VALIDATION OF THE FDM-BASED ADDITIVE MANUFACTURING METHOD FOR RAPID PROTOTYPING USING THE EXAMPLE OF THE EIFFEL TOWER MODEL

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Abstract:

Modern rapid prototyping techniques, enabled by computer-aided manufacturing, allow for the efficient and accurate materialization of highly complex 3D objects designed within CAD software environments. These methods significantly reduce manufacturing time and eliminate the need for extensive post-processing. Following the validation of a digital prototype within a CAD system, the physical model is manufactured using appropriate layer-by-layer rapid prototyping technologies, including additive, subtractive, formative, or hybrid manufacturing methods.

This paper presented the use of commercial CAD tools for the modeling of geometrically complex 3D objects and their preparation for manufacturing via the Fused Deposition Modeling (FDM) additive manufacturing process. The Eiffel Tower model was selected as a representative example due to its complex structure and large dimensions. To facilitate the fabrication process, the model was divided into simpler, yet geometrically complex segments. The results demonstrate that the integration of CAD-based design with rapid prototyping techniques enables the production of large, detailed components with high dimensional accuracy and satisfactory surface quality.

Keywords:

Rapid Prototyping, Additive Manufacturing, Prototype, 3D Printing.

INTRODUCTION

In earlier times, product designers and engineers created improvised models using basic tools to demonstrate the conceptual design of a product. The manufacturing of functional prototypes required the same processes as those used for final products. Traditional manufacturing methods, such as plastic injection molding, demanded the production of expensive tooling, making small quantities of functional prototypes prohibitively costly. Rapid Prototyping emerged in the late 1980s with the introduction of the first machine by 3D Systems, which operated based on the SLA (Stereolithography) method [1–3]. Shortly thereafter, the first machines using the principle of fused deposition of material (Fused Deposition Modeling – FDM) were introduced. Since the deposited material can take the form of photopolymer, powder, or filament, more than ten different additive manufacturing methods have since been developed [4, 5].

DOI: 10.15308/Sinteza-2025-303-308

Modern rapid prototyping methods rely on computer-aided manufacturing, enabling fast materialization of complex 3D objects created in various CAD software packages, without the need for additional post-processing. Their accessibility lies in their ease of use and the ability to work with a wide range of thermoplastics, making them suitable not only for industrial applications, but also for use in education, architecture, and the arts. Most additive manufacturing system manufacturers offer dedicated software with user-friendly instructions, allowing for simple and efficient operation. This paper presents the process of manufacturing a scale model of the Eiffel Tower, an iconic architectural structure, using FDM technology. Due to the large dimensions of the model relative to the limited build volume of the 3D printer, a segmentation approach was employed—dividing the model into multiple smaller parts of complex geometry, which were manufactured individually and later assembled into a complete structure. Special attention was given to optimizing the slicing process, selecting the appropriate orientation, and adjusting printing parameters to achieve the desired strength, dimensional accuracy, and aesthetic quality of the final construction.

2. MODEL DESIGN FOR VERIFYING THE FDM MANUFACTURING METHOD

This chapter provides a description of the design process for the Eiffel Tower model using the SolidWorks software package. SolidWorks was developed by the French software company Dassault Systèmes, which also offers the CATIA software package—primarily intended for designing complex geometries in the aerospace industry. The graphical user interface of SolidWorks is tailored to a broad range of engineers, allowing for fast learning and user-friendly operation. Unlike in the past, when conceptualizing ideas and constructing prototypes relied on sketches and technical drawings, today's 3D models allow for more thorough functionality checks. Combined with virtual simulations and environmental visualization, they enable easier decision-making and acceptance of developed prototypes. The development of 3D modeling software has brought numerous advantages: reduced design time, decreased workload for designers and engineers, improved quality of technical documentation, lower overall system design costs, and simplified unification of the entire workflow within a single project. As a result, the quality of an integrated project is significantly higher compared to working across different platforms—not to mention the limitations of manual drafting used in the past.

Figure 1a shows the Eiffel Tower model, with overall dimensions of 200 × 500 mm. Due to its complex lattice structure and hollow interior, it was necessary to reconstruct the model to make it manufacturable. Manufacturing the complete model using the FDM rapid prototyping method would require the use of support structures (Figure 1b), which are difficult to remove after printing and can negatively affect the dimensional accuracy and overall shape of the final product. In many cases, support removal requires the use of additional technologies, further increasing production costs and time. To avoid these undesired effects, the model was reconstructed by dividing the original geometry into nine simpler parts (Figure 1c). In addition, each segment was designed with appropriate technological features, allowing for the model to be assembled like LEGO blocks after manufacturing. This approach ensured the correct positioning and orientation of all components within the final assembly.

