Development of moulds for thermoforming using FFF additive manufacturing and axiomatic design

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Abstract. Additive manufacturing processes are mainly used for prototype production. However, an innovative approach consists of producing moulds or tools, which can be used for other traditional manufacturing processes. The main problem with these plastic moulds is that they cannot achieve the traditional metallic moulds properties and quality. By using an axiomatic design, the study analyses different approaches available on the market and other unconventional alternatives, thus making it possible to meet the functional requirements. The obtained methodology presents advantages in production cost and time compared to traditional processes, allowing quick production with a high degree of flexibility in the design of the mould. Thus, the printed moulds obtained were tested, and the preliminary results for different process conditions were presented.

1. Introduction
The design and production of moulds, tools and accessories for classical technologies for plastics processing, using additive manufacturing, attracts the attention of both research communities and independent users. The realization of such moulds for thermoforming is a challenging technical problem due to the multitude of processes and materials that can be used. Another limitation is the combination of geometric and process constraints specific to the thermoforming and Fused Filament Fabrication process (FFF).

For this application, axiomatic design (AD) contributes to obtaining a constructive solution (in terms of design and technological process), by eliminating unacceptable solutions and by offering a good direction and systematization of the end-use of the product production.

Subsequently, the axiomatic design method, developed by Professor Suh Nam Pyo [1], has been a research topic for many researchers worldwide. For instance, Nguyen et al. [2] develop a simple and powerful tool that delivers precise optimal results without using complicated algorithms and software solutions for on-site engineers in medium or small scale production. The researchers conducted an experimental investigation based on AD in conjunction with the Taguchi method to develop a thermoforming apparatus to obtain products with uniform thicknesses. Ferreira [3] proposed a fully integrated framework in order to support tools design for injection moulding. The conceptual solutions obtained through axiomatic design guidelines are detailed and optimized to maximize customer satisfaction. Another group of researchers from Korea [4] evaluated and analyzed existing
manufacturing techniques and developed a new process by adapting the axiomatic design to designing and developing a thermoformed multi-layered plastic product.

Inspired by the positive results of the previous researches and motivated by the fact that none of those works integrates an additive technology in mould production, the current paper aims to satisfy all the functional requirements by transposing them into process parameters (from the idea up to a final product).

2. Axiomatic design methodology

According to Professor Suh Nam Pyo [5], in order to design or to obtain a concept, four domains must be taken into consideration: the customer domain (Customer Needs- CNs), the functional domain (Functional Requirements- FRs), the physical domain (Design Parameters- DPs) and the process domain (Process Variables- PVs). Besides those, there are also Constraints (Cs), which interface with the domains and are strict requirements that must be avoided or taken into consideration. Also, the paper aims to meet Suh's design axioms [1] in order to minimize the information content (axiom two: information Axiom) and to maintain the independence of FRs through a suitable selection of DPs (axiom one: independence axiom).

For a proper application of the principles of axiomatic design, the processes involved must be fully understood as well as technological advances must be taken into account. Thermoforming is a generic term for a group of processes with identifiable processing steps [6]. The equipment is fed, the sheet is mechanically clamped and heated without any type of manipulation. After reaching the desired temperature, the heating source is closed or eliminated from the working area and the forming process can start. At this point, the sheet can be brought in contact with the mould, with or without pre-shaping. After a proper cooling of the sheet, the excess material is trimmed. On the other hand, like all additive manufacturing processes, FFF process starts from the idea of a 3D designed part and with the help of CAD software and a series of design rules, the part is generated. It is essential at this step to correctly identify the goals that the 3D printed part needs to achieve. The 3D shaped (.stl: Stereolithography file format) is sliced into layers with a CAM software. The obtained .gcode file provides information for the printer (where to move the nozzle and the build plate and also about printing parameters, such as temperatures, speeds, retractions, etc.). As the nozzle is precisely moved, at certain points, over the build plate/heated bed, it deposits a thin strip of extruded plastic. The deposited material solidifies quickly into the 3D printer chamber and come in contact with the build plate and/or with the previous layer. The process repeated until the whole piece is created. The components of the 3D printed part and the design rules will later be transformed into FRs and DPs.

