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FORM DESIGN FOR ADDITIVE MANUFACTURING

summary of the doctoral dissertation

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ABSTRACT

Additive manufacturing (AM) technologies emerge in the late 90-ies and since then, they experienced rapid growth and development. The development of these technologies creates new opportunities for their application in different areas. This raises interest in the industry and so in academic circles. One of the most important advantages of the AM is the fabrication of models with complex geometry. This particular aspect made them very popular among the industrial designers which are being limited from the traditional technologies. AM work in opposite manner than the traditional technologies, and that is by adding material, which creates numerous advantages but also challenges that has to be overcome by the user. The interest of the industrial designers for these technologies creates need for additional research in way of familiarizing AM to them. In order to produce parts with AM they should be CAD models, which mean that the development of the technologies should be followed by the software packages. The software packages for parametric modeling are capable of withstanding the need for complex geometry creation.

In this doctoral dissertation, tool that will help industrial designers in the process of design for AM is developed. The tool is a collection of rules which should point industrial designers towards for "appropriate" design for AM. In addition, benchmark model is designed, which is intended to guide the user in the process of fabrication but also help in the evaluation and optimization of the machine. In order for them to be more specific, the rules and the benchmark model are developed for one particular process and that is fused deposition material (FDM).

Key words: Design for Additive Fabricating (DfAM), Additive manufacturing (AM), Fused Deposition Modeling (FDM), Parametric Design, Industrial Design.

Contents

1. Introduction

The rapid growth of the AM performances along with the development of the software packages for freeform modeling opens new possibilities for fabricating complex shapes as a result of the designer's creativity, bionic principles and contemporary trends. Materialization of this kind of models would not be possible without the use of AM.

Most important, with the use of AM production of unique products is economically justified (Gibson et al., 2015). This is in the spirit of the post-industrialism, where with the emerge of the new cultural and social movements, setting before the industrial designers new requirements and trends. Trends as product personalization, product customization and products designed completely by the user (Micevska and Kandikjan, 2016). This means that the main focus is on the user and designing to satisfy their needs. Web platforms that allow the user to "design" the product are now a common practice for the companies.

By implementing AM in the conceptual phase, the whole design process is shortened and with that the time for getting on the market is faster. Additionally, with the AM it is possible to create functional prototypes in the conceptual phase, which are used to check the appearance but more important the functionality to see if all the requirements are satisfied. This way the conceptual phase is shorter, but at the same time tie products are more reliable.

Flexibility that is afforded by the AM is due to their working manner, by adding material in layers. Which is opposite from the traditional technologies where the part is created by subtracting material.

> ***Additive manufacturing*** *is a general term for a group of processes that use geometrical representative to create physical object with successive adding of material (ISO/TC 261 и ASTM F42).*

The possibility to fabricating parts with complex geometry is enabled by AM but for the designing despite the designer, adequate software package for parametric design are required.

> ***Parametric design*** *is a way of designing where the parameters of the part are defined and not the appearance (Kolarevic, 2003).*

In the parametric design, the designer defines “set of principles coded as a sequence of parametrical equations which are separate parts of the model can be generated and vary through time“ (Kolarevic, 2003). This is useful for all the aspects of design, offering the possibility for simple creation of set of variation for one product (Fischer, 2008; Maher, 2011) of whole series of products.

Subject of this research is setting a new methodological approach used to analyze the AM’s characteristics that need to be taken in consideration by the designers in the design process.

1.1. Research goal

The main goal of the doctoral dissertation is **development of a tool that can help industrial designers in the design for AM**. This tool has to introduce, organize and unite detail recommendations and design rules that will help the industrial designers in the process of design and preparation for AM, considering material, geometrical and visual characteristics of the parts.

Additional goals:

- Detail analysis of the previous researches in the field of design for AM that unites methods for parametric design and methods for fabricating parts with AM, in order to define the input parameters into this research;
- Selection and evaluation of certain AM process in order to determent its possibilities and restrictions;
- Design of experimental samples, used to provide answers to the key problems that designers encounter using AM;
- Analysis and synthesis of the experimental results;
- Development of a detail list of design rules for AM;
- Classification of the design rules for AM on general and specific;
- Design of benchmark model which unites major part of the design rules for AM;
- Validation of the design rules for AM.

Hypothesis

The constant development of AM creates an opportunity for fabrication of parts with complex geometry and makes them interesting for the industrial designer. The high interest of the industrial designers for AM requires new tools that can help in the preparation of models for fabrication with AM.

To accomplish this, it is necessary to develop methods and tools that are sufficiently precise, understandable and acceptable to industrial designers to allow use of AM without their detailed knowledge of the technology and unnecessary errors and redundancies.

1.2. Research methodology

The structure and methodology of the research are presented below in the block diagram in Figure 1-1. First, we summarize the baseline observations that emerge from the analysis of the literature. The process is further divided into two phases: phase 1 - quantitative and phase 2 - qualitative research. Finally, concluding observations are formed.

In the preparatory phase of the research an overview of the current situation and achievements in the areas of interest (industrial design, parametric modeling and AM) is made. The findings obtained at this stage are the basis for defining the need and direction of further research.

Phase 1 of the research consists of quantitative methods. They include a detailed examination of the current state of technology and users - industrial designers. This includes: up-to-date advances in technology, ways of working, advantages, disadvantages and problems that users face. Problems arising from user surveys are grouped and categorized into problems caused by technology and design, so that the causes of these problems can be identified and thereby facilitated. Based on the findings, the methodology for developing a design tool for AM is defined. For modeling problems, models have been designed to check each problem in precisely controlled operating conditions. Models should be designed in such a way as to ensure that relevant data can be obtained that can be further used in policy making. The design of the test models is parametric, so that they can be easily manipulated in case of need for modifications. At this stage, the technological parameters for conducting the experimental research are laid.

