Exploring the Links between CAD Model and Build Strategy for Inexpensive FDM

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Abstract

Additive Manufacturing (AM) represents a maturing collection of production technologies also known as rapid prototyping, rapid manufacturing or three-dimensional (3D) printing. One of the most promising aspects of AM is the possibility to create complex geometries. Despite a growing body of knowledge concerning the technological challenges, there is a lack of methods and tools that allow designers to effectively deal with the new possibilities of AM.

Recently, several sub $5000 AM printers have come to the market. Initiatives from the open-source community contribute to this development. These inexpensive machines are based on the Fused Deposition Modeling (FDM) technology.

In order to investigate the relationship of the FDM process and the built structures, this paper presents experiments to model and build FDM-specific structures that hold unique mechanical and visual properties.

The findings show that inexpensive FDM machines are able to manufacture complex shapes and patterns in order to achieve unique mechanical and visual properties. However, for a designer to control these phenomena, solid-modeling must be combined with tool path generation. Unfortunately adequate tools and methods that integrate these two approaches are nonexistent.

1. Introduction

Additive Manufacturing (AM) represents a maturing collection of production technologies, also known as rapid prototyping, rapid manufacturing, or three-dimensional printing. Sales of Additive Manufacturing machines has been growing steadily and AM is increasingly being used for the direct production of parts . Among the most promising aspects of AM for direct part production are the possibility to create highly complex geometries, and production of one-off products.

Most of AM machines are priced above €20.000 which has kept them unobtainable for small companies and individuals. However, recently several inexpensive sub-$5000 AM machines have come to the market [1]. In the few years this inexpensive category has been available, its number of sold machines has surpassed the total sales of the expensive machines, and this growth is illustrated in Figure 1. In general, these machines produce parts using Fused Deposition Modeling (FDM), making FDM the fastest growing technology in terms of installed machines.

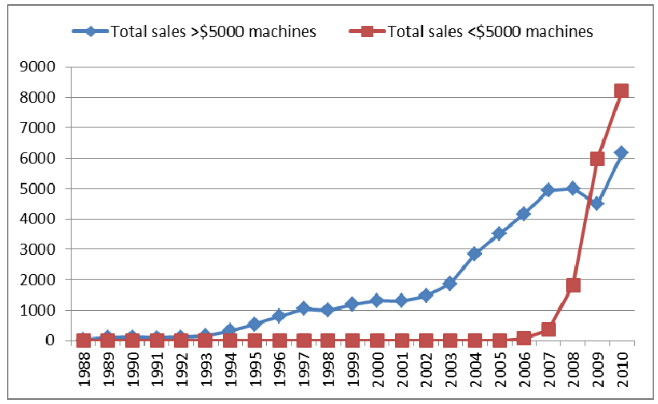

Figure 1. *Number of AM Machines Sold Worldwide (data from* [1]*)*

Similar to most AM processes, FDM builds objects by adding material layer by layer. The build material, a thermoplastic filament, is heated and extruded through a nozzle. The nozzle deposits a bead of the thermoplastic material on a flat surface, following a tool path that represents a section of the object that is being built. After completing a layer, the nozzle continues with the next section, which is positioned on top of the previous layer. Most professional FDM systems additionally deposit a support material using a second nozzle. This support material can be necessary to support overhanging structures and is removed after the completion of the part.

Mechanical properties of the built objects, such as strength and stiffness, but also surface quality and build time, are strongly influenced by FDM building parameters such as part orientation, width of extruded material, material temperature, and tool path strategy. The influence of these parameters has extensively been examined and process improvements have been made [2-8].

Also attempts to formulate design guidelines for AM and specifically for FDM have been made, mainly with the aim to reduce cost and material use [2,9]. Additionally, tools are being developed to enable the modeling and building of functionally graded materials using FDM [10,11]

Although research in FDM processes optimization and design for FDM broadly are covered in literature, there is little research in how designers can use the FDM-specific factors to manipulate properties other than strength and stiffness and what tools are necessary to achieve this. Therefore we have explored how a combination of 3D modeling and manipulation of the tool path strategy can be used to achieve a wider variety of properties. The building was done on an inexpensive FDM machine, the “RepRap Mendel”.