2.1. Structure determination of the domains

For this application, the early imposed constraints and customers' needs can be seen in figure 1. They can be defined as:

- Cs$_1$: The mould maximal gauge dimensions of 195x195x61 mm;
- Cs$_2$: Use Fused Filament Fabrication technology to produces the mould;
- Cs$_3$: Min. 0.8 mm foil thickness in order to ensure mechanical resistance of the foil to prevent the leaking of the pouring material;
- CN$_1$: Adequate mould design (for both thermoforming and FFF technology);
- CN$_2$: Mould production through FFF additive manufacturing process;
- CN$_3$: Increase mould quality by post-processing;
- CN$_4$: Preparing the foil for casting;
- CN$_5$: Safety in production of the end-product.

The next step in the AD approach encompasses the translation of the previously identified CNs and Cs into appropriate first level FRs (figure 1), which are a minimum set of functional requirements that states in the functional domain.
The customers’ requirements were focused on mould design, production in a safe manner, and improved mould characteristics (aesthetic and functional). Thus, the following functional requirements presented in table 1, were established. Consequently, at the same step in the physical domain, the first DPs at the lowest level were described and can be seen in table 1 and figure 1. PVs will be further identified and explained.

Table 1. First level FRs and DPs.

| Functional Domain: FRs | Physical Domain: DPs |
|------------------------|----------------------|
| FR1: Create the mould design | DP1: Design rules |
| FR2: 3D print the mould | DP2: 3D printing equipment and material |
| FR3: Apply post-processing | DP3: Additional equipment |
| FR4: Obtain the thermoformed sheet | DP4: Equipment and material for thermoforming |
| FR5: Protect human operator | DP5: Safety measures |

From the previously stated FRs and DPs, the design equation can be written and as can be seen in equation (1). An uncoupled mapping for the first level AD elements was obtained. At this point each FR can be fulfilled independently by a correspondent DP.

\[
\begin{bmatrix}
\text{FR}_1 \\
\text{FR}_2 \\
\text{FR}_3 \\
\text{FR}_4 \\
\text{FR}_5 \\
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 & 0 & 0 \\
0 & X & 0 & 0 & 0 \\
0 & 0 & X & 0 & 0 \\
0 & 0 & 0 & X & 0 \\
0 & 0 & 0 & 0 & X \\
\end{bmatrix}
\begin{bmatrix}
\text{DP}_1 \\
\text{DP}_2 \\
\text{DP}_3 \\
\text{DP}_4 \\
\text{DP}_5 \\
\end{bmatrix}
\tag{1}
\]

From this working principle, the identified lower-level structures were splintered into second and third level FRs and DPs. The mapping, zigzagging, and decomposition processes presented in figure 2 continues until a solution can be implemented.