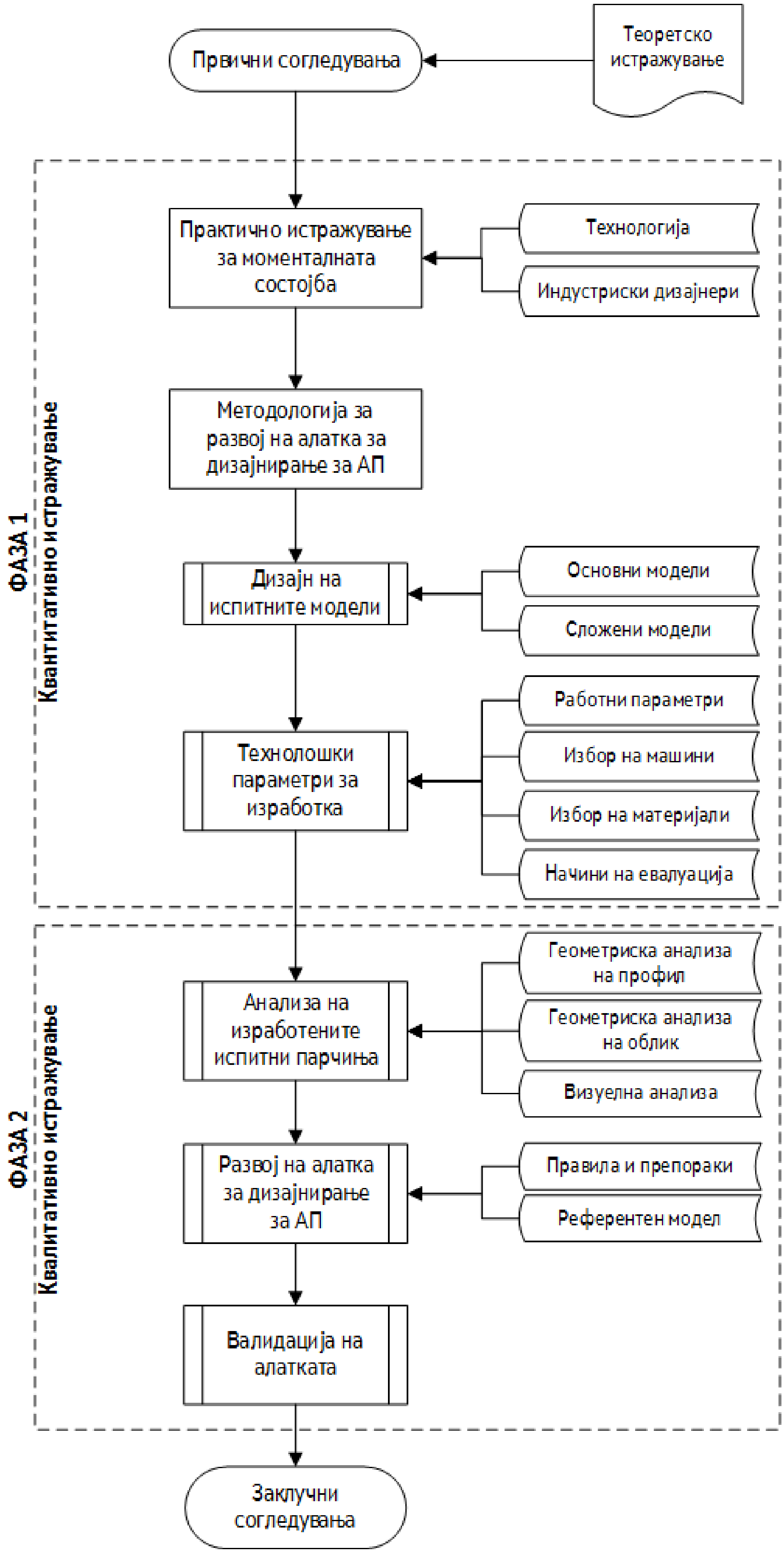


Figure 1-1. Research methodology (personal research)

The second phase represents the core of the research and consists of qualitative methods. As part of this phase, experimental research has been conducted with the development of test pieces on a specific process of AM. The pieces are analyzed in terms of profile deviation and shape deviation. The deviation of the shape is realized by comparing the CAD model and the 3D scan of the made part in 3D environment. As a next step, a visual inspection of the test parts was carried out to see if any additional deviations were observed. These include: unprocessed elements, patterns and voids in the models, compacted material, poor surface quality. The results of each of these experiments are translated into a list of recommendations and rules for designing an AM, is a specific AM process.

The concluding observations provide conclusions from the entire research as well as recommendations for future research.

1.3. Contribution of the research

The significance of the research is examined through its expected scientific but also application contribution.

The basic scientific contribution of this research is in the creation of formalized knowledge of a chosen AM process, which can be applied in effective ways by industrial designers, at the conceptual stage of model design, and further in the process of producing final products.

The tools created as a result of this research should reduce the barrier between the development and fabricating sectors and open up new opportunities in industrial design as a result of the introduction of AM in the design process.

The application of tools that assist in the design process shortens the time for product placement in the market or increases the competitiveness of the market. The application of design tools for AM, in step with the development of parametric modeling and the mass application of AM, have the potential to contribute to increased buyer participation in the process of designing 'for themselves' and 'home production' products.

2.Quantitative research methods

Input information in the first phase of the research is the research of the current achievements in the literature. In the quantitative research phase, the need for a design tool for AM for industrial designers to assist in the design process is analyzed in depth. To this end, a detailed survey of the current state of affairs has been used as the basis for designing a methodology for developing the AP design tool.

2.1. Need for design for AM tool

The general perception is that most problems can be solved or avoided through "proper" design. Proper designing means designing for the appropriate technologies, which implies sufficient knowledge of the technology. From this it is clear that there is a real need to develop a design tool for AM, in this case FDM, which will assist the industrial designers in the design process.

While conducting this research, there are still no standardized rules on many aspects related to AM and design for AM, further indicating the need for such research. The International Standardization Institute (ISO) and the Association for Testing and Materials (ASTM) are working to create standards that should lay the groundwork for further research.

Table 2-1. Comparison of the requirements of the design rules and the resulting requirements for the method to be developed (Adapted from: (Adam, 2015)

Requirements for the rules	Resulting requirements for the method
Design rules should be comprehensive.	The method must identify all design aspects for which design rules are to be worked out.
Design rules should be valid for all procedures.	The method must be applicable independently of the method and allow cross-procedural analyzes of the process-specific test results.
Design rules should be easily transferable to individual component shapes.	The method must be function-independent.
Design rules are to be developed by means of experimental investigations	The method must define specimens as well as parameters and parameters for experimental investigations.

The purpose of this doctoral dissertation is to develop a design tool for FDM. The tool is a collection of recommendations and rules for design for FDM. To do this, a list of requirements (Table 2-1) has been created to meet the rules that are generally accepted and functional. The list of requirements is the basis for defining the methodology for developing the design tool for FDM. It follows that the methodology must identify the industrial design aspects involved with the tool; it must be independently applicable and function-independent. The methodology should accurately define the look of the models used in the experimental research as well as the working conditions.

The following methodology was used to develop the design rules for FDM, design - build - evaluate - realize - validate (Table 2-2).

