) can be used again.

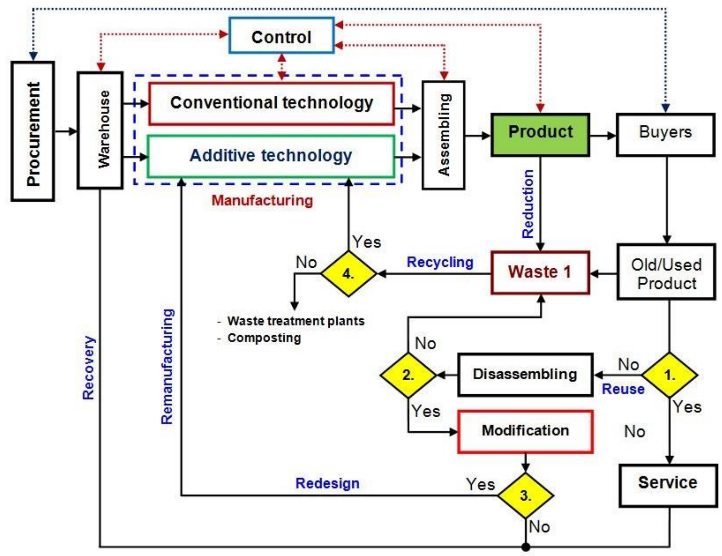


Fig. 5. Implementation of 6R strategy in enterprise sustainable development

Disassembly of the product raises another question: Can disassembled components be in use? (2). If they are not in use (NO), defective elements are disposed of (they become unusable elements). Suppose specific components of the product are technically correct (YES). In that case, they are performed through technological operations of finishing and repair (washing, cleaning, sandblasting, polishing, chemical treatment, lubrication, replacement of certain elements) and then disposed of in the warehouse of correct parts as parts for reuse in the process of assembling a new product. Here, it is possible to reuse some parts without prior upgrades and finishing. In order to apply such procedures, it is vital to design a product that allows: accessibility, easy replacement of parts/assemblies, disassembly of assemblies, the possibility of finishing and reuse [62].

From the point of view of applying the 6R algorithm in enterprise sustainable development, the following question arises here: Is there a possibility to modify the product? (3). If it is not the current strategic option (NO) related to a specific product or product range, go to the finished goods warehouse. The modification application in this algorithm (YES) is the starting point for applying AM in the redesign and reproduction of specific elements/assemblies. In order to achieve the best possible efficiency of the company in sustainable development through the application of AM, it is necessary to provide new innovative solutions through modifications in product design [63].

Finally, the algorithm provides an answer to the question of waste. Waste is seen as an essential resource, i.e. the question arises: Is it possible to recycle waste? (4). If it is not possible (NO), it indicates that the company still uses outdated technologies that require waste disposal and its delivery to the recycling plant. If possible (YES), companies have waste recycling technology for their reuse or apply the reuse process of elements/assemblies at the end of the product life cycle. The application of AM enables the recycling of declines and reduces the use of parts made conventionally.

The AM algorithm is considered a supplement to CM, and it can also take precedence in the realization of new ones. After the realization of specific components, they will be assembled, and then the output control of the product will follow. The algorithm for the application of AM in CP includes preparation for production, the process of realization of production (or reproduction), the end of the production process with post-processing and waste recycling process [64-66], see Figure 6. This algorithm describes the closed process of plastic model production and plastic reuse waste in filament making [57,67].

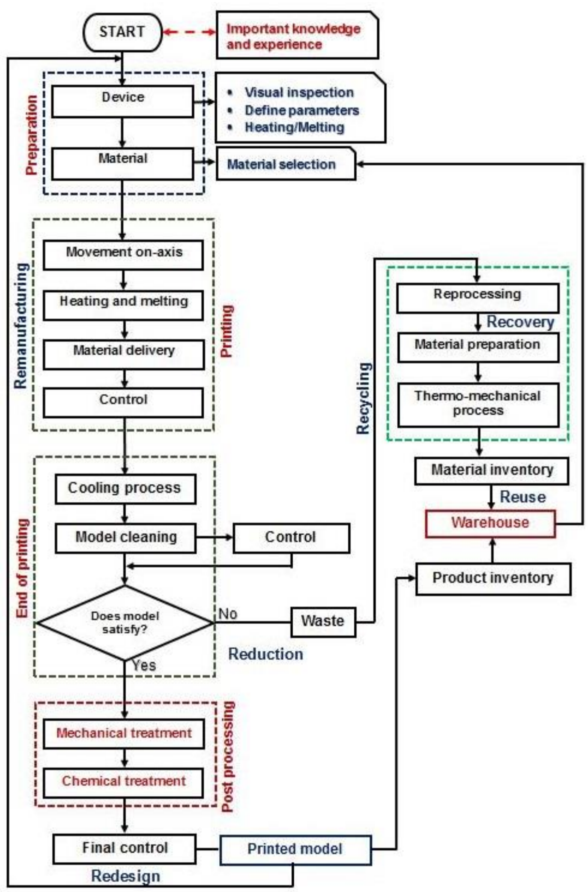


Fig. 6. Algorithm for applying AM to CP

Additional processing includes specific finishing procedures. Various abrasive procedures can be carried out at this stage, such as polishing, sandblasting, and coating surfaces with special coatings. Chemical or thermal treatment [40] is required to obtain better mechanical properties. If the desired accuracy of the product dimensions was not obtained in the FDM procedure, conventional machining up to specific tolerances is required. Preparation error control should only affect the first layer and not spread to other layers. However, a change in injector speed or an initial error in system positioning can cause irregularities that affect the overall error [68]. During printing, no information is obtained on the partial detachment of the object at any time [69]. Input errors in the preparation of production also occur by selecting printing materials, and the material by its characteristics affects the quality of printing.