To obtain the detailed FRs and DPs, presented in table 2, the 3D printing equipment, the thermoforming machine, the printing and thermoforming parameters were decomposed into functional requirements and physical components.
| Functional Domain | Physical Domain |
|-------------------|----------------|
| **CN 1: Adequate mould design** | **DP 1: Design rules** |
| FR1: Create the mould design | **DP 1.1: Design rules for FFF** |
| FR1.1: Provides design requirements for FFF part | **DP 1.1.1: Air extraction holes** |
| FR1.1.1: Ensure the air extraction through a vacuum system | **DP 1.1.2: Vacuum channels** |
| FR1.1.2: Improve air extraction | **DP 1.1.3: Min. 10 top layers** |
| FR1.1.3: Increase the thermal resistance of the upper surface | | |
| FR1.1.4: Optimize the dimensions and the details of the mould | **DP 1.1.4: CAD software** |
| FR1.1.5: Eliminate undercuts | **DP 1.1.5: Solid walls without bridges** |
| **FR1.2: Provides design requirements for thermoforming mould** | **DP 1.2: Design rules for thermoforming** |
| FR1.2.1: Eliminate sharp 3D corners | **DP 1.2.1: Chamfer** |
| FR1.2.2: Eliminate sharp edges/2D corners | **DP 1.2.2: Radius** |
| FR1.2.3: Avoid 90° angles to the base of the part walls | **DP 1.2.3: Draft angles** |
| FR1.2.4: Compensate thermal expansion of the material | **DP 1.2.4: Negative scaling** |
| FR1.2.5: Compensate material shrinkage | **DP 1.2.5: Positive scaling** |
| **FR1.2.6: Ensure mould cooling during cycles** | **DP 1.2.6: Cooling channels** |
| **CN 2: Mould production through FFF additive manufacturing process** | **DP 2: 3D printing equipment, software and material** |
| FR2: 3D print the mould | **DP 2.1: BCN SigmaX R19 Desktop 3D Printer** |
| FR2.1: Use adequate 3D printer | **DP 2.1.1: Build plate XY dim.: 200 x200 mm** |
| FR2.1.1: Consider build plate dimension | **DP 2.1.2: 2.85 mm filament diameter** |
| FR2.1.2: Ensure a corresponding material supply | **DP 2.1.3: Material with heat resistance >70°C** |
| FR2.1.3: Select a material with good thermal properties | **DP 2.1.4: Thermal conductive material** |
| FR2.1.4: Ensure a minimal printing temp. of 240 ºC | **DP 2.1.5: Heat block** |
| FR2.1.5: Ensure a minimal build plate temp. of 75 ºC | **DP 2.1.6: Heated glass build plate** |
| FR2.1.6: Ensure a constant flow of material | **DP 2.1.7: Dual Drive Gear, Bowden Tube Extrusion System** |
| **FR2.2: Appropriate selection of process parameters** | **DP 2.2: Printing parameters and software** |
| FR2.2.1: Use adequate slicing software | **DP 2.2.1: BCN3D Cura** |
| FR2.2.2: Ensure an optimal ratio for printing speed and print quality | **DP 2.2.2: Nozzle diameter** |
| FR2.2.3: Avoid or minimize surface imperfection | **DP 2.2.3: Printing speed < 50 mm/s** |
| FR2.2.4: Provide a solid internal structure of the mould | **DP 2.2.4: Infill structure** |
| FR2.2.5: Ensure a good adhesion between layers | **DP 2.2.5: Printing temperature** |
| **CN 3: Increase mould quality by post-processing** | **DP 3: Additional equipment** |
| FR3: Apply post-processing | **DP 3.1: Convection oven for thermal treatment** |
| FR3.1: Increase plastic material thermal properties | **DP 3.2: Sandpaper** |
| FR3.2: Increase mould top surface quality | |
CN 4: Preparing the foil for casting

FR 4: Obtained the thermoformed sheet

FR 4.1: Use affordable adequate thermoforming equipment
  FR 4.1.1: Choose a proper type of thermoforming process
  FR 4.1.2: Consider equipment working dimensions
  FR 4.1.3: Ensure transport and easy manipulation
  FR 4.1.4: Fixes the foil throughout the cycle
  FR 4.1.5: Provide air extraction
  FR 4.1.6: Heat the foil until it gets soften
  FR 4.1.7: Brought into contact the foil with the mould
  FR 4.1.8: Provide air extraction over the entire work table
  FR 4.1.9: Remove the thermoformed foil
  FR 4.1.10: Trim the thermoformed foil

FR 4.2: Appropriate selection of process parameters
  FR 4.2.1: Heat the foil until it softens
  FR 4.2.2: Prepare the heaters between cycles
  FR 4.2.3: Varies the heating temperature

DP 4: Equipment and material for thermoforming
  DP 4.1: Desktop Vacuum Forming Machine
    DP 4.1.1: Formech 450DT- One Step vacuum desktop forming machine
    DP 4.1.2: Min. forming aperture: 200 x 200 mm
    DP 4.1.3: Trolley
    DP 4.1.4: Clamping frame
    DP 4.1.5: Vacuum pump
    DP 4.1.6: 4x Quartz infrared heating elements
  DP 4.1.7: Sliding mechanism
  DP 4.1.8: Wire mesh
  DP 4.1.9: Pump exhaust
  DP 4.1.10: Cutters for manual trimming
  DP 4.2: Thermoforming parameters
    DP 4.2.1: Heating time > 40 sec
    DP 4.2.2: Heating percentage between cycles > 25%
    DP 4.2.3: Independent heating percentage for each zone

CN 5: Safety in the production of the end product

FR 5: Protect human operator
  FR 5.1: Ensure a safety environment in the working space
    FR 5.1.1: Filter hazardous fumes and particles
    FR 5.1.2: Reduce noise during 3D printing
    FR 5.1.3: Clean air after 3D printing and thermoforming
  FR 5.2: Ensure fire prevention
    FR 5.2.1: Eliminate the contact with the hot surfaces
    FR 5.2.2: Use smoke and fire detection system
  FR 5.3: Supervision over the manufacturing process

DP 5: Safety measures
  DP 5.1: Particle (PM) retainer and cleaning
    DP 5.1.1: HEPA filter
    DP 5.1.2: Enclosure
    DP 5.1.3: Venting system
  DP 5.2: Fire protection features
    DP 5.2.1: Metallic case for heating equipment
    DP 5.2.2: Smoke and fire sensors
  DP 5.3: Monitoring system

From table 2, the basic design matrix for all level FRs and DPs, presented in figure 3 are yielding uncoupled design, except from the design equation for FR 1.2.s and FR 2.1.s and their correspondent DPs.
Figure 3. Fundamental design matrix for all level FRs and DPs.