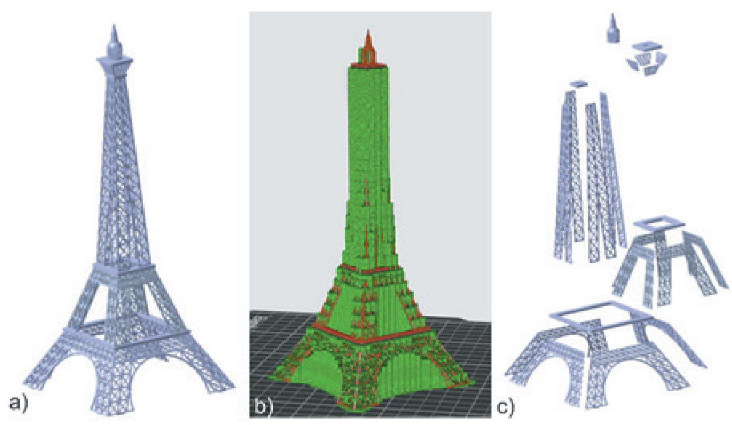

Figure 1. Eiffel Tower model: a) complete model, b) model with supports during manufacturing, c) exploded view showing all individual assembly components

3. RAPID PROTOTYPING TECHNOLOGIES

Rapid Prototyping refers to a layer-by-layer manufacturing technology used for producing parts. There are four main types of rapid prototyping technologies [1], schematically illustrated in Figure 2. What unifies them is the use of the standard .stl file format for preparing models for the selected manufacturing method. Whether the process involves material addition or subtraction, in addition to the .stl model of the desired prototype, an appropriate software tool is required for technology setup and generating machine instructions. The layer-by-layer material addition approach (Additive Manufacturing) is a natural solution for producing the presented Eiffel Tower prototype. This technology offers nearly unlimited design freedom, does not require special tooling, and can manufacture parts with mechanical properties comparable to those made by traditional manufacturing methods. Commonly referred to as 3D printing technologies, these methods have existed since the 1990s; however, their high cost and complexity at the time made them far less accessible than they are today. With technological advancement and cost reduction, 3D printers have become widely available. In-house 3D printing allows engineers and designers to quickly iterate between digital models and physical prototypes. Today, it is possible to manufacture a prototype within a single day and make multiple design modifications related to shape, size, or fit within the same timeframe, based on test results and real-world performance analyses.

Subtractive technologies represent a group of manufacturing methods in which material is removed layer by layer from the initial workpiece to achieve the desired shape and dimensions of the product.

Unlike additive technologies, which build up material, subtractive processes include milling, turning, drilling, grinding, and electrical discharge machining. These methods form the foundation of traditional manufacturing and are used across a wide range of industries, from automotive to precision engineering. Key advantages of subtractive technologies include high dimensional accuracy, excellent surface finish, and the ability to process a variety of materials, including metals, plastics, composites, and various types of model-making foams. An added benefit is the availability of user-friendly software for programming additive manufacturing machines, which typically allows for simple programming in just a few steps and does not require extensive user training. Hybrid techniques combine both additive and subtractive manufacturing processes. They are commonly used for producing functional parts, where the basic geometry is built using additive technologies, followed by precision machining of functional surfaces while the part is still positioned in the machine's working envelope. This approach enables high dimensional accuracy and superior surface quality, particularly after subtractive post-processing. Formative technologies are widely used for manufacturing parts through casting or forming processes. In practice, these methods are known as Rapid Tooling—the rapid production of tooling components. The tools are created using a combination of the three previously mentioned technologies, after which the desired material is poured into the prepared molds. Commonly used materials include epoxy-based resins for functional components and silicone-based compounds for creating molds intended for further use.

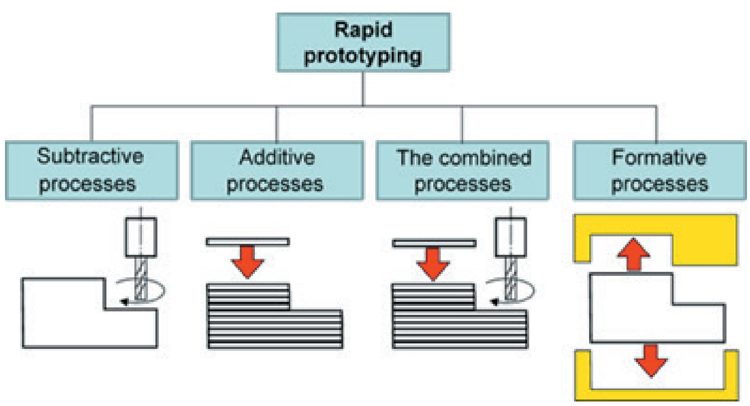

Figure 2. Overview of Rapid Prototyping Technologies [3]

4. PREPARING THE MODEL FOR FDM MANUFACTURING

This chapter presents the additive manufacturing machine used for producing the segments of the Eiffel Tower model and illustrates the preparation process of those segments. Finally, the manufactured parts were assembled into a complete structure, and the prototype model of the Eiffel Tower was presented.

