Development of Fused Filament Fabrication desktop 3D printer enclosure using axiomatic design principles

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Abstract. Additive manufacturing through Fused Filament Fabrication is one of the most spread methods for obtaining functional prototypes and components, mainly for single parts demands or small manufacturing lots. This direction of use presumes the use of engineering polymers in the manufacturing process, materials that require precise control of the environment regarding printing temperature and moisture. A Do-It-Yourself enclosure mock-up for engineering polymers processing was obtained using the Axiomatic Design principles. The enclosure is compatible with low-cost Fused Filament Fabrication desktop 3D printers and satisfies the functional requirements regarding manufacturing and secure usage of engineering-grade polymers. In addition, the presented design solved the requirements regarding surveillance and remote control during the manufacturing process.

1. Introduction
Fused Filament Fabrication-FFF is an Additive Manufacturing technology with one of the most economic growth due to the low cost of equipment and the great range of thermoplastic material available on the market [1]. Using engineering polymers (e.g., ABS, PC) implies proper control of the environment regarding temperature and moisture [2] to reduce part curling and increase mechanical characteristics. Thermal sensitivity is a common characteristic of this group of materials, making parts shrink, warp, or detach from the printing surface. Problems related to the thermal stability of the environment occurs when hot thermoplastic material is deposited on the previously solidified layer, causing rapid cooling and warping. The temperature difference between solidified layers and molten thermoplastic increases as the part grows due to the distance from the heated deposition surface. This phenomenon creates internal stress in the part structure and can cause previous layer curl or led to layer delamination [3]. This drawback can be avoided using a heated chamber [4], but the total cost of FFF equipment increases with the printing capabilities [3].

Given these facts, the main goal of this article is to use the Axiomatic Design-AD principles in the conception activity of a Do-It-Yourself-DIY controlled environment that can accommodate different FFF equipment. The motivation for this project came from the need to extend the manufacturing capabilities of the 3D printing machines from our disposal for research activities.

2. Methods
As a method for the Computer-Aided Design–CAD modelling process, five key steps were established for the constructive design; after each stage, a validation process was applied. The key steps are:

- Step 1: Determinate the Bill of Materials-BOM for equipment and system using the AD;
- Step II: Volume allocation and preliminary positioning an orientation of the main components;
- Step III: Generate preliminary design and fastening method;
- Step IV: Complete the design and fastening method;
- Step V: Integrate all hardware components.
2.1. Axiomatic design theory (principles)

The AD is a creative design method that comprises four areas: the customer domain, the functional domain, the physical domain and the process domain. Followed in this order, firstly, the Customer Needs (CNs) must be established and reshape in Functional Requirements (FRs) and Contains (Cs). Then, based on specified FRs, the Design Parameters (DPs) are developed. Each physical solution is then characterized by Process Variables (PVs) to obtain the desired solution. Finally, the designer must outline two main questions: “What we want to achieve?” and “How do we choose to satisfy the need?” with respect to the two axioms of the AD method [5]:

Axiom 1: Maintain the independence of the functional attributes (FRs)–which provide adaptability, controllability and minimize iterations and unintended consequences;

Axiom 2: Minimize the information content–that maximizes the probability of success.

The AD method comprises three fundamental parts: axioms, structure and process. Regarding the structure, the design domains were, which must be decomposed vertically in design hierarchies and detailed as physical components. In other words, the design requirements are formulated, and design solutions are developed from ambiguous to detailed between the domains in a process called decomposition with respect to the axioms [6].

Thompson (2013a) provides a deeper understanding of the CNs by describing the need to identify the possible stakeholders (STCHs.) and their needs (SNs). Frequently multiple stakeholders benefit from the same design. Thus, it is imperative to identify them to search for all potential customer needs by asking “who?” and “what he wants?”. Afterwards, requirements classification must occur to apply the AD method successfully. Therefore, it is essential to identify the non-functional requirements (nFRS) and consider them in parallel domains to the traditional domains [7, 8].

2.2. Application of AD principles

This design activity aims to enhance the manufacturing and control capabilities of current FFF machines types at our disposal, a Prusa i3 Mk3S+ and an Ultimaker 2+, to produce components from engineering-grade thermoplastic materials for research. The first group of stakeholders, Students and Researchers (STCH1), resulted by abstracting this statement.

Other identified stakeholders are hobbyists (STCH2) and self-employed persons (STCH3). So, the resulting product must satisfy the needs of these users (with 3D printers from different vendors and various configuration); the final design must be more adaptive than specific.