From equation (2), it can be concluded that the number of DPs is larger than the number of FRs and based on Theorem 3 [7], the design is called uncoupled redundant design.

\[
\begin{pmatrix}
\text{FR1.1} \\
\text{FR1.2} \\
\text{FR1.3} \\
\text{FR1.4} \\
\text{FR1.5} \\
\text{FR2.1} \\
\text{FR2.2} \\
\text{FR2.3} \\
\text{FR2.4} \\
\text{FR2.5} \\
\text{FR3.1} \\
\text{FR3.2} \\
\text{FR4.1} \\
\text{FR4.2} \\
\text{FR5.1} \\
\text{FR5.2} \\
\text{FR5.3}
\end{pmatrix}
\begin{pmatrix}
\text{DP1.1} \\
\text{DP1.2} \\
\text{DP2.1} \\
\text{DP2.2} \\
\text{DP3.1} \\
\text{DP3.2} \\
\text{DP4.1} \\
\text{DP4.2} \\
\text{DP5.1} \\
\text{DP5.2} \\
\end{pmatrix}
\begin{pmatrix}
\text{FR1.1} \\
\text{FR1.2} \\
\text{FR1.3} \\
\text{FR1.4} \\
\text{FR1.5} \\
\text{FR2.1} \\
\text{FR2.2} \\
\text{FR2.3} \\
\text{FR2.4} \\
\text{FR2.5} \\
\text{FR3.1} \\
\text{FR3.2} \\
\text{FR4.1} \\
\text{FR4.2} \\
\text{FR5.1} \\
\text{FR5.2} \\
\text{FR5.3}
\end{pmatrix}
\begin{pmatrix}
\text{DP1.1} \\
\text{DP1.2} \\
\text{DP2.1} \\
\text{DP2.2} \\
\text{DP3.1} \\
\text{DP3.2} \\
\text{DP4.1} \\
\text{DP4.2} \\
\text{DP5.1} \\
\text{DP5.2}
\end{pmatrix}
\]

\[
\begin{pmatrix}
\text{FR1.1} \\
\text{FR1.2} \\
\text{FR1.3} \\
\text{FR1.4} \\
\text{FR1.5} \\
\text{FR2.1} \\
\text{FR2.2} \\
\text{FR2.3} \\
\text{FR2.4} \\
\text{FR2.5} \\
\text{FR3.1} \\
\text{FR3.2} \\
\text{FR4.1} \\
\text{FR4.2} \\
\text{FR5.1} \\
\text{FR5.2} \\
\text{FR5.3}
\end{pmatrix}
\begin{pmatrix}
\text{DP1.1} \\
\text{DP1.2} \\
\text{DP2.1} \\
\text{DP2.2} \\
\text{DP3.1} \\
\text{DP3.2} \\
\text{DP4.1} \\
\text{DP4.2} \\
\text{DP5.1} \\
\text{DP5.2}
\end{pmatrix}
\]

\[
\begin{pmatrix}
\text{FR1.1} \\
\text{FR1.2} \\
\text{FR1.3} \\
\text{FR1.4} \\
\text{FR1.5} \\
\text{FR2.1} \\
\text{FR2.2} \\
\text{FR2.3} \\
\text{FR2.4} \\
\text{FR2.5} \\
\text{FR3.1} \\
\text{FR3.2} \\
\text{FR4.1} \\
\text{FR4.2} \\
\text{FR5.1} \\
\text{FR5.2} \\
\text{FR5.3}
\end{pmatrix}
\begin{pmatrix}
\text{DP1.1} \\
\text{DP1.2} \\
\text{DP2.1} \\
\text{DP2.2} \\
\text{DP3.1} \\
\text{DP3.2} \\
\text{DP4.1} \\
\text{DP4.2} \\
\text{DP5.1} \\
\text{DP5.2}
\end{pmatrix}
\]