Table 2-2. Methodology for development of the design rules for EDM (personal research)

Step 1 – Design of the test models	According to the research so far, the problems that arise during the preparation of the parts have been defined. Based on this, a list of problems has to be solved. Accordingly, parametric models are designed to answer the problems.
Step 2 – Definition of the technological parameters	The basic working parameters used in conducting the experimental research are defined.
Step 3 – Fabrication of the test models	Working conditions are defined for the design of the models. It should be noted that there are no major deviations from the baseline values, as the goal is to test the possibilities of the process rather than optimizing the machines.
Step 4 – Evaluation of the test parts	The evaluation of the models made is based on the differences in the profile and dimensions but also on the visual aspect.
Step 5 – Development of the design rules	The results of the evaluation are used to develop design rules for FDM.
Step 6 – Validation of the design rules	The validation of the design rules is conducted through four examples.

2.2. Design of the test models

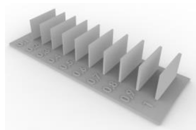
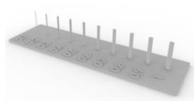
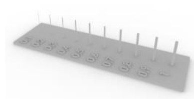
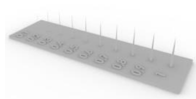
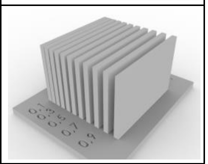
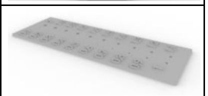
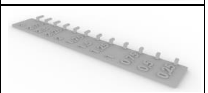
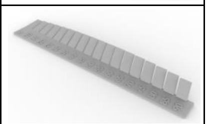
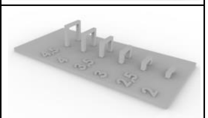
The models used in experimental research are parametrically designed. When designing, it is important that the models are designed so that the results of the analysis can be interpreted uniquely.

2.2.1. Design of the basic models

The basic models are designed to answer the problems that arise when using FDM. At this stage, 10 models have been created, shown in Table 2-3, which are used to check the baseline values. These models should provide information on: minimum wall and gap thickness, minimum hole diameter, maximum overhangs, bridges and inclined elements without supporting material that can be made on the machine to be used in the tests. The main focus in this part of the research is to define the limit values of fabrication without the use of supporting material.

The basic models are designed using the DS Solidworks software package. When designing, an attempt was made to standardize the models, placing them all on rectangular foundations with thickness of 1mm. The text indicating the dimensions of the test elements is arranged on the right, 3 mm in size and 2.5 mm in thickness / height.

Table 2-3. Design of the basic models (personal research)

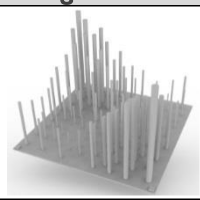
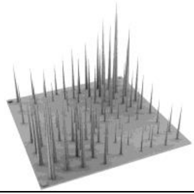
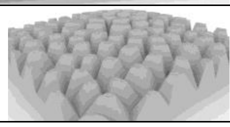
Group	Form	Evaluate	Figure
Model 1-1	Prismatic form	Minimal wall thickness	
Model 1-2	Prismatic form	Minimal stand-alone wall thickness	
Model 1-3a	Prismatic form	Minimal thickness of a stand-alone element, surface quality	
Model 1-3б	Cylindrical form	Minimal thickness of a stand-alone element, surface quality, cylindricity	
Model 1-3в	Conic form	Minimal thickness of the stand-alone element, surface quality, conicity	
Model 1-4	Prismatic form	Minimal gap between walls	
Model 1-5	Cylindrical form	Minimal diameter of the hole, deflection in the dimensions, cylindricity	
Model 1-6	Prismatic form	Length of overhangs avoiding support material, surface quality	
Model 1-7	Prismatic form	Inclination angle, surface quality	
Model 1-8	Prismatic form	Length of bridges avoiding support material, surface quality	

2.2.2. Design of the complex models

Models with complex geometry are designed to provide additional information about the limit values for the problems most FDM users face. Basic models are good for laying out basic data, but such forms are rarely used in reality, so the results have more indicative value. At this stage, 8 models for checking the boundary values of complex geometries have been created. The design and dimensioning of the models used the insights gained from the design of the basic models. Table 2-4 gives an overview of the sections and what each of them examines. These parts cannot be respected everywhere without the use of supporting material. **The main characteristic examined at this stage is the reproducibility of the texture and the scalar effect, but also the quality of the surface in complex organic forms. Repeatability is a very important feature for ensuring consistent quality, but it is also critical for all AM processes, and especially FDM.**

Complex models are designed using the Rhinoceros or Rhino software package. In Rhino with the Grasshopper plugin the pattern design is more flexible allowing for the creation of complex geometries. Rhino is a 3D modeling program that finds application in many areas. It is based on NURBS (non-uniform rational B-spline) surfaces, which allows the creation of free organic forms.

Table 2-4. Design of the complex models (personal research)

Group	Form	Evaluate	Figure
Model 2-1a	Cylindric form	Minimal diameter and height of a stand-alone element, cylindricity, repeatability, stringing, staircase effect	
Model 2-16	Conic form	Minimal diameter and height of a stand-alone element, conicity, repeatability, stringing, staircase effect	
Model 2-2	Prismatic form	Minimal wall thickness, avoiding supports	
Model2-3a	Prismatic form	Surface quality, staircase effect, repeatability	

Model 2-36	Prismatic form	Minimal wall width, surface quality, staircase effect, repeatability	
Model 2-4a	Organic form	Rounded faces, minimal wall thickness, bridging, staircase effect, surface quality	
Model 2-46	Organic form	Rounded faces, minimal wall thickness, bridging, staircase effect, surface quality	
Model 2-4в	Organic form	Rounded faces, minimal wall thickness, bridging, staircase effect, surface quality	

3.3.3. STL conversion

Fabricating parts with AM requires for .stl file as an input to the machine. During the .stl conversation the model has to be poligonized, so that the tolerance deviation has to be smaller in order to result with finer surface. Model with small tolerance deviation can result with large file which can overload the system. So, it is necessary to make compromise with the degree of the poligonization and the file size.

2.3. Technological parameters

The models are fabrications of two machines, Prusa Mk3, referred to as M1 and Crealty Ender 3, referred to as M2. The M1 has working volume of 210x210x210 mm, and the M2's working volume is 220x220x250 mm. Used material is PLA (Prusament PLA – mat1, Gembird PLA – mat2, Gembird PLA plus – mat3). In Table 2-5 overview of the parameters for the experimental research is presented.

