



Design and Development of Custom Functional Parts Using FDM 3D Printer

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ABSTRACT

Rapid Prototyping (RP) has transitioned from a basic visualization tool into a robust production methodology capable of fabricating complex functional components. This paper presents a structured, comprehensive study on the design, calibration, and manufacturing efficiency of custom mechanical parts using a desktop Fused Deposition Modeling (FDM) system. Utilizing a Creality Ender-3 V3 SE platform, various functional elements—including calibration cubes, mechanical gears, brackets, and threaded fasteners—were modeled via Computer-Aided Design (CAD) and processed into physical components using Polylactic Acid (PLA). The investigation provides a detailed framework of the additive workflow, detailing slicing parameter optimization alongside an exhaustive cost analysis encompassing material utilization and regional domestic electrical tariffs (UGVCL, Gujarat). The empirical outcomes validate that optimized desktop FDM printing yields a highly dependable, dimensionally accurate, and economically disruptive alternative to conventional subtractive manufacturing techniques for small-scale engineering applications and vocational laboratories.

Keywords: Additive Manufacturing, Fused Deposition Modeling, CAD Modeling, Cost Optimization, Mechanical Components.

1. Introduction & Background

Traditional subtractive manufacturing methods (such as milling, drilling, and grinding) are inherently bounded by geometries that allow tool-path clearance, resulting in high material waste, expensive tooling setups, and elongated lead times. Conversely, Rapid Prototyping (RP) incorporates a suite of additive manufacturing (AM) processes that automatically construct high-fidelity physical models directly from Computer-Aided Design (CAD) datasets. Historically formalized in commercial sectors around 1994, early adopters like Pratt & Whitney demonstrated that integrating layered manufacturing into corporate operations could yield an order of magnitude cost reduction and time savings ranging from 70% to 90%.

The paradigm shift from subtractive methodologies to freeform layer-by-layer deposition relies entirely on the synchronization of digital mesh models with deterministic toolpaths. In modern manufacturing frameworks, this agility permits real-time revisions and allows the user to fabricate customized components without high structural tooling penalties.

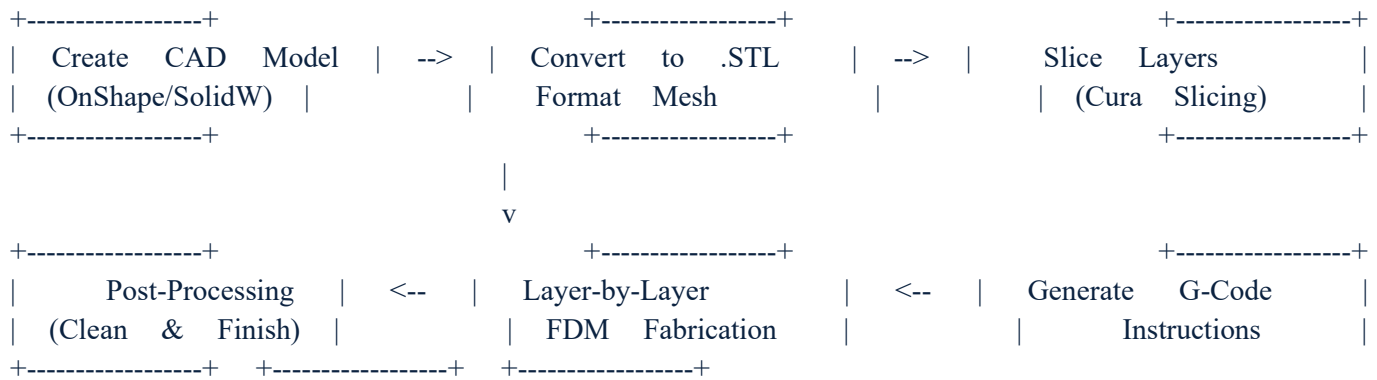


Figure 1: Sequential Process Flow Vector of Digital-to-Physical Additive Manufacturing.