The set parameters during 3D printing significantly affect the surface roughness of the manufactured parts. Such parts usually have a high surface roughness and require additional processing to obtain smooth surfaces. As the layer thickness increases, the surface roughness of the part increases. For suitable surface treatment, it is crucial to choose a material that allows additional mechanical and chemical treatment [70].

Before starting FDM printing, the printing parameters must first be defined and the material selected. The shape of the model and the required size of the equipment also dictate the production flow. By putting the device into operation, the operator must permanently control the printing through the supply of material, heating and melting of material, print quality. Geometry and surface control are performed during the model's realisation at the end of the production process. Finally, the accepted model is further refined (mechanically and chemically). With such treatment, a model/prototype is obtained equivalent in size, shape and dimensions to the original made by conventional technologies. All this is acceptable if the model meets, but it is disposed of in the waste if it does not meet the mentioned criteria.

Thus, the activities in the realization of the model/prototype by use of AM are [71,72]:

1. Design (Virtual modelling) and production preparation - includes material selection, control of input parameters, optimization of design parameters, development of the analytical model, development of algorithms and databases based on quality prediction;
2. Printing (or additive production) - includes quality control and supervision during the printing process;
3. Finishing - means final control, finishing on the manufactured elements, correction of defects (thermal, chemical and mechanical);
4. Analysis - this includes checking the operating parameters of the device as well as interpretation of the obtained parameters. The validation and assessment of the reliability of the work are indispensable here.
5. Product economy - includes validation of processes and parameters, defines the best orientation of the work, and estimates workability.

6 Algorithm 6R in the realization of the electronics enclosure

An example of applying the 6R algorithm in CP was the realization of the electronics box for the temperature transmitter in the enterprise ICTM-CMT, Serbia. ICTM-CMT is emerging in the domestic market as manufacturer of sensors and electronic transducers of pressure, level and temperature. Development and realization of temperature transmitters in CMT includes the following activities:

- electronics design;
- selection of electronic components and assembly technology;
- development of laboratory and industrial prototype electronics and testing software;
- design and manufacturing of electronics hardware;
- development of software for signal processing and computer communication;
- construction and production of threaded parts for connecting sensors and electronics; and
- final measurements and determination of transmitter characteristics.

The realised temperature transmitter with CM is shown in Figure 7. The temperature transmitter consists of the following modules: 1) Pt-100 sensor, 2) electronics enclosure, 3) electronic block, and 4) electrical connection (Binder - Miniature Round Plug Connector Series 680 with 5 pins), see Figure 7. All of the modules in the assembly define a new product.

From this point of view, the modules on the temperature transmitter are produced separately, i.e. they can be: replaced, reused, modified and finally recycled. The paper [73] using QFD and AHP tools concluded that the modular architecture is of great importance in the sustainable development of ICTM - CMT because all product modules are designed to be reused and recycled.

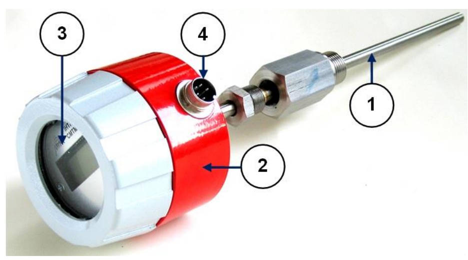


Fig. 7. Realized temperature transmitter, TPt-101

The electronics enclosure consists of a cover and a central part of the enclosure. The main part of the enclosure is used to accommodate the electronic block and the temperature probe. In conventional processing methods, the enclosure is made from aluminium, and its appearance is shown in Figure 8.

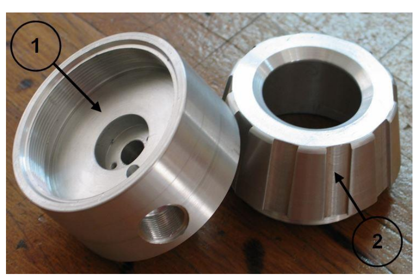


Fig. 8. Temperature transmitter enclosure (made of amuminium): 1- central part, 2- cover

In this paper, an electronics enclosure was manufactured using the FDM procedure, see Figure 9. After 3D printing, there are many irregularities in implementing the model, which includes additional analysis of input parameters and additional processing.

Fig. 9. Realized electronics enclosure using FDM procedure

First, the surface roughness of 3D printed parts is observed with a microscope. *Roughness* is a surface texture that occurs after printing and after additional processing, and mechanical or chemical post-treatment methods are then used to reduce surface roughness. Surface roughness cannot be easily assessed before printing, as it largely depends on the resolution of the printer and the printing material [74].

The most commonly used mechanical methods to improve the surface quality of FDM prints are machining, grinding, polishing, abrasion and finishing, while chemical methods include dyeing, coating, heating and vapour deposition [75].

7 FDM procedure in the production of the electronics enclosure

Before 3D printing, a 3D CAD model of the electronics enclosure is made. The 3D assembly of the electronics box consists of 1) cover, 2) glass, 3) Zeger ring, 4) O ring, 5) brass hot melt insert nuts and 6) central part, see Figure 10. The cover has an opening, and the opening serves to read the data printed on the electronics display.

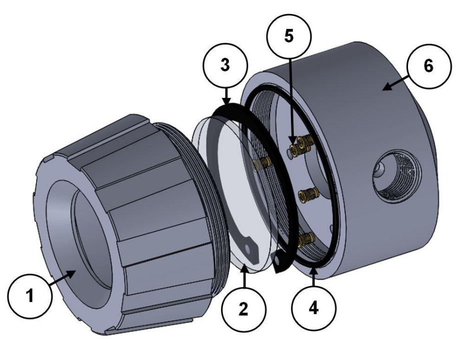


Fig. 10. Electronics enclosure - Virtual CAD model

Virtual CAD is transformed into a physical object (prototype) on a 3D printer. At this level, the designer is enabled to correct measurements and change the complete design. The created CAD model is transformed into *stl. file that goes on to be processed. Preparation for printing are made in the Ultimaker Cura software and, finally, * gcod. is generated.