Table 2-5. Working parameters for the experimental research (personal research)

Machine	**M1**	**M2**
Material	mat1 / mat2 / mat3	mat2 / mat3
Software package	Slic3r	Ultimaker Cura
Layer	0.1 mm /0.2 mm	
Nozzle diameter	0.4 mm	

Working temperature	210° C (215° C first layer in Prusa)
Build plate temperature	60° C (65° C first layer in Prusa)
Infill percentage	20 %
Infill pattern	Grid
Infill angle	45°
Support material	No (except in specific cases)

Operating temperature is determined by the material selected for operation. The thickness of the working layer when making the first batches is 0.1 mm. But since the design of the models has no finer details on the vertical surfaces, in subsequent workings the thickness of the working layer has changed to 0.2 mm.

The models are made over and over again in order to ensure repeatability of the results. Repeatability of results in parts made with FDM with open access is one of the major problems. It is important to keep the parameters as consistent as possible. The diameter of the blade and the thickness of the work layer are the same in both test cases. However, due to different machines and different operating modes, operating speeds vary. A different software package is also used for layer design, as the respective machines have defined profiles that can be used.

3. Qualitative research methods

In the second phase of the qualitative research, an analysis of the test pieces was conducted. Three types of analysis were conducted within the analysis: geometric profile analysis, geometric shape analysis and visual analysis. The analysis carried out is the basis for the development of the design tool for AM. The developed tool consists of rules and recommendations that give guidance to the industrial designers in the design phase, ie in the conceptual phase. In addition, a reference model has been developed that integrates most of the rules and assists industrial designers in determining the limit values of the FDM machine on which they operate. The validation of the design tool for AM is made through four real-life examples of design products.

3.1. Geometric analysis of the test parts

The geometric analysis of the test parts made includes profile deviation analysis and shape deviation analysis. The geometric analysis was carried out on the basis of the pieces made with the experimental research. The general conclusions are that elements less than 0.5 mm in dimension can be made with the selected working parameters (Chapter 2.3) and the selected model orientation (base mounted parallel to the working surface, and the tested elements at an angle of 90 ° relative to the working surface).

The comparison of the profile deviation of the test parts is made in the Datinf Measurement software package and the profile contour curve is caused by the nozzle diameter.

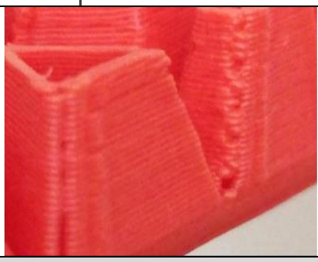
Comparison of model variance is performed between CAD models and 3D scanned models. The comparison show that in most models the deviations is within 0.1 mm, except for the stand-alone elements reaching ± 0.5 mm.

3.2. Visual appearance of the test parts

Unlike the geometric analysis, the visual impression check is much more subjective because it is influenced by the feelings, perceptions and experiences of the individual. However, the visual impression is of great importance to designers and in many cases is decisive. Therefore, this dissertation pays close attention to such verification. During the visual inspection, the type of surface (flat - uneven, matte - shiny), touch feel, non - finished elements, and elemental errors were analyzed. Visual inspection of the parts shows that the quality of the workmanship and the surface quality are quite good. Most of the elements are made with minor drawbacks as shown below. The scalar effect is present, but is significant only in certain cases. The following are the most common visual problems that occur with FDM models.

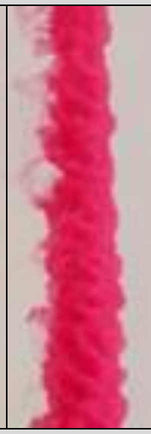
Non-fabrication of items

Non-fabrication of items may result from:
- Inadequately molded part. The problem arises when converting to STL and model polygonization designed as a surface model;
- goes beyond the capabilities of the machine.




Surface quality

A good look at the parts made implies a shape of geometry corresponding to that of the CAD model, that is, no larger deviations from the nominal geometry such as bending, twisting and bending. Another aspect of the good shape of the parts is that there is no cracking or stripping of the material. Poor surface appearance may be the result of several reasons:
- fabricating problems (no extrusion of material, high operating temperature, high operating speed);
- a weaker machine, which does not have the capacity to produce such fine details;
- avoiding use of support structures.




Staircase effect

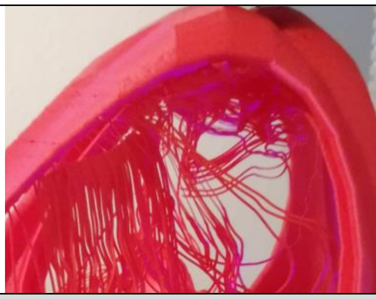
The working principle of FDM and all AM processes in general results in the appearance of scales across the entire surface of the section. Removing the scaling effect is not possible at all, you can only think about reducing it. The scaling effect is more pronounced on inclined surfaces and curved surfaces, while it is least visible on surfaces that are parallel to the work surface.

Stringing effect

The emergence of laces is a common occurrence when making parts with FDM. It is especially pronounced when it comes to small size elements. If the design is such that there are multiple elements with a small cross-section at a short distance, the effect of the stitches is even more pronounced.

Poor bridging

The principle of FDM work, of laying material on top of one another, necessitates material over overhangs or bridges.



Consequences of using support structures

The support structures help to create parts with complex geometries. However, physical removal of the supporting material may cause damage or breakage of the part. Additionally, after removal of the support structures, visible traces remain on the part itself. The traces can be in the form of damage due to the force applied to remove the support structures or due to the large contact area between the part and the support.

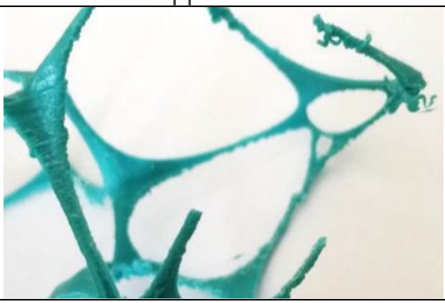


Table 3-1 presents the possibilities for making different elements of different machines using different materials.