The foundational workflow of any layered rapid prototyping methodology operates via a deterministic series of operations:

1. **Geometric Modeling:** Generation of a precise three-dimensional digital model within a CAD environment.
2. **Mesh Tessellation:** Conversion of the native geometric entities into standard stereolithography (.STL) format, translating solid faces into triangular mesh arrays.
3. **Slicing Deconstruction:** Utilizing dedicated software packages to deconstruct the digital solid into mathematically precise horizontal cross-sectional layers, typically on the order of 0.1 mm to 0.35 mm.
4. **Layer-by-Layer Deposition:** Physical execution of material deposition sequentially atop preceding layers.
5. **Post-Processing:** Mechanical extraction, support structure mitigation, and surface refining.

2. Taxonomy of Rapid Prototyping Methodologies

To properly contextualize the operational benefits of Fused Deposition Modeling (FDM), it is critical to evaluate it against alternative rapid prototyping systems established within current engineering paradigms.

A. Stereolithography (SLA)

Patented in 1986 as the premier commercially viable freeform manufacturing architecture, SLA leverages vat photopolymerization. A focused Ultraviolet (UV) laser traces defined cross-sectional boundaries onto the surface of a liquid photocurable acrylate resin. Upon interaction with the intense UV beam, the low-viscosity monomer cross-links and solidifies. An internal elevator platform subsequently lowers the cured layer, allowing fresh liquid resin to submerge the part before the next exposure pass. While setting industry benchmarks for fine resolution and smooth surfaces, SLA exhibits notable trade-offs, including part warping, post-curing cycle dependencies, and the handling of toxic, volatile chemical reagents.

B. Laminated Object Manufacturing (LOM)

LOM utilizes sheet lamination mechanisms where individual layers of material (frequently paper or plastic sheet stock embedded with a heat-activated polyester adhesive) are bonded sequentially via a heated roller. A carbon-dioxide laser then cuts the specific outer perimeter of the current cross-section. The primary benefit of LOM centers on its non-toxic nature, low material cost, and lack of external support structures since the un-cut sheet grid remains as a natural support matrix. However, LOM requires extensive subtractive post-processing to split the completed component away from the surrounding scrap block, and parts are prone to environmental moisture degradation.



C. Selective Laser Sintering (SLS)

Operating on a Powder Bed Fusion (PBF) mechanism, SLS distributes fine polymer, metal, or ceramic powders evenly across a fabrication bin via a counter-rotating roller system. A thermal-fusing carbon-dioxide laser sweeps the powder bed, elevating the local particles hit by the beam to their exact sintering point, which bonds them into a cohesive mass without complete melting. Fresh powder beds are layered over prior steps continuously. SLS removes the need for supplementary support structures because the surrounding loose powder acts as a natural floating bed. Nevertheless, materials like fine nylon or polycarbonate powders present inhalation health risks, the machinery requires expensive thermal controls, and parts often exhibit a grainy surface texture.

D. Solid Ground Curing (SGC)

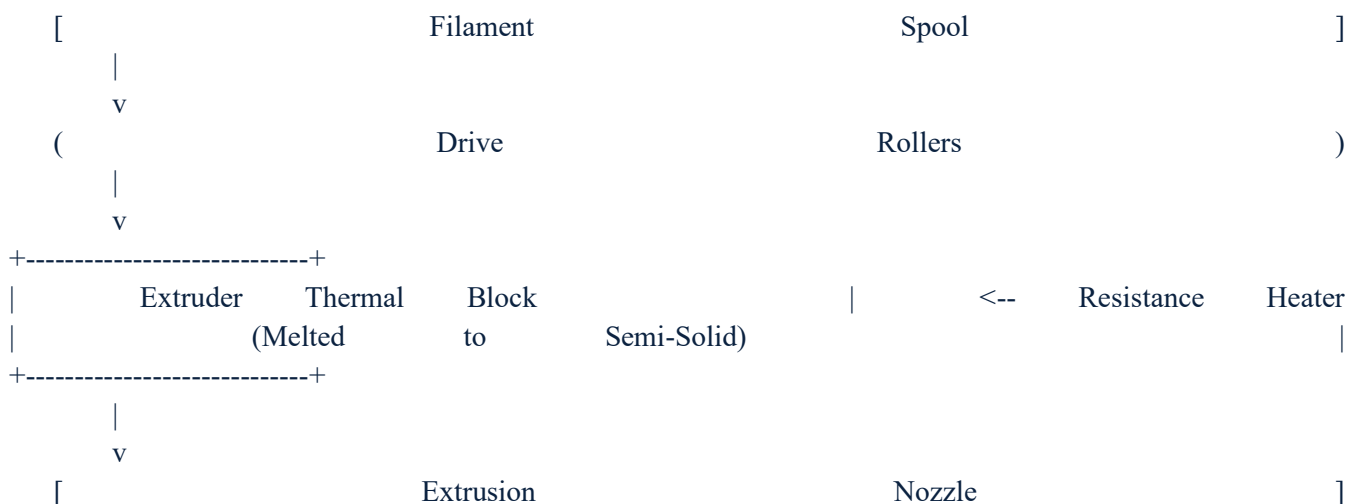
SGC is a complex photo-reactive technique where each layer's cross-section is digitally printed onto a glass mask plate. A high-power UV lamp flashes through the glass sheet directly onto a photopolymer vat layer, instantly solidifying the exposed geometry. Excess liquid resin is vacuum-removed and substituted with melted wax, which is subsequently cooled and milled completely flat to establish a perfect reference plane for the next layer. Glass templates are erased and re-masked cyclically. While highly precise and omitting post-curing cycles, SGC systems are mechanically complex, loud, expensive, and generate high chemical overhead.