2. Background

2.1 Three Link Chain Model for AM

AM manufacturers claim that this fabrication means yields many technological benefits. In order to reason on the technology affordances that AM enables, we base our approach on Olson's Three Link Chain Model (3LCM), which originated from the material science domain [12]. This model considers the linear relationships between the elements performance, properties, structure, and process. The performance is the behavior of the product to be designed. This behavior is, to some extent, included in a list of requirements by the designer. To achieve the desired behavior of the product, the designer can determine specific properties for the product's parts. These properties can be based on quantifiable desired behavior, such as maximum weight or strength, or less easy to quantify behavior, such as visual properties. The structure is the physical layout that directly controls the properties of the product. These structures can be on the scale of product features, such as handles, ribs, and cooling elements, or smaller, in the form of cell structures that build up bigger elements or, even smaller, on the material level, the density or structure of the material. Finally, processing represents a specific manufacturing method.

In the original article, 3LCM links material science to material engineering. Analysis of materials follows the deductive path, by investigating the material's structure that follows from its processing and deducing the properties and eventually the performance by cause and effect logic. Complementary, material engineering follows an inductive path by determining the desired performance and properties, the material structures that comply with this performance and processes that result in the desired structures. Usually, a design process does not follow any of these two directions through the framework linearly but by a iterative process where both induction and deduction plays an important role.

In line with the Design for Additive Manufacturing framework proposed by Rosen [13], we adopt the 3LCM as a reasoning framework for design. The distinction between processing, structure and properties allows an expressive reasoning model to consider the benefits of AM, such as lightweight structures, material behavior in graded materials and the influence of the fabrication means on such phenomena. A full discussion on this scope is found in [14].

When used for DfAM instead of material science, the meaning of the model remains the same but the context changes. Traversing from performance to processing represents a design process where, starting with a desired performance, a choice is made for the manufacturing process. Following this inductive path, depending on the needed structure, a suitable AM process for manufacturing can be selected that is able to create the needed structure. The deductive path can also be taken, which will be in the form of a simulation. Starting with an AM technology, a designer can deduce what structures a specific AM process can produce. These structures influence the product's properties and thus it can be reasoned whether the performance of the product will be satisfying.

2.2 Inexpensive FDM setup

The RepRap Mendel is an open source 3D printer based on the FDM principle. As most parts are made of plastic, it can build most of its own parts. Other components, which cannot be printed, include metal rods, 4 stepper motors, and electronics. Mendel is available both as an unassembled kit and as an assembled printer, with the former available from $800. We have used a self-assembled version of Mendel with laser-cut wooden parts instead of plastic available at TechZone [15].

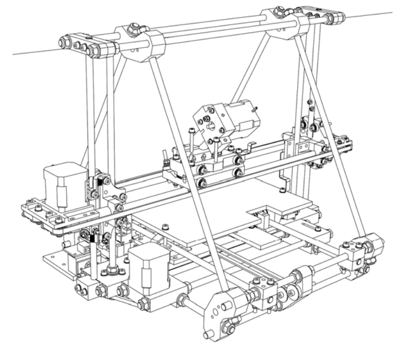

***Figure 2**. Inexpensive FDM machine "RepRap Mendel"*

The machine consists of an extruder which is actuated to move over 2 axis, X and Z, by two stepper motors. Movement over the Y axis is achieved by actuating the build platform. A fourth stepper motor is used in the extruder to push the filament through the nozzle. The nozzle is heated using a Nichrome wire and the temperature is measured by a thermocouple. The electronics consist of an Arduino-based motherboard and a controller for each stepper motor. Mendel reads g-code files as an input. A g-code file is a universal file format originally used for controlling CNC machines [16]. The file contains all the X, Y and Z coordinates the Mendel nozzle has to pass to build the layout. Also data concerning the extrusion speed, deposition speed, and nozzle temperature are included. A wide variety of thermoplastic materials can be used as filament, including Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) – these can be ordered from stock.