In conformity with the above-identified stakeholder, the customer needs were identified. Then, those demands were used to formulate the principal FR0: Obtain a DIY controlled environment for

- **CN1**: Compatibility with multiple desktop 3D printers
- **CN2**: Filament supply
- **CN3**: Material change while printing
- **CN4**: Minimum noise on printed parts
- **CN5**: Easy manipulation for movement
- **CN6**: Possibility to use engineering grade polymers
- **CN7**: Live surveillance
- **CN8**: Safety in exploitation
- **CN9**: Remote control
- **CN10**: DIY configuration

- **FR1**: Accommodate different desktop 3D printers
- **FR2**: Provide material supply
- **FR3**: Change material during printing
- **FR4**: Reduce vibrations
- **FR5**: Transport housing
- **FR6**: Increase environment temperature
- **FR7**: Survey printing process
- **FR8**: Protects against hazard
- **FR9**: Control enclosure

- **DP1**: Adequate volume allocation
- **DP2**: Feeding channel
- **DP3**: Access location
- **DP4**: Damping system
- **DP5**: Transport features
- **DP6**: Heating method
- **DP7**: Surveillance system
- **DP8**: Danger proof configuration
- **DP9**: Control system

- **PV1**: Different architecture of FFF 3D printers
- **PV2**: Machine's extrusion system
- **PV3**: Different material feeding locations
- **PV4**: Anti-vibration system or anti-vibration material
- **PV5**: Make or buy
- **PV6**: Heating source
- **PV7**: Make or buy the system
- **PV8**: Material characteristics
- **PV9**: Hardware and software specification

**Figure 1.** Customer, functional, physical and process domain of AD process for the heated chamber.

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FFF desktop 3D printers and have as DP0: DIY FFF desktop 3D printer heated chamber. Afterwards, the first-grade attributes are determinate in the functional domain and Cs (figure 1). Finally, in concordance with the identified FRs, the first-grade DPs were developed with their PVs.

According to the DIY project specifics, regarding the need for customization [9, 10], some of the design parameters have generic names (e.g., webcam) to not to limit the freedom of choice, each potentially stakeholder having the possibility to use the specific device according to his needs.

As presented in figure 1, the first three PVs refer to the construction principles of the FFF machines and are important factors of the design process. This type of equipment combines an extrusion system with a Computer Numerical Control-CNC system. Starting from this assumption, all FFF technology vendors designed their products differently. Prusa and Ultimaker are two great examples of FFF cartesian 3D printers with distinct configuration. Firstly, Prusa produces i3 machines with direct extrusion systems (PV2) on 1.75 mm filament diameter and Ultimaker vends machines with indirect extrusion systems, Bowden (PV2) on 2.85 filament diameters, both of them having different feeding locations for the raw material (PV3). In the case of Ultimaker equipment, the extrusion system moves horizontally in the XY plane, and after each completed layer, the build platform moves down across Z-direction (PV1). For machines with i3 configuration, the extrusion system moves in the XZ plane, and the build platform translates in the Y-direction (PV1). After each completed layer, the extrusion system moves up in a vertical direction.

![Figure 2](image-url)
The second half of this AD process, yellow labelled charts, involved designing the equipment integration, system and safety features as presented in figure 2. The PVs for the DPs were highlighted as previously, and they are PV6.1: Manufacturing method, PV6.2/PV7.1/PV7.3/ PV9.2/PV9.5: DIY approach, PV8.2: Filtering method, PV8.3: Filtration degree, PV8.6: Solution complexity, PV9.1: Command board architecture.

Due to the insufficient information, for particular DPs, a third level decomposition was necessary. Thus, the identified requirements are presented as follows:

- FR1.3.1: Minimize heat losses
- FR1.3.2: One-way fastening
- FR1.3.3: Design locking feature
- FR1.3.4: Provide clamping force
- FR1.3.5: Ensure door mounting position
- FR1.3.6: Facilitate door mounting/demounting
- FR1.3.7: Minimize space usage
- FR3.1.1: Provide access for direct extrusion systems
- FR3.1.2: Provide access for indirect extrusion systems
- FR6.1.1: Minimize heat exchange
- FR6.1.2: Allow process observation
- FR6.2.1: Heat actively
- FR6.2.2: Measure environment status
- FR8.2.1: Detect harmful fumes
- FR8.2.2: Filter environment’s air
- FR8.2.3: Minimize heat losses