Table 3-1. Crafting opportunities in use of different machines and materials (personal research)

Manufacturability of	M2		M1		
	mat2	mat3	mat2	mat3	mat1
Stand-alone elements					
wall thickness < 0.5 mm	red	red	red	red	red
wall thickness 0.6 – 0.8 mm	yellow	yellow	yellow	yellow	green
wall thickness < 0.8 mm	green	green	green	green	green
cylinder diameter < 0.6 mm	red	red	red	red	red
cylinder diameter 0.6 - 1.2 mm	blue	blue	yellow	yellow	yellow
cylinder diameter > 1.2 mm	yellow	yellow	green	green	green
element with square profile < 0.6 mm	red	red	red	red	red
element with square profile 0.6 - 1.2 mm	blue	blue	yellow	yellow	yellow
element with square profile > 1.2 mm	yellow	yellow	green	green	green
cone diameter < 0.6 mm	red	red	red	red	red
cone diameter 0.6 - 1.2 mm	blue	blue	blue	blue	blue
cone diameter > 1.2 mm	yellow	yellow	green	green	green
Holes					
hole diameter < 0.2 mm	red	red	red	red	red
hole diameter 0.2 - 0.6 mm	red	red	blue	blue	blue
hole diameter 0.6 - 1 mm	blue	blue	blue	blue	yellow
hole diameter > 1 mm	yellow	yellow	yellow	yellow	green
Overhangs					
overhang length < 2 mm	yellow	yellow	yellow	yellow	green
overhang length 2 - 4 mm	blue	blue	blue	blue	yellow
overhang length > 4 mm	blue	blue	blue	blue	yellow
bridge length < 4 mm	yellow	yellow	green	green	green
bridge length 4 - 8 mm	blue	blue	blue	blue	green
bridge length > 8 mm	blue	blue	blue	blue	yellow
Inclination					
inclination 0° - 15°	blue	blue	blue	blue	blue
inclination 15° - 45°	blue	blue	yellow	yellow	yellow
inclination 45° - 90°	yellow	yellow	yellow	green	green

Legend:

red	It is not fabricated at all
blue	It is fabricated, but deviating from the basic form
yellow	It is fabricated, but with unsatisfactory surface quality
green	It is properly fabricated

4. Developed recommendations and design rules for FDM

Developing general design rules for AM is a overwhelming task and can only be implemented in certain segments. The subject of this doctoral dissertation is developing recommendations and design rules for FDM. The recommendations and design rules for FDM resulting from this research are presented below.

4.1. General recommendations

General recommendations provide basic and general guidance when preparing to design and develop models with AP or EM. They were developed based on the findings of the literature analysis, the survey questionnaires and their own experiences, and later confirmed by the findings of the conducted experimental research. According to the problem they are treating the recommendations are divided into two groups:

- General recommendations for design for AM (GRD) и
- General recommendations for fabrication preparation (GRFP).

General design recommendations (GDR)	
GDR01	Before designing and fabricating the part, one needs to know the intent and the use of the part in order to choose the appropriate AM process and appropriate working parameters.
GDR02	In the design process drastic changes in the geometry should be avoided as it results with residual stress.
GDR03	In the design process thin inclined walls with small angles of inclination should be avoided as it results with a staircase effect.
GDR04	In the design process the focus should be designing a part that does not need supports.
GDR05	When designing long overhangs and bridges use of supports should be considered.
GDR06	In the design process, large flat surfaces should be avoided as they can result in part deformation due to the uneven cooling.
GDR07	When designing edges touching the build plate, fillets and chamfers should be considered, for easier removal of the part.
GDR08	When designing tall and thin stand-alone elements, occurrence of elephant’s foot has to be taken into consideration which is a common thing.

GDR09	In the design process it is recommended to use polygonal mesh in order for smoother and more accurate polygonisation of the model (.stl file).
GDR10	In the design process, overall dimensions of the build area should be taken into consideration, since scaling especially scaling down of the model is not recommended.

General recommendations for fabrication preparation (GRFP)	
GRFP01	In the fabrication preparation process it is recommended to check the model for any deviations in the geometry, as flipped or unknitted surfaces.
GRFP02	Correction of the model's geometry should be made in the software used for designing. If that is not possible there are specialized software's for editing (Meshmixer, Geomagic, etc.).
GRFP03	In the slicing process, the manufacturability of the model should be examined, to check if any of the elements is exciding the possibilities of the machine and the current set up.
GRFP04	Constant temperature in the working environment is should be must (for machines with open build space).
GRFP05	During the fabrication of thin and tall elements, working speed should be monitored and if needed to be decreased.
GRFP06	In the fabrication preparation process the orientation of the model should be carefully chosen since it affects the mechanical characteristics, surface quality and the fabrication time.
GRFP07	In the fabrication preparation of model with circular or cylindrical elements, the orientation should be carefully chosen as it can result to major profile deflection.
GRFP08	In the fabrication preparation of model, layer height should be carefully chosen since it affects the surface quality but also the fabrication time.
GRFP09	In the fabrication preparation of model with fine details positioned perpendicular to the build plate, the fabricated part is mainly affected by the layer height.
GRFP10	In the fabrication preparation of model with fine details positioned parallel to the build plate, the fabricated part is mainly affected by the nozzle diameter.
GRFP11	In the fabrication preparation process, the infill pattern and percentage should be carefully chosen as it effects on the mechanical characteristic, but also on the fabrication time and used material.
GRFP12	In the fabrication preparation process, support structures should be avoided whenever there is a possibility for it.
GRFP13	When the support structures cannot be avoided the most suitable pattern and creation manner should be chosen depending on the part's application.
GRFP14	For parts where the high surface quality is required, additional post-processing should be considered (chemical or mechanical).

4.2. Specific rules

Specific rules have been developed based on the specific experimental research that is part of the research for this doctoral dissertation. These rules define the exact minimum values that must be observed in the design process of certain elements, as well as the working conditions that must be met for successful design. The rules and recommendations are again divided into two groups according to the problem they are dealing with:

- Design rules (DR),
- Rules for fabrication preparation (RFP).

Design rules (DR)	
DR01	In the process of creating .stl file, tolerance deviation of 0.001 mm and tolerance angle of 15° should be used.
DR02	When designing integrated wall, minimal wall thickness that can be fabricated is 0.5 mm.
DR03	When designing integrated wall in the large model, the wall thickness should be ≥ 1 mm.
DR04	When designing integrated wall, in specific orientations, rounded edges should be expected.
DR05	When designing stand-alone wall, minimal wall thickness that can be fabricated is 0.5 mm.
DR06	When designing stand-alone wall with large dimensions, the wall thickness should be ≥ 1 mm.
DR07	When designing stand-alone wall, in specific orientations, rounded edges should be expected.
DR08	When designing stand-alone element with square profile, minimal thickness that can be fabricated is 0.5 mm in any orientation.
DR09	When designing stand-alone element with square profile, the thickness should be ≥ 1 mm.
DR10	When designing stand-alone element with circle profile, minimal thickness that can be fabricated is 0.5 mm in any orientation.
DR11	When designing stand-alone element with circle profile, the diameter should be ≥ 1 mm.
DR12	In cases when the cylinder is a part of assembly the minimal diameter should be ≥ 5 mm.
DR13	When designing high stand-alone elements with thickness ≤ 2 mm, major defilations in the shape can be expected.
DR14	When designing conical stand-alone elements, elements with diameter ≤ 2 mm should be avoided.