7.1 Model printing

In this paper, the Wanhao Duplicator 3D printer, type i3 plus, manufactured by the People's Republic of China, was used in the implementation of the 6R algorithm. It has working volume of 200x200x180mm, minimum print resolution layer of 0.1mm, print speed 10-100mm/s, see Figure 3. The model used PLA filament, diameter 1.75mm (manufacturer Wanhao). First layer distance between the nozzle and the bed plate was set to 0.1 mm while the subsuquent layers were printed with 0.2 mm layer thickness (it was found to be a good compromise between print quality and time). The nozzle movement during realization of enclosure elements using the Ultimaker Cura interface (as defined by the *gcod.) is given in Figure 11.

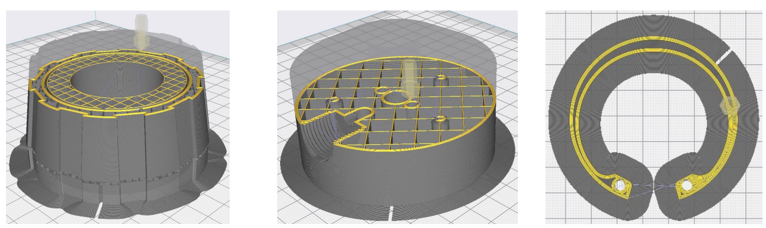

a) b) c)

Fig. 11. Nozzle movement in Cura software: a) cover, b) central part, c) Zeger ring

The used print parameters are displayed in the parameter list; see Table 1.

Table 1. 3D printing parameters

Parameter	**Value**
Layer Height	0.2
Wall Line Contour	3
Top Layers	3
Bottom Layers	3
Printing Temperature	210°C
Build Plate Temperature	60°C
Printing Speed	50 mm/s
Travel Speed	60 mm/s
Infill Density	20%
Infill Orientation	-45°/+45°
Build Plate Adhesion Type	Brim

Printing parameters affect the printed part's appearance, quality, and mechanical characteristics. Concerning this, guidelines are given to realize the part with the best possible printout and characteristics:

- Layer Height [mm] - ranges between 0.1 mm to 80% of the nozzle size. If the gap between the layers is more significant than 0.1 mm, there is a possibility that the molten material may not bond properly to the plate. Such a part becomes loose and easily disconnects (separates);
- Printing Temperature [°C] - represents the temperature that ensures a constant flow of material through the nozzle;
- Building Plate Temperature [°C] - This temperature depends on the material type, while the selected temperature allows quality adhesion and first layer printing;
- Printing Speed [mm/s] - lower material application speed means better work accuracy, longer printing time, and higher energy consumption [76,77]. A speed of about 20-30 mm/s has proven to be a very high-quality model. However, that makes sense for small pieces. It was found that good balance between quality and speed is obtained at a speed of about 50 mm/s. Everything beyond this speed leads to lower geometry quality and final dimensions degradation. Print speed adjustment is primarily related to nozzle temperature, filament type, and printer quality [78];
- Infill Density [%] - indicates the amount of material within the work. With higher filling percentage better mechanical properties are obtained however printing time is much longer, requires larger amount of material and the finished part is heavier. Depending on the use infill density can be varied typicaly between 10% and 100%. Infill type is important as well and most common are grid infiils made of squares or hexagons. With lower infill densities, the printing process is much faster, saves material and makes the printed part convenient for prototyping. When connecting the filling with the outer wall, an enormous amount of plastic accumulates and is squeezed out on the outer wall. That is why it is always necessary to increase the outer wall thickness [79];
- Inýll Orientation [°] ï depending on the infill type, layers can have different orientations during printing. This option is especially useful when considering parts with uniaxial od biaxial loads;
- Build Plate Adhesion Type - this is a way to provide better adhesion of the object to the plate. The Brim option allows for an extra amount of molten plastic before printing. Brim avoids printing with an empty nozzle, and later formed edges have an excellent contour quality.

AM allows two or more parts to be joined together, which avoids the use of various connectors, adapters or unnecessary assemblies. Mounting elements such as fasteners and the use of various screws are reduced. The enclosure printed elements are shown in Figure 12.

The òstepò effect is typical for 3D printing and is especially visible on curved and non-vertical surfaces. There are many different methods to eliminate this effect: manual grinding of the part, traditional machining, and finishing with chemical treatment [80]. Unfortunately, all of these methods can damage the model and take time, and the process can take from a few hours to a few days.

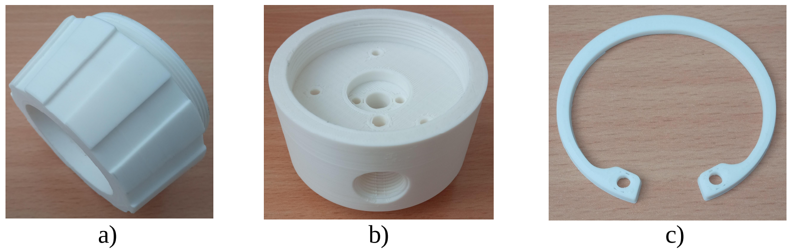


Fig. 12. Finished elements : a)cover, b) central part, c) Zeger ring

7.2 Model removal, visual inspection and cleaning

Once the elements of the electronics enclosure are printed, they are removed from the plate, and then a visual inspection of all irregularities is performed. The presence of gaps and cracks in the structure increases the stresses in the material, and these shortcomings further enhance the cracks propagation so that manufactured parts will not be able to provide sufficient mechanical stability for different applications [81].