The Mendel has the benefit of being one of the most inexpensive FDM machines available. Furthermore, because both the hardware and the accompanied software is open source, it is relatively easy to modify the system for experiments by adjusting the process and hardware configuration. The Mendel also has some weaknesses compared to a professional FDM machine. The Mendel has only one extruder, leaving no option for a second material to be used as support. Professional FDM machines heat the building envelope to prevent warping. The Mendel lacks this function, although optionally the building bed can be heated. The machine used for this investigation is not equipped with this heating. Finally, the process variables are less optimized compared to a professional machine leading to potentially less accurate builds with less smooth surfaces. One final disadvantage is the amount of effort it takes to construct and commission the machine. During the building of the kit, we have come across several issues on both software and hardware level. For example, the firmware needed some adjustment to run properly with the software. Also the construction of the extrusion nozzle proved not to be durable and had to be redesigned and rebuild.

The software used to produce the tool paths provides options such as build speed, layer thickness, temperature, path width, and in-fill density. These functions are comparable to those present in software of professional machines

3. Explorations

We have aimed at exploring new workflows for modeling designs and producing them on an FDM machine. Two properties were selected, namely optical and mechanical. For each property we developed two structures that utilize FDM-specific possibilities. The modeling of these structures has been done using various software packages. As a material, we have used, extruded PLA at a temperature of 483K through a nozzle with a diameter of 0.5mm.

3.1 Optical properties: Optical Fiber

Behavior and Functionality

Optical fibers are used for light transport, typically for communication. The basic layout of an optical fiber consists of a transparent core surrounded by a transparent cladding. The cladding has a lower index of refraction, causing the light to be transported through the core from one end to another by total internal refraction. We have explored the possibility of printing patterns that conduct light through a pattern. The chosen paths are illustrated in Figure 3.

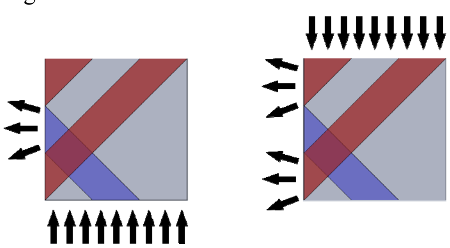

***Figure 3**. Directions of Optical Fibers.*

The PLA material that has been used is transparent but does not have a cladding and consequently does dot exhibit optical fiber properties. Therefore, the focus of this exploration was the implementation of directed fibers in a volume produced by FDM. The fibers were formed by depositing paths of transparent PLA in a 0□-90□ grid of the same material.

Modeling

For each of the two directions of the optical fibers, illustrated in Figure 3, vector images were drawn in the vector graphics editor Adobe Illustrator . The two vector images, shown in Figure 4 were converted to a g-code file containing generic tool using DeskProto software. This g-code is a file contains all the X, Y and Z coordinates the Mendel nozzle has to pass to build the drawn layout. The codes for the two layers were placed in alternating order. To make the g-code usable for Mendel, additional values need to be added such as values for temperature, speed, and the amount of extruded material for each element. This was done using a spreadsheet in Microsoft Excel. As the beads that will act as optical fibers must maintain a cylindrical shape as much as possible to maintain their optical properties, they must not be fused to other beads from other layers. To prevent this, the nozzle temperature was set 30 degrees lower for the deposition of these beads. In the future, for a more flexible workflow, we plan to use a script, for example in Matlab, to convert vector images directly to usable g-code.

Manufacturing & Result

During the manufacturing of the part some artifacts have occurred in the form of extra beads. These were caused by excessive material coming out of the nozzle during relocation of the nozzle. As expected, the lower temperature during extrusion of the optical paths compared to the infill has caused a smaller interlayer bonding of the optical fibers. This has limited the deformation of these beads, theoretically improving their optical performance. The resulting piece is shown in Figure 4. As expected no optical fiber properties were visible as the used material does not have a cladding.