DR15	When designing gap between vertical walls, minimal thickness that can be fabricated is 0.1 mm.
DR16	When designing gap between vertical walls, the thickness that should be used is ≥ 0.2 mm.
DR17	When designing holes, minimal diameter that can be fabricated is 0.2 mm.
DR18	When designing holes, minimal diameter that should be used is ≥ 0.8 mm.
DR19	When designing holes it should be considered that the fabricated hole will have smaller diameter than one of the CAD model.
DR20	When designing holes with demanding function should be created in different manner, in the post-processing phase.
DR21	When designing overhangs, length of the overhang should be ≤ 2 mm, in order to be fabricated without supports.
DR22	When designing inclined elements, it should be considered that inclination from 45° to 135°, so that supports could be avoided.
DR23	When designing bridges maximum bridge length should be ≤ 4 mm, so that supports should be avoided.
DR24	When designing high elements with small thickness, their grouping should be avoided so that stringing does not occur.
DR25	When designing, fillets are not necessary for proper fabrication of the part.
DR26	When designing it is recommended to use fillets on the edges touching build surfaces.
DR27	When designing fillets should be used in the basis of thin and high elements in order to enhance touching surface.
DR28	When designing chamfers are not necessary for proper fabrication of the part.
DR29	When designing a model it is desirable to use the tilting of edges that are parallel to the desktop, with minimal layer thickness.
DR30	When designing text you should be careful when choosing typography. The typography should be bold.
DR31	When designing text whether horizontal or vertical, it is preferable to use protruding text instead of embedded text.
DR32	When designing a embedded text, it should be placed on a horizontal plane and made with a diameter of the smallest diameter and layer of thickness.

Rules for fabrication preparation (RFP)	
RFP01	When preparing a model, the choice of 0.2 mm layer height is appropriate for most models.

RFP02	When preparing for the construction of an integrated wall with proper model orientation and adjustment of working parameters a wall thickness of ≤ 0.5 mm can be fabricated.
RFP03	When preparing a stand-alone wall with proper model orientation and adjusting working parameters a wall thickness of ≤ 0.5 mm can be fabricated.
RFP04	When preparing a large-scale model, a large layer height and a large nozzle diameter should be chosen to save time on fabrication.
RFP05	When preparing a model for thin-walled and small elements, small layer height and low nozzle diameter should be selected to ensure that all elements are properly fabricated.
RFP06	When preparing a pattern with a pattern and fine details set at 90 ° relative to the build plate, the layer height should be chosen as a minimum, so that all elements will be fabricated appropriately.
RFP07	When preparing a pattern with a pattern and small details laid parallel to the work surface, a smaller diameter of the knob should be selected than the standard 0.4 mm, so that all the elements would be made accordingly.
RFP08	When preparing a model for text, the text surface should be placed parallel to the desktop so that the text would be fully and qualitatively produced.
RFP09	When preparing a model where surface quality is of high importance, it should be positioned perpendicular to the build plate, ensuring the best surface quality.
RFP10	When constructing models with cylindrical elements and cylindrical openings, the axis of the aperture should be positioned at an angle of 90 ° relative to the build plate, in order to avoid deviation from the profile.
RFP11	When preparing a model where it is important not to deviate from the profile, it should be positioned at an angle of 90 ° to the build plate.
RFP12	When preparing a model where the strength is of primary importance, it should be placed parallel to the work surface, with the top layer having the largest surface area.
RFP13	When preparing a model to reduce the scaling effect, care should be taken not to fall within ≤ 30 ° of the build plate.
RFP14	When preparing a model with organic surfaces and large radii of curvature, the lowest thickness of the work layer should be chosen to reduce the effect of the ladder.
RFP15	When designing a model with large overhangs and bridges, the use of support structures should not be avoided.
RFP16	When preparing to build a model with complex geometry, tree support structure should be used against the standard.
RFP17	Cases where the use of support structures may be omitted: - The part is positioned horizontally on the build plate, - No overhangs larger than 1 mm, - No bridges longer than 4 mm, - The inclined sections occupy an angle of 35 ° to 145 ° with the build plate, - The part can be divided into two parts.

RFP18	When preparing a model with support structures, the surface area between the support and the model should be as much as the layer height.
RFP19	When preparing a model for fabrication on a FDM machine designed to work with support structures they should not be avoided, as otherwise the fabricated surface will have poor quality.
RFP20	When preparing a model for fabrication on a FDM machine with two or more extruders, the use of soluble support structures should not be avoided.
RFP21	Repeatability in fabrication can be maintained if the same operating conditions and parameters are maintained.
RFP22	Infill of 100% should be used when preparing a model in which the mechanical characteristics such as strength are of great importance.
RFP23	A standard 20 % infill should be chosen when preparing a model in which the strength characteristics are irrelevant.
RFP24	When preparing a model that should have certain elasticity, it is recommended to use of gyroid pattern and 5 % infill.
RFP25	When preparing for a large-scale model and with different strength requirements, a different pattern and percentage of fulfillment in individual regions of the model should be used.

This research has developed 24 general recommendations and 57 rules for designing with EM. The recommendations and rules are based on the experimental research presented in Chapter 3. The recommendations are general and apply to all extrusion processes, while specific rules may vary in values depending on the equipment used and the operating conditions.

5. Benchmark model

For the purpose of this doctoral dissertation, the development of a design tool for AM has been designed as a reference model (hereinafter referred to as BM). The RM should be of assistance to industrial designers in the set-up phase, but also to the evaluation of the FDM machine they use.

The main goal of the research presented in this paper is the creation of a geometric benchmark model (GBM) for fine geometric details. The GBM proposed in this work will help users of open-source FDM AM systems to evaluate their machines on their own. For this purpose, a GBM aiming to test the most challenging aspects of the FDM process is created.

There are different types of BM in the literature that are intended for different AM processes. In the following, only BMs related to FDM are detailed in Table 5-1.