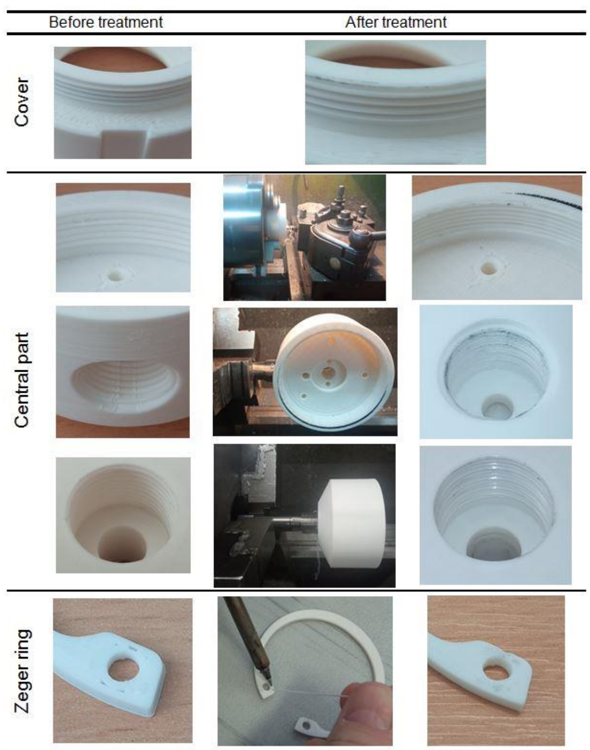


Fig. 13. Enclosure printing errors

Some observed errors that lead to unsatisfactory infill, shell and internal/external threads realisation are shown in Figure 13.

When removing auxiliary material, care must be taken not to deviate from the accuracy of the measures corresponding to the original model. Table 2 shows the weights of all manufactured components (weight measurements were performed on a KERN technical weight scale (± 0.01g)). Removing auxiliary material requires a certain degree of skill of the operator because his mistakes can lead to damage to the model.

Table 2. Enclosure manufactured parts weights

Enclosure part	Full weight [g]	Clean part weight [g]	Waste [g]	Cura prediction [g]
Cover	80.04	52.42	27.62	82
Central part	82.02	67.81	14.21	84
Zeger ring	2.89	2.08	0.81	3

In general, the prototype cannot be used immediately, and it is necessary to perform additional processing of surfaces, holes, threads, which is described in the paper [82]. According to the mentioned source, the excess material, various irregularities and added material are removed with pliers, scalpel, knife, drill, various files, sandpapers, see Figure 14.

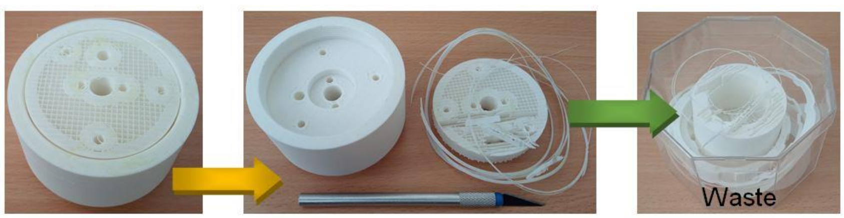


Fig. 14. Supplementary material removal

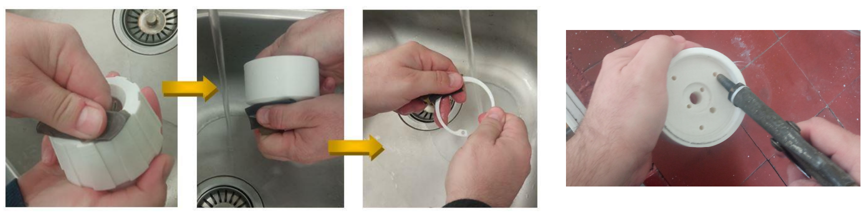
The rough processing includes mechanical removal of all surpluses in the material and finishing at machining centres (scraping, milling, drilling); see Figure 13 and 14. 3D printed parts are made to have a solid shell surrounding the porous (partially hollow) interior to save on plastic and print time. The removed excess material (from all made parts) is collected in a special box, see Figure 14. This material is waste that can be recycled and reused, following the CP algorithm.

7.3 Model sanding

Sandpaper of various granulations was used in model polishing. This necessary procedure removes the òstep effectò and thus gives a smooth curved or flat texture. First, the elements are treated with larger sandpaper, and then with smaller granulation (P180-P320-P400-P600-P1000) with constant cooling with water, see

Figure 15. The cooling process with water is necessary to prevent heating and melting of plastic parts. In addition to sandpaper, the following tools and equipment are required for this procedure:

- Compressor - constant air flow for cleaning and drying surfaces;
- Auxiliary hand apparatus for fine sanding and polishing; and
- Device for measuring dimensions before and after processing.



a) b)

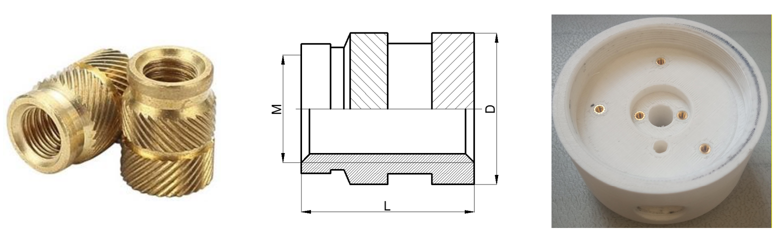
Fig. 15. Supplementary material removal: a) using sandpapers, b) using compressor

The removal procedure with sandpaper help is performed in the following steps:

1. Surfaces irregularities were treated with sandpapers P100 and P320. Additional grinding equipment was used to eliminate significant irregularities and excess materials in some inaccessible places. In addition to visual control, dimensional control was performed.
2. Then sandpapers P400 and P600 were used. Surface treatment was performed by uniform pressure in circular motions with continuous water cooling. Irregularities on curves, grooves, openings and threads have been eliminated here. The goal is to reduce the dimensions to the most accurate measurements and get a polished surface. After this operation, the elements are ready for the plastering process.