The corresponding DPs are DP1.3.1: Sealing ring, DP1.3.2: Guiding tenons, DP1.3.3: Locking knob, DP1.3.4: Compression mechanism, DP1.3.5: Pre-mounting tenon, DP1.3.6: Ergonomic handle, DP1.3.7: Removable handle, DP3.1.1: Front side pocket, DP3.1.2: Rear side pocket, DP6.1.1:
Multilayer walls, \textit{DP6.1.2}: Transparent wall, \textit{DP6.2.1}: Heating device, \textit{DP6.2.2}: Temperature-humidity sensor, \textit{DP8.2.1}: Fume sensor, \textit{DP8.2.2}: Active carbon filter and \textit{DP8.2.3}: Automatic trap door, with their associated PVs: \textit{PV6.1.1}: Material compatible with the manufacturing method, \textit{PV6.2.1}: Heat source working principle, \textit{PV6.2.2}: Sensor configuration.

3. Design results

According to the AD principles, it is necessary to determine which design matrix was obtained. Therefore, several questions must be asked: “which type of design the matrix represents?”, “was the first axiom respected?” and if axiom one was not respected, “how the design should be changed to respect the independence axiom?”.

The design matrix of the DIY heated chamber for desktop FFF 3D printers is presented above, in figure 3. As can be observed, the result is an uncoupled design matrix, each FR having a corresponding DP. Thus, the first axiom of the AD principles was respected. This design is the result of several reiterations of the first matrix. The main challenges in obtaining an uncoupled design matrix were given by the previous improper decomposition of the FRs and the trial of respecting the identified constraints.

Further on, the result obtained following Axiomatic Design principles will be presented. It consists of two parts, the constructive design and the equipment integration and safety system design.

3.1. Equipment integration and safety system design

The AD method was beneficial in defining which type of components are necessary to satisfy the identified FRs, and through PVs, possibilities for achieving the design results. Therefore, all electronic components highlighted in figure 4 are generic to respect the DIY project’s characteristics (e.g., customization, standard component). This way, the stakeholder can adapt the presented schematic to his needs. For example, if the stakeholder chooses a Raspberry Pi as a command board (DP9.1), all the other DPs defined in the electronic scheme must be compatible.

It should be noted that parts of DPs can be changed or removed in particular cases. For instance, if the stakeholder decides that passive heating (heat generated through build plate), \textit{DP6.2.1} can be removed from the schematic, which influences \textit{DP9.2} (a smaller PSU can be used).

![Figure 4. Heated chamber’s electronic scheme.](image)
3.2. Constructive design

Regarding the constructive design of DP0 (developed in Catia V5 environment), after the volume allocation step (Step II) of the inside environment (DP1.1/DP1.2), the next stage (Step III) consisted of the construction of the chamber frame (DP4.1) and walls (DP6.1.1/6.1.2) as shown in figure 5. Thus, a part of the DPs transposed in a CAD model suffered iterated changes (zigzagging between Step II and Step IV), part of them being at the third version (e.g., DP2, DP1.3, DP1.3.2).

Figure 5. Partial representation of the DIY heated chamber (Step III to Step IV).

The insufficient decomposition of the FRs, because of the early stage of the CAD design process (Step II and III), determined several changes in the CAD model specification. This way, the AD matrix was updated several times.

All parts were developed according to C2, and components such as DP1.3, DP1.3.2, DP1.3.5 (which are in Step V of the constructive design) were designed by respecting Design for manufacturing (DMF) guidelines for laser cutting and FFF (figure 6). At this stage, the AD matrix presented in figure 3 is at the sixth version. However, it will require several add-ins as the CAD constructive design will be further developed in Steps VI & V (e.g., in the Electrical Harness Integration stage, where cable fixtures and passing points are necessary). Therefore, those extensions will be added as third or fourth level design features in the current AD matrix.

Figure 6. CAD mock-up of the detachable front door and the fastening mechanism (Step IV).
4. Conclusion
The Axiomatic Design method is a powerful instrument for enhancing the development of the constructive design process due to its systematic framework, which provides directions to be followed regarding what needs to be done and how to do it. Even if the AD matrix is comprehensive regarding functional requirements and the design solutions, the result must be filtered through a validation process to ensure the appropriate solution. An increased degree of attention should be paid to formulating the FRs. The decomposition process can be prematurely stopped if the requirements are not well formulated.

Regarding the association of the AD method with the CAD constructive design, it is very important to identify the best fit solution at the early stages of the modelling process to reduce the number of redesign iterations.

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