E. 3-D Ink-Jet Binder Printing (3DP)

Developed originally at the Massachusetts Institute of Technology, 3DP distributes an alumina or silica powder medium over a moving bed. Liquid adhesive binder is selectively jetted from an inkjet printhead array to bind adjacent particles. This process repeats until a green-state shell or mold is completed, which is fired in a furnace and filled with molten engineering metal alloys. It allows functional metal part generation but demands substantial thermal furnace post-processing.

3. Fused Deposition Modeling (FDM) Architecture & Core Dynamics

Fused Deposition Modeling (FDM)—alternatively termed Fused Filament Fabrication (FFF)—stands as the most accessible and mechanically straightforward iteration of additive manufacturing. Thermoplastic filament wound onto a spool is continuously driven into a moving extrusion assembly. Inside the print head, the material passes through a thermal block fitted with a resistance cartridge heater, transitioning the material into a non-Newtonian semi-solid state. The softened polymer is forced through a precisely machined circular orifice nozzle, depositing continuous micro-strands onto a heated build platform along pre-calculated coordinates. As the material leaves the hotend, it undergoes rapid thermal dissipation, solidifying to form a distinct laminate layer that thermally fuses with adjacent tracks and underlying coordinates.



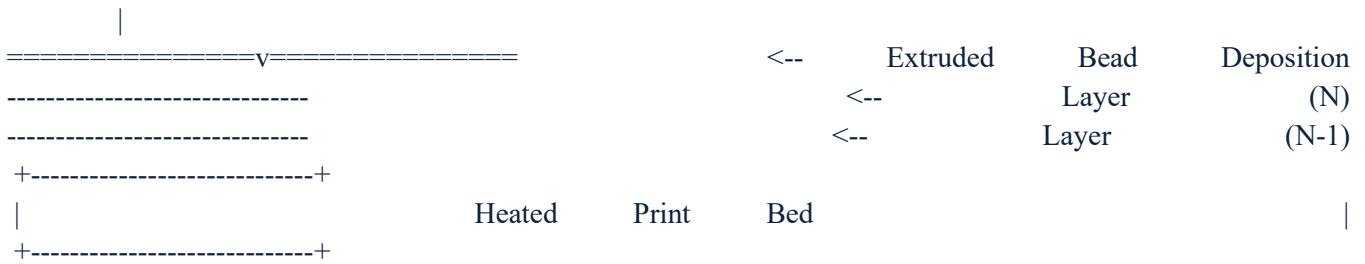


Figure 2: Schematic Cross-Sectional Diagram of FDM Thermal Extrusion Extruder Configuration.