7.4 Brass inserts

In this step, brass hot melted insert nuts were used. They are perfect for installation in plastic materials. The plastic surrounding the insert becomes locally stronger during drowning because a strong connection is established between the metal insert and the plastic. Figure 16 shows the hot melt insert nut. So, with the help of inserts, a much stronger extraction and torque are provided compared to direct threading.



a) b) c)

Fig. 16. Brass hot melted inserts: a) image, b) technical drawing, c) position in central part

The characteristics of the brass insert nut with internal thread are presented in Table 2.

Table 3. Enclosure manufactured parts weights

Material	Inside Diameter M - [mm]	Outside Diameter D - [mm]	Total Lenght L - [mm]
Brass	3	4.6	4

The adhesion strength of the brass inserts was tested with the setup shown in Figure 17a). The test sample (shown in Figure 17b)) was designed and fabricated in such matter as to corespond to the printed enclosure i.e. the same thickness of the wall and infill ratio. For sample positioning and to ensure that the force is applied to the brass insert only, a specially designed aluminium enclosure was manufactured. The applied force was measured with a load cell.

At least 3 samples were tested in order to minimize eronoious results. The average load adhesion strength before failure was measured as 38.65 kg with a standard deviation of 9 kg. On Figure 18. the averaged force time diagram for all specimens is shown. Although in most specimens the brass insert was pulled out of the PLA specimen, in the one shown in Figure 17c) fracture of the PLA specimen ensued prior to the brass insert failure.

Fig. 17. Brass insert adhesion strength test: a) test setup, b) test sample, c) sample after test

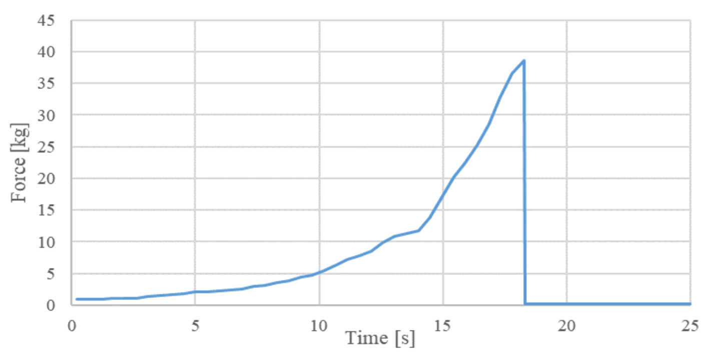
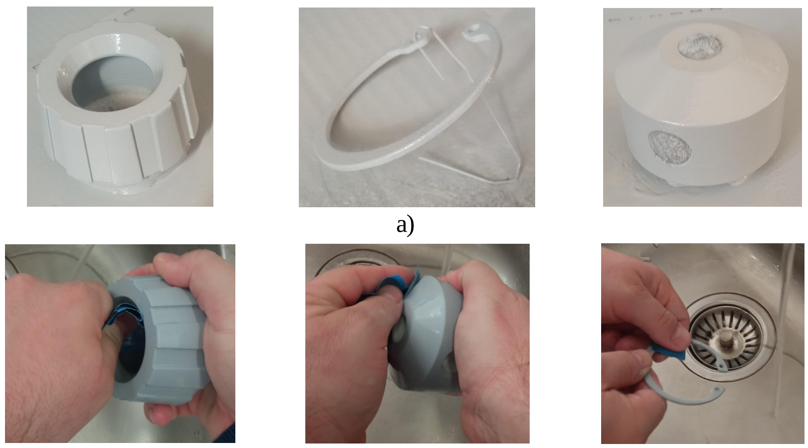


Fig. 18. Brass insert test force diagram

7.5 Model grouting

To obtain a smooth surface before painting, application of filler and additional surface treatment with P 1000 sandpaper was performed, see Figure 19. The manual polishing process significantly increases the quality of treated surfaces. This process increases the risk for employees because they can be exposed to toxic particles if not careful.

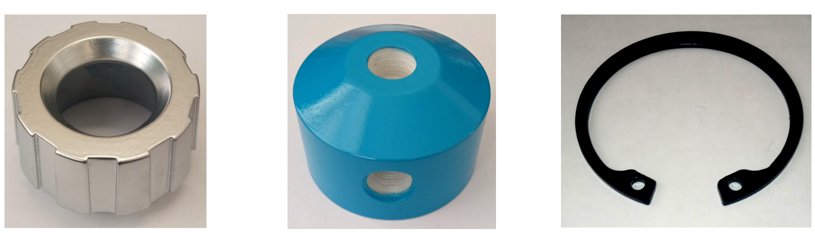


a) b)

Fig. 19. Grouting procedure: a) sprayed with primer, b) surface treatment after poliester filler

7.6 Model painting

The model's surface should be washed with water to remove pollutants, brushed with a clean cloth, and left to dry. A prepared model in this way is ready for painting. The painting process can be done with a paint gun or spray. The model should be sprayed in a position that provides a good jet outlet, and the spray nozzle should be kept at a distance of about 20-25 cm during spraying. The painting procedure should be done 2-3 times. The painted electronics enclosure elements are shown in Figure 20.



a) b) c)

Fig. 20. Images of coloured elements: a) cover, b) central part, c) Zeger ring

7.7 Electronics enclosure finalizing

The cover and Zeger ring were manufactured from PLA with the FDM procedure, while Plexiglas was used instead of glass. Made part has dimensions of Ø60x3mm. Laser engraving and cutting machine FL-350 (Slovenia) with a working surface of 300x500mm was used for cutting the plexiglass; see Figure 21.