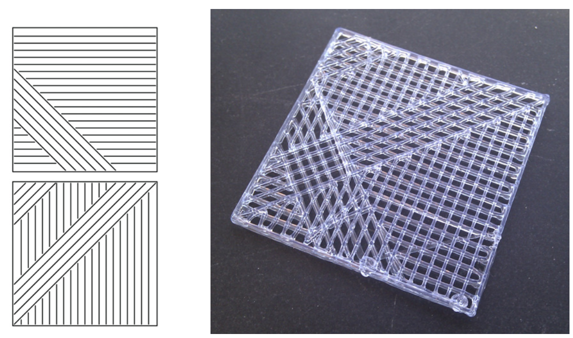

***Figure 4**. Tool paths and produced test piece.*

Implications

The fabrication of optical fibers using AM is not broadly covered in literature. In [17] a process similar to Stereolithography is described that allows the creation of directed optical fibers. Optical fibers processed with an FDM system have not yet been described. This exploration has shown that is it feasible to implement optical fibers in a volume built by FDM.

To model such structures it is required to directly draw paths within an FDM infill. For these paths the extrusion width, speed, and temperature must be controlled to maintain a spherical shape of the section cut of these fibers. In this exploration the optical fibers were running on one layer. One direction of future research is the inter-layer path of optical fibers. Also the extrusion of cladded material, which is needed to get sufficient light conduction, needs to be investigated.

Possible applications of such structures are: integrated optical communication between two components within a product and illumination of buttons, displays or other components.

3.2 Optical properties: Reflection & Refraction

Behavior and Functionality

In our experience with FDM we have observed that structures produced by FDM in transparent materials sometimes display unique reflective and refractive properties. Under some lighting angles, some areas of FDM-produced objects reflect significantly more light than other areas. This phenomenon seems to occur on areas where a wall is built up by layers of a single extruded path. When a second path is fused to the path on the same layer, this effect disappears. In order to reproduce this phenomenon a test piece was designed that consists of a checkered pattern, illustrated in Figure 5. On the thinner areas the two paths -the front and the rear in Figure 5- fuse while on the thicker parts two paths maintain a distance of several tenth of a millimeter.

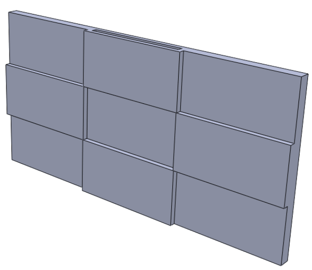

***Figure 5**. Layout of test piece with alternating thickness.*

Modeling

Before making the tool paths, the needed distance of the paths required for full fusion versus non-fusion were empirically determined. Because of the simplicity of the geometry, the coordinates for the tool paths were edited directly in MS Excel. The paths that needed to be fused were set to a distance of 0.6mm, paths that had to remain single beads were set to a distance of 0.8mm. The resulting layout of tool paths is illustrated in Figure 6.

Manufacturing & Result

The test piece that we produced indeed exhibited the desired reflective properties. Under some lighting angles, the reflectance of the single-path areas is significantly more than the areas where two paths are fused. This difference in reflection is illustrated in Figure 6.

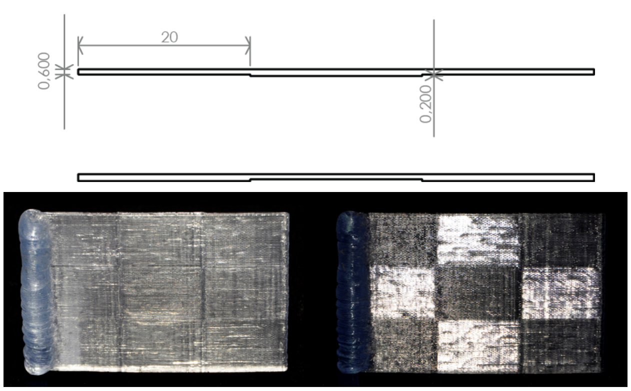

***Figure 6**.Tool paths (top) and produced part (bottom).*

Implications

Designing parts for AM that have desired visual properties is discussed for the Objet MultiJet system in [18] but completely absent for FDM. The FDM process can build structures that have unique reflective and refractive properties.

To obtain these properties, precise control over the fusion of paths within a layer is imperative. The build parameters *layer thickness* and *deposition speed* determine the amount of reflectance. This is probably because these parameters strongly influence the surface roughness. Research is needed to model the light reflection and refraction that describes this behavior.