2.2. Preliminary experiments and the influence of the process variable

In order to submit both axioms during the mapping of the AD elements, preliminary tests were performed to reduce the number of PVs and to choose the best DPs option. During this step, the process domain is introduced and PVs can be seen in figure 4, along with their correlations with DPs.
The preliminary tests, the reliable and robust BCN3D SigmaX R19 (DP₂.₁) professional Desktop 3D printer is used. This equipment has a dual drive gear Bowden extrusion system (DP₂.₁.₂) and works with a filament of 2.85 mm in diameter (DP₂.₁.₂). The used 0.4 mm brass nozzle size influences FR₁.₁.₃ and FR₂.₂.₂. Besides that, an enclosure that ensures noise reduction (DP₅.₁.₂) and a protected medium from external air currents keeps the warmth (up to 48°C) from the heated bed inside the printer. The materials used (PV₃.₁.₃) to print the tested moulds and the extraction holes orientation test were the following: 2.85 mm brown PLA filament from ICE and a white heat-resistant PET filament from 3dk.berlin (PV₂.₁.₃). The thermoforming machine is the Model 450 DT (DP₄.₁.₁) from the manufacturer Formech. It has a maximum forming area of 430 mm x 280 mm (DP₄.₁.₂ and PV₄.₁.₂) and allows working with workpieces products with a maximum thickness of 6 mm (CS₃), according to the technical specification [8]. The following materials and thickness sheets were used for the thermoforming process: 0.8 and 1 mm black PS and transparent PET (CS₃).

The experimental study starts from a male type mould with a 35 mm deep female cavity, 61 mm vertical wall, sharp corners, round surface, which can be seen in figure 5 (left side). The mould presented in figure 5 (right side) is modified based on the thermoforming and 3D printing design rules (DP₁) for corners (FR₁.₁.₂), edges (FR₁.₂.₂), draft angle (DP₁.₁.₃), webbing and vacuum holes (DP₁.₁.₁) and channels (DP₁.₁.₁). In order to further improve the quality of the final thermoformed parts, new holes have been added to the vertical surface, and the bottom vacuum channels (DP₁.₁.₁) have been modified to improve the air flowing and air drawing.
Figure 5. Initial mould design (left) and the modified mould design (right). (adapted from [8])

For proper 3D printing and to improve the lifetime of the mould, the following printing parameters have been chosen: the 80% infill density was gradually decreased in 2 steps of 5 mm (DP2.2.4 and PV2.2.4), 3.2 mm top thickness equivalent of 16 Top Layers (DP1.1.3 and PV1.1.3) and 1.6 mm for wall thickness.

The printing of the mould, from figure 6 (left side), needed five days and 4 hours. In order to increase the crystallinity grade and make the mould temperature resistant up to 230 °C (DP2.1.3), the printed object must be post-processed inside a convection oven (DP3.1). To prevent the warping during tempering, the printed mould was placed at 60 °C inside the oven altogether with the printing table (DP2.1.6). After 30 min. of preheating, the mould was further tempered at 110 °C for 2 hours. For cooling, the mould was let inside the oven to cool down slowly, without opening the door. The tempered mould was used to produce thermoformed foils (figure 6, in the middle) with thickness from 0.8 mm up to 1 mm, without any mould deformation. The obtained foil was further used with success to pour and obtain the cement end-product (figure 6, right). All necessary safety measures (DP5) were taken during all the processes described above.

Figure 6. 3D printed mould, PET thermoformed sheet and the cement end product [8].

3. Conclusion

This paper proposes a framework for developing thermoformed mould obtained through FFF technology using axiomatic design. The method also helps to systematize and make decisions regarding the design of the mould, process parameters for both technologies involved, as well as to ensure the necessary measures to protect the human operator. The systemized accumulated database through AD, will reduce the required period of development, minimize failures and mistakes during the design steps and provide instant cause analysis to further develop a mould for industrial use.

By using this approach, it is possible to obtain a ready to use custom mould within hours or days, with a high degree of flexibility in the design (optimized air suction holes and channels, manufactured during the same process) and at a low cost for equipment compared to classical technologies. Furthermore, the proposed design technique and the manufactured mould were both successfully validated by testing the mould with 0.8 mm and 1 mm sheets. The results attained highlight the great potential of the proposed concept.
4. References

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