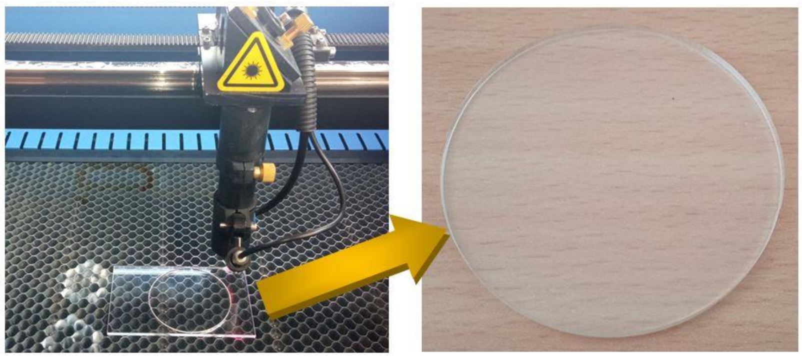
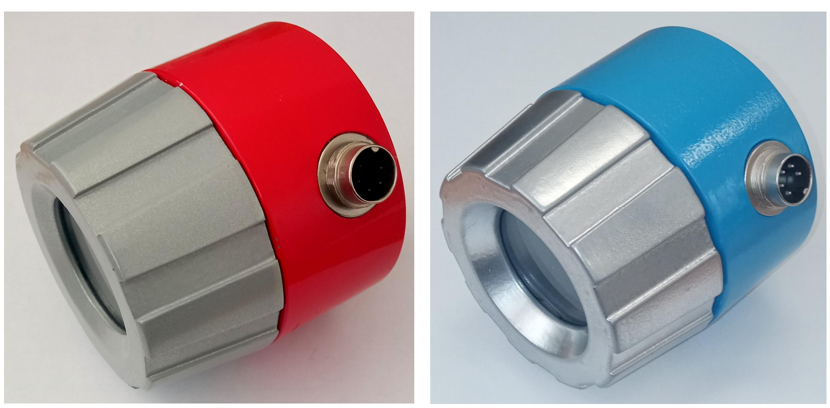


Fig. 21. Transparent plexiglass cover element - Making proces

The enclosures made with the conventional procedure and with AM are shown in Figure 22. First, all the enclosure cover elements are placed, and then the cover is connected to the central part via a screw connection.

The formed PLA enclosure represents a prototype, which, combined with different modules, enables the realization of different range of products. If the box does not meet the end-user criteria, it is placed in recyclable waste.



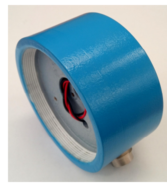
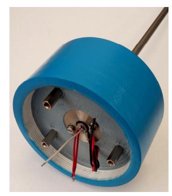
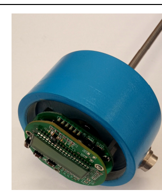
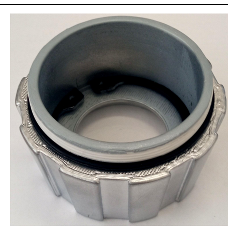
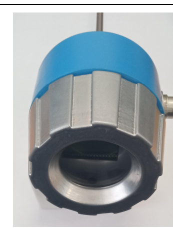
a) b)

Fig. 22. Temperature transmiter enclosure made of: a) aluminium, b) PLA

7.8 Connections between electronics enclosure and modules

The electronics enclosure implementation strategy in the assembling procedure of the temperature transmitter is given in Table 4.

Table 4. Enclosure assembling procedure

Step	Description	Image	
1.	An electrical connection is placed on the enclosure		
2.	A temperature probe (transducer with Pt-100 sensor) with cable is connected to the electronics enclosure		
3.	The electronic block is placed and fastened in the enclosure central part and then connected to the probe cable		
5.	Transmitter testing		
6.	The connection between cover and central part ï Formed electronics enclosure		

The temperature transmitter disassembling process according to the mentioned strategy takes place according to the following schedule:

1. Remove the cover of the electronics enclosure and visually check for any mechanical damage;
2. Remove the electronics assembly from the electronics enclosure. If the assembly works, it is separated into a warehouse box, and if it does not work, it is separated into a special waste box. The algorithm thus provides care for the environment;
3. Separate the temperature probe (Pt-100) and visually check for mechanical damage. If there is no damage, its correctness is checked. A correct probe goes to the warehouse, while a defective one goes to waste.
4. Finally, the electronics enclosure with an electrical connection is visually inspected for mechanical damage, and the connector is detached if damaged.

Thus, AT could be classified as a technology-focused on detailed product design through disassembly and reuse for multiple life cycles. By applying CP, the product must be reliable, durable, replaceable, repairable and re-available.

8 Electronics enclosure testing

Besides the already presented testing of the brass insert adhesion strength, in order to validate the design and investigate the behaviour of the enclosure in its exploitation environment, two different tests were performed on the realized 3D printed model.

In the first experiment, the enclosureôs capability to whitstand large temperature changes was tested. Three temperatures were cycled three times -10 °C; + 10 °C and + 50 °C. The experiment simulated the operating conditions in dry and closed spaces. Heraeus VotschVMT 08/140 air conditioning chamber (Germany) and Iskra multimeter MI 7039 (Slovenia) with temperature probe type K as a temperature indicator inside the enclosure were used, see Figure 23.