3.3 Mechanical properties: Compliance

Behavior and Functionality

In general, FDM is used to construct stiff structures. We explored an internal structure that results in a flexible (compliant) object. A truss has been designed consisting of parallel and perpendicular elements, similar to the standard infill geometry of the RepRap software. A simplified model of this structure is shown in Figure 7. This specific construction deforms in a symmetrical manner when a force is applied from the top.

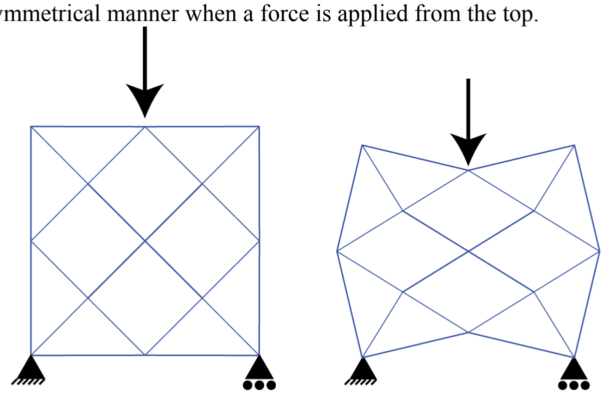

***Figure 7**. Model of flexible internal structure before and after deformation.*

Modeling

Because the layout of the internal structure has a 45-45 grid, it was possible to use the standard infill function of the RepRap software to model a test piece for this property. In order to create a flexible internal structure, the temperature for the extrusion of the internal structure was set to 30 degrees lower than the outer shell. The lower temperature diminishes the bonding between layers and thereby increases the interlayer mobility. The infill grid was set to a path distance of 2 mm.

Manufacturing & Result

The building of this part had gone as expected. However, directly after production the test piece was not flexible. It required a relatively large force of 400N to break the weak interlayer connections of the internal structure, after which the piece obtained the expected properties of deformation. A test piece under deformation is shown in Figure 8. As can be seen on the bottom of the piece, the deformation is symmetrical, similar to the simplified model in Figure 7. Furthermore, deformation is fully elastic; when the force is released, the structure returns to its original shape.

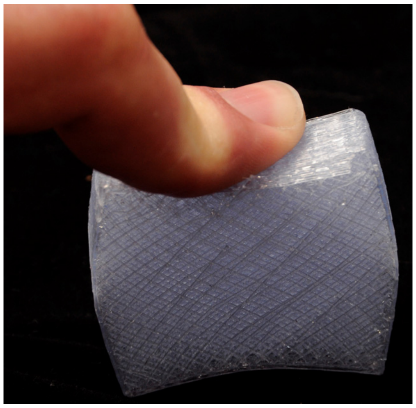

***Figure 8**. Produced compliant test piece.*

Implications

Using standard infill patterns it is possible to create flexible, compliant objects with designed deformation. The temperature parameter must be modified in order to achieve this. In this case all was done using the RepRap software without any manual modification of the tool paths.

The described structure has elements in the range of 0.1mm to 10mm and thereby is defined as a mesostructure. Mesostructures have been applied for the creation of compliant structures in literature. The applications range from airfoils to shoe soles. An overview of literature that approaches compliance with mesostructures is provided in [14].

3.3 Mechanical properties: Button

Behavior and Functionality

In an attempt to explore the elastic deformation of single paths of FDM material, we have designed, modeled, and manufactured a clicking button. Figure 9 illustrates the working principle of the designed clicking button in a section cut.

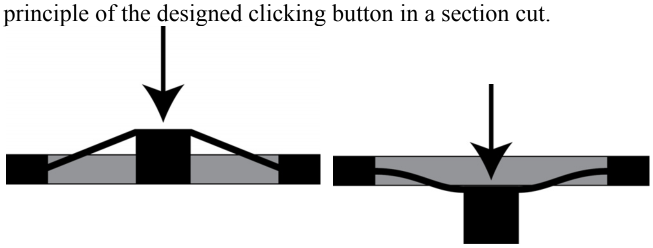

***Figure 9**.Secion cut of button clicking behavior.*

Modeling

The coordinates for the tool paths were edited in MS Excel with a direct output of readable g-code. The extrusion speed for the paths that cross layers was set to 0.6% of the nominal speed. This causes the bead to be pulled by the nozzle, preventing it to drop down, as support structure is lacking.