4.1. MODEL OF THE BAMBU LAB P1S 3D PRINTER

When The mentioned 3D printer represents a new-generation additive manufacturing machine tool. It features an XY Core axis configuration, where the extruder moves within the XY plane while the platform gradually lowers along the Z-axis by the thickness of the defined layer. Movement in the XY plane is driven by a toothed belt, which offers several advantages. One of the main benefits is high speed and the possibility of implementing an H-bot mechanism. The Z-axis is powered by trapezoidal lead screws, which provide high accuracy and a self-locking effect. With the addition of the AMS (Automatic Material System) unit, which is purchased separately, the printer can produce parts in multiple colors. In essence, this unit functions as a material storage system that supplies the required filament during the printing process. The supporting structure of the Bambu Lab P1S 3D printer is a fully enclosed, box-type frame, which provides structural rigidity and maintains a stable ambient temperature—contributing to the high quality of the manufactured parts. Bambu Lab has developed its own proprietary software for programming all models in its 3D printer lineup. Additionally, the printer model used in this work is equipped with a touchscreen display for operator interaction and machine operation.

When connected to a network via Wi-Fi, the printer can receive programs directly and allows for real-time monitoring via a built-in camera and a mobile application. Figure 3 shows the Bambu Lab P1S 3D printer model.

4.2. PREPARATION OF THE PRINTING PROGRAM

This subsection provides a description of the procedure and software used for preparing the print program. The preparation was carried out using the Bambu Studio software package. In addition to basic model manipulation commands, the software offers a wide range of settings related to the printing process itself. It allows the user to define the number of layers on the top and bottom surfaces of the model, as well as the number of perimeters on the outer contours. Infill density is a critical parameter, as it directly affects the stiffness of the printed part, as well as its weight and material consumption. The software allows users to select the material type and, based on the selection, automatically recommends optimal extruder speeds and material deposition rates. The optimal printing speed of the extruder is 500 mm/s, with accelerations reaching up to 20,000 mm/s². Additionally, the P1S printer features advanced vibration compensation algorithms and improved pressure control during extrusion, which contribute to smooth and accurate prints even at high speeds. It is important to note that although the P1S can achieve high printing speeds, optimal results depend on the correct adjustment of print parameters and the use of appropriate materials [7]. Figure 4 shows a set of parts prepared for printing.

As part of the basic commands for model management, the user can position and orient parts on the build plate. Part orientation is especially important because the direction of layer deposition directly affects the mechanical strength of the part in different directions.

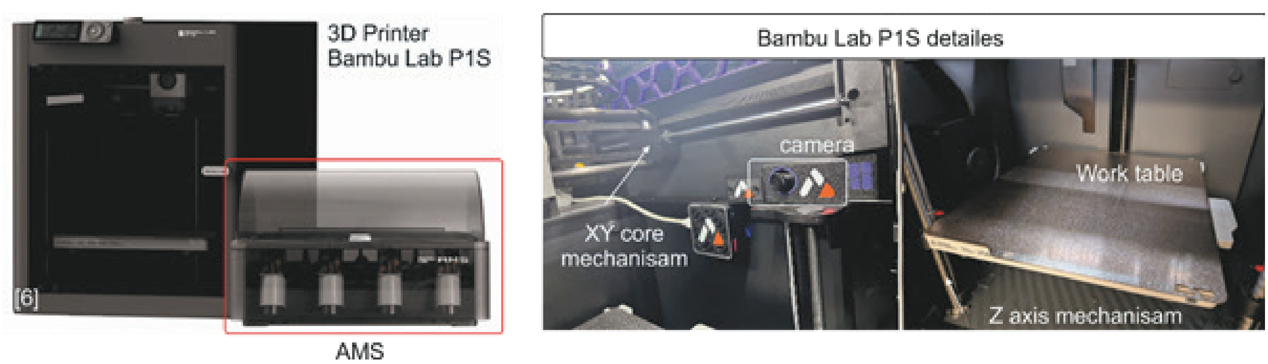

Figure 3. Bambu Lab P1S 3D Printer Model with Details

Irregularly shaped parts may require additional support structures, which are mechanically removed after printing—as shown in Figure 1b. Recently, support filaments based on cornstarch have been developed. These materials dissolve in water, making support removal much easier, especially for complex geometries like this one. The only requirement in this case is that the printer must be equipped with dual extruders, where one extrudes the support material and the other extrudes the main filament to build the part geometry. Parts prepared for printing can be scaled or duplicated if multiple copies are required. The software also includes an automatic arrangement function, which optimizes part placement on the build plate to maximize space utilization and enable simultaneous printing of as many parts as possible. This feature contributes significantly to reducing total manufacturing time. After completing the preparation of parts—which includes defining the printing parameters—it is necessary to slice the selected parts into layers of the specified thickness.