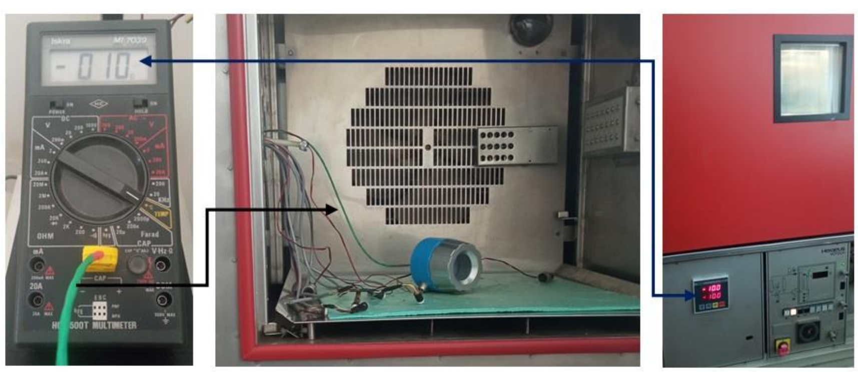


Fig. 23. Temperature influence on enclosure - Climate chamber tests

During the temperature cycling testing, more detailed observation of the temperature distribution inside the chamber was performed with a FLIR E5 thermal imaging camera (-20 °C to + 400 °C), see Figure 24. The thermal coefficient ε_r= 0.44 for air was set on the camera [83].

After the temperature cycling, visual inspection and geometrical measurements of the enclosure were done in order to check for deformation or damage and it was concluded that the enclosure resisted the temperature changes and that there were no visual damages or deformations.

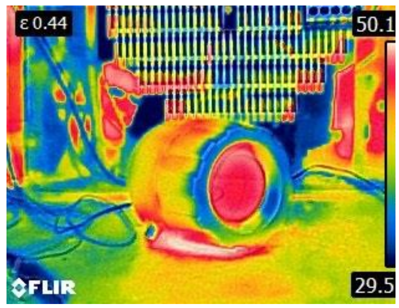


Fig. 24. Temperature observation using a thermal imaging camera (+50°C)

The enclosure should protect the temperature sensor and electronics during operation and transport so the second experiment was set to test the resistance of the structure to impact. For this purpose, a so called drop test was performed i.e. the PLA enclosure was allowed to fall freely from 1m, 2m and 6m, see Figure 25.

Fig. 25. Impact test using digital camera

In order to gain better insight of the impact, the 3D printed enclosure was droped on a reinforced concrete floor, and the expected impact site was filmed using a Photron SA6 high speed camera set to 1000 fps frame rate, see Figure 26.

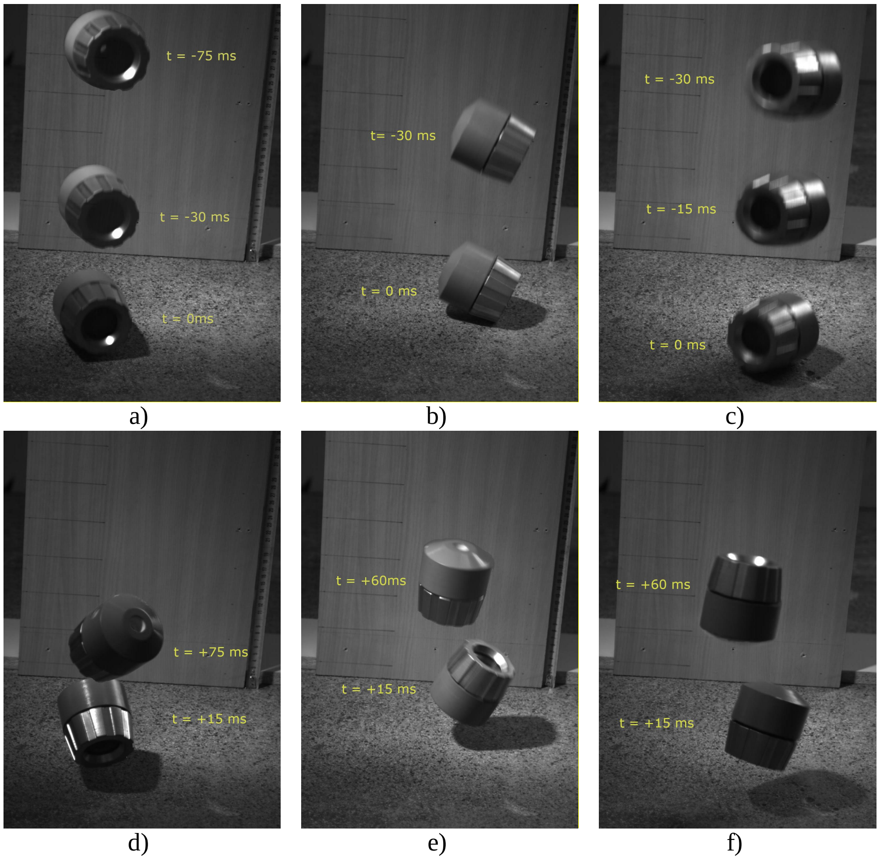
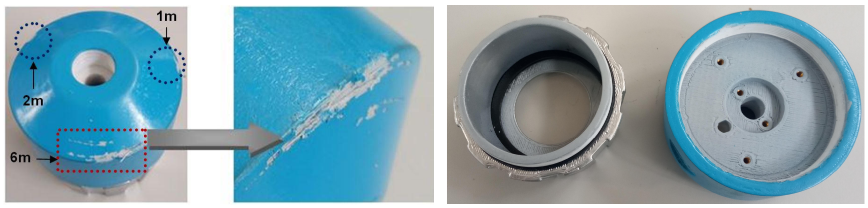


Fig. 26. Enclosure impact test: a,d) 1m; b,e) 2m; and c,f) 6m

By observation of the image files, it was established that the enclosure had a speed of approximately 3.96 m/s, 5.55 m/s and 10 m/s before impact for 1m, 2m and 6m respectively. The kinetic energy before impact was calculated as: 1.07 J, 2.1 J and 6.85 J.