Manufacturing & Result

During the manufacturing the process parameter speed has proven to be the most important. Not only does a fast deposition cause less accurate paths on such a small scale, above a certain speed, the extruder cannot move over the Z axis sufficiently fast. This is a problem for the beads for which the extruder moves over all 3 axis at once, in this case the beads that connect the center with the outside part of the button.

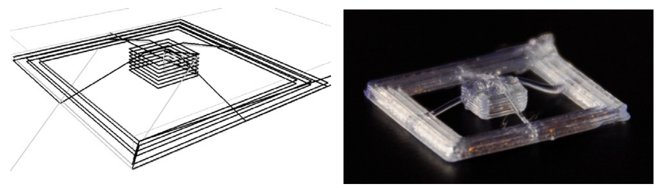

***Figure 10**. Tool paths and produced button.*

Implications

This exploration shows that a single extruded bead can be used for its mechanical functionality, in this case elasticity. Also, we have shown that extruded beads can be drawn between layers, up to a limit without support. A similar concept entitled Curved Fused Layer Deposition modeling was presented by Chakraborty et al., for the creation of stronger and stiffer shell structures [8]. Inter-layer g-code is currently not possible to generate using off-the-shelf software.

4. Discussion

4.1 Printing Strategy

In the past 40 years the developers of 2D-digital printing devices have learned to sample and map scanned or digital generated images as a grid of picture elements (pixels, dots). In the early black&white printers each pixel was assigned to a tonal value (black, white) which represented a binary code (zeros, ones). The binary digits (bits) for each pixel were stored, for instance in the memory of the computer, in the so called bitonal bitmaps.

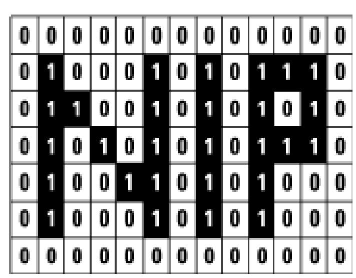

***Figure 11**. Bitonal image*

These bitmaps were interpreted by the printer controller to produce the print on paper. In a dot matrix (impact) printer the maximum resolution is 360 dots per inch. By introducing the laser printer the resolution could be enhanced to 2400 dots per inch. To realize the most optimal bitonal image all kinds of image rendering techniques were developed. Digital halftoning has substantially improved the quality of the rendered images and gives on paper the illusion of continuous tone output with a binary printing device. Used methods are 'ordered dither', 'clustered dot screens 'and 'error diffusion'. The last step was enhancing the number of bits used to define each pixel (grayscale), typical from 2 bits (4 grey values) to 8 bits (256 grey values).

But the printing device is not ideal. In practice the final image quality is also a result of the selected print strategy for optimal performance. The strategy can be related to artifacts like banding, noise, and sharpness of the printed images.

Additive manufacturing is still in its infancy. The three dimensional object is created by laying down successive layers of material. Comparable to the first dot matrix printers a bitonal image is made for each layer on base of the CAD file (3 dimensional bitmap). The relevant 3D-image quality improvements and print strategies must be developed. On top of that the physical and mechanical parameters of the material can be changed (porosity, lattices, resonant frequency, ..).

4.2 Workflow

To discuss the current information flow of FDM production and discuss its implications on the functionality of the built objects, we place this flow in the scope of the 3LCM. For clarity the flow is simplified to a linear one-directional flow from design requirements to a physical model, the inductive path. Obviously, in reality the design process is nonlinear and iterative.