For this investigation, an open-source Cartesian mechanical structure was adopted. Cartesian architectures operate using three orthogonal linear axes (X, Y, and Z) driven by precise digital stepper motors. The specific operational characteristics of the FDM platform utilized throughout the experimental phase are detail-mapped below:

Technical Parameters of the Experimental FDM Unit

Build Volume Dimensions: 220 x 220 x 250 mm

Peak Translation Velocity: Up to 250 mm/s (Nominal operational baseline maintained at ~180 mm/s)

Layer Resolution Limits: Scale variance from 0.1 mm up to 0.35 mm

Volumetric Accuracy: Within a margin of +0.1 mm

Extrusion Feed Mechanism: Sprite Direct Drive Extruder assembly

Filament Diameter: Standardized 1.75 mm stock

Material Compatibility: Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG), and Thermoplastic Polyurethane (TPU)

Levelling Topology: Built-in CR Touch automatic multi-point strain gauge compensation

Z-Axis Configuration: Dual synchronized Z-axis lead screws driven to suppress high-speed mechanical vibration

4. Digital Engineering, Modeling, and Slicing Strategies

Transitioning from a functional design intent to an active component requires tight coordination across geometric creation, exchange standardizations, and spatial toolpath generation.

A. Role of Computer-Aided Design (CAD)

Advanced geometric modeling requires defining physical boundaries through analytical and mathematical parameters inside systems like SolidWorks, AutoCAD, or OnShape. The digital design stage allows engineers to verify clearances, simulate mechanical movements, and establish structural tolerances to avoid interference issues before initiating physical production. To maintain data integrity across disparate software systems, standard file conversion structures are utilized:

IGES (Initial Graphics Exchange Specification): Used primarily to translate line-based wireframes and complex three-dimensional surface profiles across varied software packages.

STEP (Standard for the Exchange of Product Model Data): An advanced modern international exchange standard that retains complete volumetric solid data and topological parameter information.

STL (Stereolithography Standard): The universal interface for slicing tools, representing solid outer geometry as a continuous tessellated mesh of triangles.



B. Optimized Slicing Strategy

Slicing instructions translate the fixed mesh geometry into sequential numerical toolpaths (G-code parameters). Slicing optimization was established using Ultimaker Cura and Creality Print platforms under strict execution guidelines. The spatial and physical parameters were defined according to specific technical baselines to prevent print failures and dimensional inaccuracies.

Layer Height = 0.2 mm | Nozzle Diameter = 0.4 mm | Infill Density = 20% (Grid Matrix Type)

The extrusion heating zone was locked at a constant temperature of 180°C to match the thermal flow properties of the Polylactic Acid (PLA) filament, while the heated bed was held at a stable 60°C baseline to ensure consistent first-layer adhesion and minimize thermal contraction stresses at the bottom of the part.

5. Experimental Methodology & Material Processing

The experimental research framework followed a rigorous sequence designed to evaluate printing performance, component cost structures, and directional accuracy. Five mechanical reference models were selected to analyze structural accuracy, thread forming, and load support capacity across different geometry layouts:

1. **Calibration Cube:** Utilized to perform fundamental axis dimensional cross-checks (+0.1 mm threshold evaluation).
2. **Involute Spur Gear:** Formulated to test surface quality and accuracy along continuous curved mechanical motion profiles.
3. **Ergonomic Phone Stand:** Selected as a standard functional product example involving cantilever loads.
4. **Threaded Nut & Bolt Assembly:** Processed to analyze dimensional tolerances and thread clearance fits.
5. **Structural Mounting Bracket:** Engineered as a rigid mechanical support element to test load distribution.

6. Comprehensive Production Cost Analysis

A core objective of this study was developing a reliable economic formula to compute the cost of custom FDM parts relative to commercial production baselines. The financial assessment includes both raw plastic consumption and local electrical utility overhead.

A. Material Cost Formulation

Filament expenses are derived using a basic linear weight equation:

$$\text{Material Cost } (C_M) = [\text{Filament Bulk Cost (INR)} / \text{Total Filament Mass (Grams)}] \times \text{Part Weight (Grams)}$$

Based on current commercial acquisition data for high-grade PLA, the bulk filament cost is fixed at ₹700 per 1 kg (1,000 grams), yielding an exact unit expense of ₹0.70 per gram.

B. Electrical Power Overhead Analysis

Electrical operating costs are derived using localized domestic tariff allocations defined by Uttar Gujarat Vij Company Ltd (UGVCL), Gujarat, India. The standard multi-tier residential billing structure is outlined in Table 1.



Consumption Energy Slab Range	Base Rate (₹ / kWh Unit)
0 - 50 Units	₹3.10
51 - 150 Units	₹3.95
151 - 250 Units	₹5.20
251 - 500 Units	₹5.75
Above 500 Units	₹6.25

Table 1: Regional UGVCL Energy Slab Tariff Matrix.