Geometrical measurements and visual inspection of the enclosure after each test were performed (see Figure 27) and it was concluded that:

- no significant geometric deviations were measured;
- after the 1m and 2m tests, minor damage to the central part edge was observed;
- after the 6 m drop test, layer separation on the back of the enclosureôs central part has occurred, however not jeopardizing the structural integrity of the part;
- the enclosure cover did not show signs of any damage or failure;
- no damages were noticed on the thread which worked as intended; and
- brass inserts did not show any signs of movement or separation.



a) b)

Fig. 27. Enclosure after the impact test: a) main damages, b) separated enclosure parts

9 Discusion

The paper describes the technologies of manufacturing an electronics enclosure using FDM. The CP algorithm enabled us to see the advantages and disadvantages of the AM application in further product realization.

Table 5 compares the use of CT and AT in the manufacturing process of an electronics enclosure.

Table 5. Comparation between CT and AT in enclosure realization

Elements	CT	AT	Comment
Material	Aluminum	PLA	/
Raw material	Aluminum rod Ø80x100mm	Filament spool Ø1,75mm	▪ Metal material is cut to the desired length, and the filament is used until it is used up. Consumption is measured in meters.
Raw material weights	1.41kg	2kg	▪ Applying AT requires 165g of PLA material. So it is possible to make approximately 12 boxes from one spool.
Raw material prices	14.1ú (10 ú/kg)	40ú	▪ By applying AT, the enclosure price would be approximately 3.33ú, which is about four times cheaper than CT.
Enclosure weights	630g	137g	▪ Using an AT enclosure is 4.5 lighter. Here it must be taken into account that the infill was 20%, and with the infill increase, a higher material consumption was obtained (higher mass).

Waste	780g	43g	▪ By applying AT, waste is reduced to a minimum. The waste obtained by AT is 18 times smaller than the enclosure realization by CT.
Number of operations	▪ Cover: 9 ▪ Cent. part: 15	▪ Cover: 1+1CT (see Figure 13) ▪ Cent. part: 1+5CT (see Figure 13)	CT: ▪ Cover (on lathe machine ï 6; on milling machine ï 2) ▪ Central part (on lathe machine ï 10; on milling machine ï 5)
Manufacturing time	▪ Preparation: 1.5h ▪ Cover: 2.5h ▪ Cent. part: 3h	▪ Preparation: 0.5h ▪ Cover: 10.5h ▪ Cent. part: 10h	▪ The total enclosure realization using CT is three times shorter, although it requires more operators and additional tools and accessories. The printing time can be significantly shortened with higher quality printer.
Number of operators	3	1	/

10 Conclusion

The presented CP algorithm allows users to be designers and manufacturers of products for their own needs and the needs of end-users. Due to unrealistic expectations in realising models/prototypes using CT, more and more people resort to the application of AT in terms of speed and cost of prototype realisation.

The paper presents an algorithm including coexisting procedures for implementing the 6R strategy in sustainable enterprise development demonstrated on the example of an electronic enclosure manufacturing. The proposed algorithm introduces AM through rapid realization of the model, quality communication with customers and timely reaction on the market. Also, waste (and its reuse) is an essential resource in sustainable development, and reusing obsolete products with redesign and reproduction gives a unique look at the enterprise's business excellence.

The paper describes a strategy by which designers adapt to the end user's complex needs. By introducing customers as suppliers of used products, the transformation process receives feedback, which is the essence of CP. A new business philosophy in designing products for multiple life cycles has validated the essentials of sustainable manufacturing.

However, despite these advantages, some manufacturers see the repaired/old products as an obstruction in the research area and development activities in new product realisation. The application of AM in product design is primarily reflected in reliability, upgradeability, adaptability, compatibility, disassembly (reassembly) and recycling of individual parts/assemblies.

Today, significant work is being done to increase the model making speed and develop better quality materials/composites. The presented algorithm includes AM as a supplement to CM and as independent manufacturing in realising a redesigned/new product. By detailed analysis and application of the algorithm in practice, companies would be able to:

- produce new products with the lowest possible losses of energy, materials
- significantly reduce or annul environmentally harmful waste using new (biodegradable) materials and technologies;
- extend product's life cycle;
- shorten launch to market time.

The paper presents the complete procedure of making an electronics enclosure implementing AM in the 6R strategy. AM reduces costs in the design phase and during processing. With additive technology using the CP algorithm, it is possible to make a quick prototype, perform experiments and introduce changes on an existing product if neccessary. The electronics enclosure shows the complexity in the design, which should include mechanical and electronic components conforming to a defined geometry and dimensions.

In order to validate the proposed design and manufacturing methodology, experimental tests were performed showing that the 3D printed part can satisfy the defined technical and exploitation specifications.

Further improvements in the test example of the proposed methodology can be achieved by recycling an existing unsatisfactory component and introducing standardized test procedures including tests for:

- aging of the enclosure (3D printed parts experience considerable decrease in mechanical properties with aging [40]). The effect of sealing and painting should be further investigated.
- leaks when immerged in water or in high humidity environments (as mentioned PLA is quite hygroscopic and due to the printing parameters the realized model is porous, i.e. with small infill percentage). The effect of sealing and the influence of printing parameters on the porosity of the part should be further investigated.

Acknowledgement

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