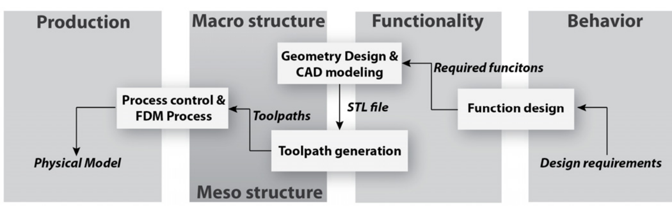

Figure 12. *Current flow for FDM manufacturing of a Design*

During the "function design" process the designer determines which functionality the object must have to obtain the needed behavior. This is followed by the actual embodiment of the functionality by designing the geometry and modeling it in Computer Aided Design (CAD) software. The "CAD modeling" outputs an STL file which holds all the geometric data in the macro scale. The STL file is read by software which slices the geometry and implements the building strategy, being the tool paths for each layer and other values, such as temperatures and speeds. Since these values are process specific, the software is usually provided by the AM machine manufacturer or is integrated in the AM machine software. At this point some parameters can be altered by the user, such as fill density, build speeds, and extrusion width. These will influence the tool path generation process but not directly the tool paths themselves. In the final step, the FDM machine reads the tool path file and produces the object.

The current flow has some limitations. As illustrated in Figure 12, the CAD modeling determines the macro structure of the object and the tool path generation determines the micro structure. Both directly influence the functionality of the object while the designer can only manipulate the CAD model directly. The tool paths can only be manipulated indirectly by changing variables and must be done after fully determining the CAD model.

In the experiments described in this paper we went beyond this limitation. For the modeling of the parts with the unique properties, the drawing of tool paths has been essential. Creating the structures with current tool path generation software would have been impossible.

From the experience from the experiments we propose a new workflow for FDM production, this flow is illustrated in Figure 13. The essential difference is that the "Geometry design", "CAD modeling" and "Tool path generation" are integrated into one process. This allows the designer to design the geometry on feature scale (macro) and on meso scale.

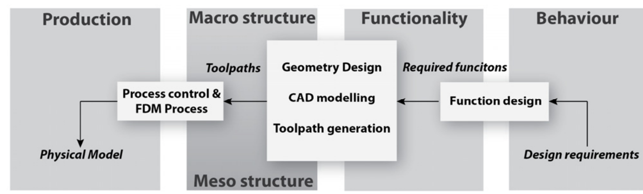

Figure 13. *Proposed flow for FDM*

We illustrate the proposed flow with an example, the compliant button, located on a solid object. The designer initially sets required functions regarding the object and the button. During the CAD modeling, the designer can model the shape of the object, similar to current CAD modeling. Additionally, in a specific area of the object, the designer models the small structure of the button by directly modeling the tool paths, as this is the only method to acquire the needed functionality. If the functionality of the object allows, tool paths of areas other than the button can be generated automatically, similar to how this is done with current software. The tool paths of these two areas must be integrated into one file that is read by the FDM machine.

5. Conclusions

Additive Manufacturing offers an unsurpassed freedom in 3D shapes. Despite a growing body of knowledge concerning the technological challenges, there is a lack of methods and tools to allow designers to deal with the new possibilities of AM. In order to investigate the relationship of the FDM process and the built structures, this paper presented a number of explorations to model and build FDM-specific structures. In order to reason on the possible performance of resulting test pieces, we adopted the three-link chain model that relates the production process to structure (micro and meso), properties, and performance. In the case of FDM, the process dictates the possibility to 'plot' contours to achieve different spatial structures.

In the case of FDM, there are many new and unique in designing structures which influence the performance. For example, the internal structures play an essential role in achieving different reflective and refractive visual properties. This can be used to bend light or to influence the appearance of a product. Similarly, the button example shows that unique behavior can be printed by abandoning the regular, layer-by-layer technique. Finally, by adapting the internal structure to allow for movement, unique compliant structures can be manufactured.

We propose a novel workflow that encompasses tool path creation – also known as print strategies – during modeling, not as a post-processing step. The development of a hybrid CAD-g-code tool is necessary to achieve this. Although the examples in this paper reveal opportunities, a good working mechanism has not yet been conceptualized. Further research will increasingly look at these points.

This investigation was executed on a self-made FDM machine, known as the RepRap Mendel. This provided us an open platform to adjust the tool path and other parameters. The material used was Polylactic acid, a biodegradable material commonly used by the FabLab community. We can conclude that low-cost FDM printers are a proper research platform to investigate the process-structure-property relationship for FDM.

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Authors Biography

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