Accounting for Fuel Adjustment Charges (FAC) and government duty assessments, the active operating electrical tariff is standardized at an effective rate of ₹8.00 per kWh unit.

The printer operates with an average measured power requirement of 350 W (0.35 kW) under full thermal load. The exact electricity cost per part is calculated using the following formula:

$$\text{Electrical Cost } (C_E) = \text{Power Rating [kW]} \times \text{Print Time [Hours]} \times \text{Utility Tariff Rate [INR/kWh]}$$

$$\text{Hourly Operational Overhead} = 0.35 \text{ kW} \times 1 \text{ Hour} \times ₹8.00 = ₹2.80 \text{ per printing hour.}$$

C. Total Production Cost Synthesis

Summing the individual material and electrical cost factors yields the total production cost (C_T) for each fabricated part: $C_T = C_M + C_E$. Table 2 synthesizes the material consumption, operational print tracking times, and calculated final production costs for the five reference components:

Component Identity	Part Weight (g)	Production Time	Raw Material Cost (₹)	Electrical Cost (₹)	Consolidated Total Cost (₹)
Calibration Cube	12 g	25 min	₹8.40	₹1.40	₹9.80
Involute Gear	18 g	40 min	₹12.60	₹2.10	₹14.70
Phone Stand	45 g	80 min	₹31.50	₹4.20	₹35.70
Nut & Bolt	10 g	20 min	₹7.00	₹1.17	₹8.17
Mechanical Bracket	30 g	55 min	₹21.00	₹2.80	₹23.80

Table 2: Integrated Cost Optimization and Material Consumption Matrix.



7. Results, Discussion & Environmental Aspects

The experimental data confirms that proper calibration and leveling are critical to achieving dimensional consistency and high surface quality across FDM-printed parts.

A. Parameter Interdependencies

The mechanical strength and dimensional precision of the printed components depend directly on slicing parameter choices. Lower layer heights reduce the noticeability of surface stair-stepping but increase total print times. A layer height of 0.2 mm provided an optimal balance between visual quality and printing efficiency. The 20% grid infill pattern provided sufficient internal structure to handle functional mechanical loads without excessive material consumption. Aligning print orientations relative to expected load directions significantly minimized structural anisotropy under stress.

B. Environmental Impact Assessment

As additive manufacturing expands into broader academic and industrial workflows, its environmental lifecycle must be closely evaluated. FDM processes generate significantly less material scrap than conventional subtractive machining, as material is deposited only where required by the part geometry. Additionally, Polylactic Acid (PLA) is derived from renewable starches (such as corn or sugarcane), making it inherently biodegradable under industrial composting conditions. However, continuous thermal cycles result in electrical energy consumption. Using dedicated ventilation enclosures, utilizing recycled filament feedstocks, and optimizing slicing toolpaths effectively minimize carbon emissions and lower energy consumption.

8. Conclusions & Future Outlook

This investigation successfully demonstrates the technical viability and cost-effectiveness of custom functional part production via desktop Fused Deposition Modeling. By systematically managing the workflow from digital CAD modeling to physical part extraction, reliable slicing and calibration protocols were established that ensure accurate geometric reproduction. The integrated economic cost analysis confirms that optimized FDM printing provides a highly affordable method for producing custom components, prototypes, and specialized fixtures compared to traditional manufacturing alternatives.

Future research in this domain will focus on several emerging technological advancements:

Intelligent In-Line Monitoring: Integrating real-time Machine Learning (ML) algorithms with computer vision to analyze layer deposition, predict printing anomalies, and adjust parameters dynamically to prevent structural failures.

IoT Integration: Deploying smart sensor networks and Internet-of-Things (IoT) modules to enable secure remote operation, automated fault detection, and predictive maintenance scheduling.

Advanced Composite Feedstocks: Characterizing high-performance engineering filaments—such as carbon-fiber-reinforced or glass-filled polymer matrices—to fabricate lightweight, high-strength functional parts for demanding mechanical environments.

Circular Economy Practices: Developing localized recycling systems to process industrial plastic waste into printable filament, enhancing the long-term sustainability of additive manufacturing workflows.



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