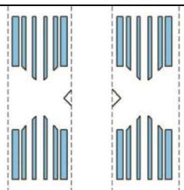
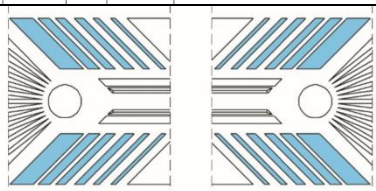
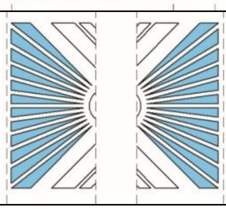
Table 5-1. Comparison of the geometric features of the BMs designed for evaluation of the FDM process (personal research)

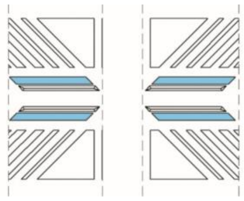
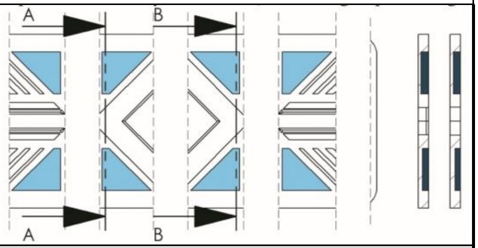
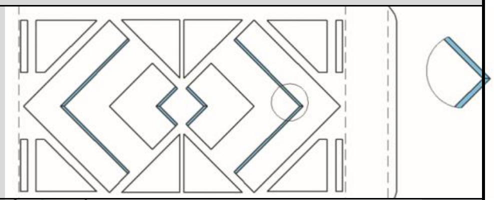
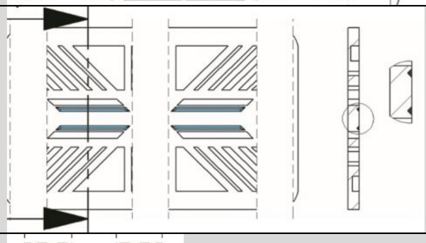
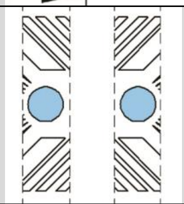
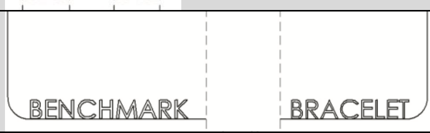
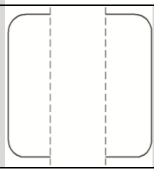
features	Johnson et al. 2011	Saqib & Urbanic 2011	Cruz Sanchez et al. 2014	Lanzotti et al. 2015	Chang et al. 2015	Decker & Yee 2015	Proposed BM
Thin vertical wall (<1 mm)	-	-	-	-	-	-	+
Vertical circular holes (<3 mm)	-	-	-	-	-	-	+
Small vertical gaps(<1 mm)	-	-	-	-	-	-	+
Fillet	-	-	-	-	-	-	+
Sharp corner	-	+	+	+	+	+	+
Inclined wall/feature	+	-	+	+	+	+	+
Bridge	-	-	-	-	-	-	+
Fine feature (< 1 mm)	-	-	+	-	-	-	+
Time to print [min]	150	NA	NA	NA	NA	NA	120
Used material [mm^3]	36,4	NA	NA	NA	NA	NA	5046
Symmetry	-	-	-	-	-	-	+
Usability of the model	-	-	-	-	-	-	+
Evaluated processes	FDM (open)	FDM	FDM (open)	FDM (open)	FDM	FDM	FDM (open)

It is evident that most of the features included in the purposed BM do not exist in other BMs (Tab. 1). That is because the presented BMs are primarily selected according to the dimensional accuracy and surface finish, despite the fact that the purpose of the proposed BM is to define the minimum dimensions of features that can be fabricated. In addition, the proposed BM should enable visual representation of the geometric deviations and limit values of the respective machine (Chang et al., 2015) without the use of complex measuring machines.

The proposed BM is designed as a blend of multiple sets of elements that examine different aspects of the design process, but set up in a way that creates a pleasing composition. The developed form of the BM clearly shows the different groups of elements that examine the limit values of the machine. In addition, the symmetrical alignment of the elements with respect to the vertical and horizontal plane also investigates the repetition of the work. A detailed overview of the features that the proposedB possesses and which are used for evaluation of the FDM machine capabilities is shown in Table 5 2.

Табела 5-1. Карактеристики на предложениот РМ (сопствено истражување)

	Feature	Dimension	Evaluate	Figure
Overall	Cylindrical open shape	φ 60 mm	Cylindricity, wrapage	
	Thin walled model	1.5 mm	Wrapage	
	Symmetry		Consistency, precision, repeatability	
Primary features group	Thin vertical features & holes	0.4 mm 0.5 mm 0.8 mm 1mm	Linear accuracy, parallelism, retraction	
	Thin inclined features & holes	0.4 mm 0.5 mm 0.8 mm 1mm	Linear accuracy, parallelism, staircase effect, retraction	
	Small vertical gaps	0.4 mm 0.5 mm 0.8 mm	Ability of the machine to build certain features	

	Inclined features (circular array features)	± 7.5° ± 15° ± 22.5° ± 30° ± 37.5° ± 45°	Ability of the machine to fabricate those features without support material, staircase effect	
	Bridges	12.7 mm 8.76 mm 6.84 mm	Ability of the machine to build without support material	
Secondary features group	Sharp edges		Heat accumulation at the angle tips	
Secondary features group	Fillet	0.3 mm	Straicase effect, precision	
Secondary features group	Chamfer	45°	Staircase effect, precision	
Secondary features group	Circular hole	φ 4 mm	Cylindricity, staircase effect	
Secondary features group	Detail (embody and emboss text)	height 3 mm depth 0,2 mm	Small details	
Secondary features group	Large “flat” surfaces		Wrapage	
	Fine feature	Thin walls, small holes, text	Ability of the machine to build certain features	

The dimensioning of the elements is done according to the analysis of the experimental studies in Chapter 3 and the developed recommendations in Chapter 4. Rules have been chosen that truly test the limits of machine capabilities. The elements are grouped into two major groups primary and secondary. The primary group of elements consists of elements that examine in detail the minimum element thicknesses, inclined elements, vents and bridges. The secondary set of elements is made up of elements that examine the possibilities and quality of making parts with rounded and inclined edges, fine details and circular holes.

5.1. Validation of the BM

In order to check and validate the BM, it is fabrication with pre-defined working parameters of different machines. A comparison of the pieces made on different machines is made to see if the primary model groups perform their role, which is a different degree of craftsmanship (Figure 5 1).

The proposed BM is designed as a geometric BM, with the primary purpose of dealing with model results and model dimensions. The results of the work are presented and discussed below. The discussion is structured so that the first recommendation is to adjust the process parameters so as to achieve better end results. If adjusting the process parameters does not result in a fully fabricated part, this indicates that the machine limit has been reached. In this case, the geometry of the model can be modified so that it can be fully fabricated.

The fabricated BM is generally of high quality, there are no deviations in the shape of the model, and the cylinder is fully respected. The surface quality is solid and the effect of the staircase is almost unnoticeable.

From the picture shown in Figure 5 1, it is noticeable that the last example M1-mat1 has the best results, almost all elements are fabricated. The fine details, such as 0.5mm thinner elements and protruding text, are not made, but it requires the use of a smaller diameter 0.4mm.