The software performs the necessary calculations and provides estimates of the total printing time and material consumption, which can be of great importance in certain situations. Rapid prototyping machine tools operate based on control systems that interpret instructions from a program written in G-code, defined by the ISO 6983 standard, also known as RS-274. Most G functions are standardized and identical across various types of 3D printers from different manufacturers. Differences between manufacturers may arise in the implementation of certain M functions, which control specific processes such as enabling extrusion, activating cooling fans, or turning on bed heaters via thermocouples. Figure 5 shows the assembled model of the Eiffel Tower. Thanks to the technological features added for positioning and orientation, the assembly process was completed quickly, and a specific two-component adhesive used to bond the parts provided additional structural strength to the final model.

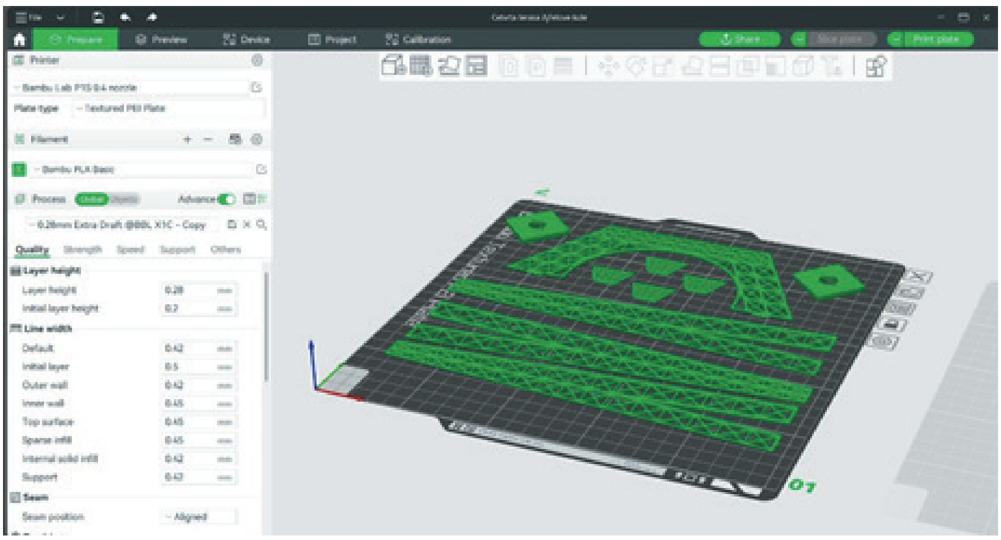

Figure 4. Bambu Studio Interface with Preparation of the First Group of Parts

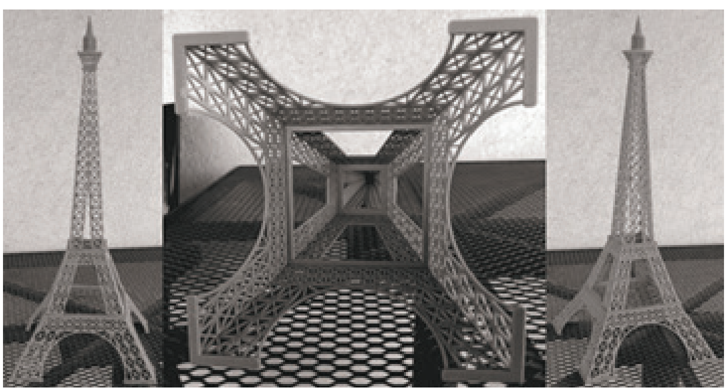

Figure 5. Assembled Model of the Eiffel Tower

5. CONCLUSION

The process of manufacturing the Eiffel Tower model using additive manufacturing proved to be an efficient and flexible method for producing parts with complex geometries. Thanks to the ability to directly convert CAD models into physical prototypes, it enabled rapid testing and visualization of intricate structures, as well as timely revisions of design solutions. Dividing the model into multiple segments further facilitated manufacturing, assembly, and quality control of the final structure. Although there are certain limitations regarding dimensional accuracy, printing speed, and the mechanical properties of the produced parts, the demonstrated method has proven to be highly suitable for creating models and visual prototypes. Rapid prototyping offers significant advantages to engineers and designers by accelerating product development, reducing costs, and shortening the time-to-market for new products.

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