Elements at an angle of 45° are fabricated with no problem in the last example, while in the first example (M2 - mat2) it is clear that the support structures are missing.

From the discussion it is evident that the proposed BM can evaluate a particular FDM machine. Since the model is parametric, it is possible for the user to modify the model itself, thereby further optimizing the process and machine.

Figure 5-1. Comparison of details of the BM fabricated on different FDM machines with same parameters (personal research)

6.Conclusion

The development of a tool to assist industrial designers in designing for AM is the main purpose of this doctoral dissertation, which is illustrated in the exposition given in the previous chapters. The tool presented organizes and unifies rules and recommendations that will assist industrial designers in the process of preparing for prototyping and production with AM, as they relate to the material, geometric and visual properties of parts and assemblies. In addition, a reference model has been developed, which contains the key rules regarding the limit values of FDM machines and can significantly shorten the setting time and eventual optimization of the machine. The following are the ways of realizing the set additional goals

Detailed analysis of previous research in the field of industrial product design for AM

AMs offer a number of advantages over composite geometries. But whether and to what extent these opportunities are exploited depends on the industry designers and their knowledge of AM technology, as well as the design opportunities offered by current software programs. From the researches it can be concluded that the application of AM in the design process is more common in the production of finished products. Some authors are looking to improve current software programs or create new ones to change the traditional way of designing made possible by the advantages offered by APs. This approach changes the way the design is designed and the way the product is placed on the market and distributed to the consumer.

However, the most extensive research is to help designers of industrial design to shorten and speed up the design process. They propose a change in the design process itself by introducing the AM into the conceptual phase and developing a new approach called AM design, following the example of production design (DFM) and assembly design and production (DFAM).

Selection and evaluation of the characteristics of a particular process by the AM in order to define its capabilities and limitations

For a process that has been thoroughly analyzed and elaborated, FDM has been selected as the most accessible and widely distributed, especially among targeted users, industrial designers. The focus is on open access FDM machines, since they are widely used and so far no research of this type has been conducted on them. The biggest limitation and the biggest advantage of this type of machine is that the user has to adjust all the working parameters by him. This can be a problem for beginner users and can create a drawback. But with the tool (recommendations, rules, and BM) offered by this doctoral dissertation, that barrier should be easily overcome. With the introduction of the FDM working principle and the specific machine, the conclusion is that parts of quite solid quality can be made.

Design of experimental samples

Through modern parametric modeling software packages, 16 test models have been designed to address the key issues that industry designers face in applying AM. The design focuses on the uniqueness of the problems treated with each test model so that the results would be valid and generally useful.

Conduct analysis and synthesis of experimental results

Parametrically designed test models are made according to precisely defined working parameters of two machines with different materials. The obtained results are analyzed and compared on the basis of geometrical deviations of profile and shape and visual aspect. Analyzed results show that open access FDM machines do not lag behind in quality of fabrication compared to other FDM machines.

Develop a detailed list of AP design recommendations and rules

Based on the analysis carried out, a detailed list of recommendations and design rules for AM or FDM has been developed. The rules generally refer to specific rules to be followed in the design process in order to design a model that will be successfully developed using an FDM machine. However, there are also recommendations and rules that are not directly related to the design process and have an impact on the quality of the surface. These include the positioning and orientation of the part, the working parameters, such as: layer height, nozzle diameter, infill pattern and percentage and operating speeds.

Classification of general and specific design rules for AM

To make the rules more useful to the user-industrial designer, they are grouped into categories for easier navigation. In the first group are general recommendations, which are generally general rules and are recommended to be followed. The second group is consisted of specific rules regarding the design itself. This group contains rules that apply to specific elements and their permissible values, such as: minimum wall thickness, maximum discharge and bridging. In the specific rules group there is another subset of rules for making. This set does not include all the rules of fabrication, but only those that affect the quality of the piece, to the greatest extent the quality of the surface.

Benchmark model design

The reference model should help industrial designers quickly set up the machine and get started. It is designed to encompass the main elements that are problematic for FDM production, such as: grouped thin elements, bridges, angled elements. Additionally, no support structures are used in the design. The design of the reference model is intended to be a finished product that has both functional and aesthetic value.

Validation of the design recommendations and design rules

The validation process serves to check the functionality of the AP designing rules in real-world contexts or real-world examples. The two examples used in the validation process are designed by following the rules and made on an open access FDM machine. Successfully crafted pieces confirm the success of recommendations and rules.

By completing the research that is part of the doctoral dissertation, new knowledge has been created in the field of industrial design, AM and FDM. The new knowledge is:

- Advantages and challenges for industrial designers in using open access FDM machines.
- Creating a methodology for developing FDM design rules applicable to all AM processes.
- Design of test models that are the basis for experimental research.
- Detailed analysis of the profile deviations and shape of simple geometries when working with open access FDM machines.
- Visual analysis of simple and complex geometry pieces made on open access FDM machines.
- Development of design rules for FDM.
- Checking the applicability of developed FDM design rules through concrete real-life examples.
- Development of an open source FDM design machine reference model.

The biggest problems with surface quality when fabricating parts with FDM are the scaling effect and the rupture. But with the introduction of these new technologies, one has to think about changing the way of thinking and designing so that they can fully utilize their advantages. One can think in terms of the scaling effect and the rupture that will be taken as challenges and become an integral part of the design itself. This way the parts made with FDM will be unique

The use of FDM for making parts at the conceptual stage is recommended, and in some cases for making final parts. The biggest obstacle to mass use of FDM is the imprecision, ie the deviation in dimensions of FDM machines, which is ± 0.1 mm, while that of open access FDM machines is ± 0.5 mm. Experimental investigations have shown that all fabrication parts have deviations within ± 0.1 mm except for stand-alone cylindrical elements. An additional limitation for mass production is the relatively slow process. This process is recommended for use in situations where small series of personalized products or single unique products are required.

6.1 Recommendations for further research

Further research should expand the list of recommendations and assembly rules. Efforts should also be made to put these recommendations and rules on the web to make them more accessible and generally useful. In addition, they can create an interactive tool that would lead the designer to select appropriate rules through simple and intuitive steps.

Other ways (besides the tool presented) need to be found to deepen the knowledge of FDM designers and AMs in general, so that they can take full advantage of them. In this way, technology is not an obstacle but an opportunity to create something new and different. This could potentially lead to the creation of new products that have not existed as such or the application of AMs in areas that were not imaginable until now.

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[1]This list consist only the literary units that are part of the summary. In the doctoral dissertation 112 literary units are consulted and reviewed.