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INFLUENCE OF FILL PATTERN ON PRINTING TIME IN 3D PRINTING AND MATERIAL CONSUMPTION

BY

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Abstract. 3D printing has become a core technology in multiple industries, enabling the rapid creation of complex, customized, and cost-effective objects. A crucial aspect of the 3D printing process is the infill pattern, which not only influences the strength and weight of the final product but also has a significant impact on the printing time. This article explores the relationship between printing time and the different types of infill patterns used, providing a detailed analysis of the trade-offs involved between production speed and the physical characteristics of the printed objects.

Keywords: 3D printing, part design, infill pattern, printing time, material consumption.

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1. Introduction

3D printing, also known as additive manufacturing, is one of the most innovative technologies of the 21st century, having a significant impact in multiple fields from industry and medicine to education and design.

This technology allows three-dimensional objects to be created by depositing successive layers of material based on a digital model.

From its early uses in rapid prototyping, 3D printing has evolved into an essential tool that redefines the way products are designed and manufactured.

Over the past decades, 3D printing has grown rapidly, facilitating mass customization and the production of complex objects that would have been impossible to make using traditional methods (Ciorap *et al*., 2023).

Fields such as medicine have benefited enormously from this technology, with the ability to create customized prosthetics, implants, and even printed biological tissues, marking a revolutionary advancement in patient treatment (Bogue, 2013; Ventola, 2014).

Key parameters that influence the quality and characteristics of the final product include fill density and fill pattern. In general, the fill pattern is chosen according to the structural needs of the object and the time available for printing (Ning *et al.*, 2020).

As technology continues to evolve, 3D printing poses new challenges and opportunities, including issues of sustainability, cost, and regulation (Chitariu and Munteanu, 2018).

This article explores the evolution, current applications, and future prospects of 3D printing, providing an overview of how this technology continues to transform various industries.

2. Time-consuming for different infill patterns

In this article, we will compare the different infill patterns and the printing times needed to realize them.

This experiment aims to evaluate the impact of 10 different filling patterns on the printing time, and material consumption.

By holding all other printing parameters constant, we will be able to isolate the specific effects of each filling pattern and provide clear recommendations for users and designers according to their specific needs.

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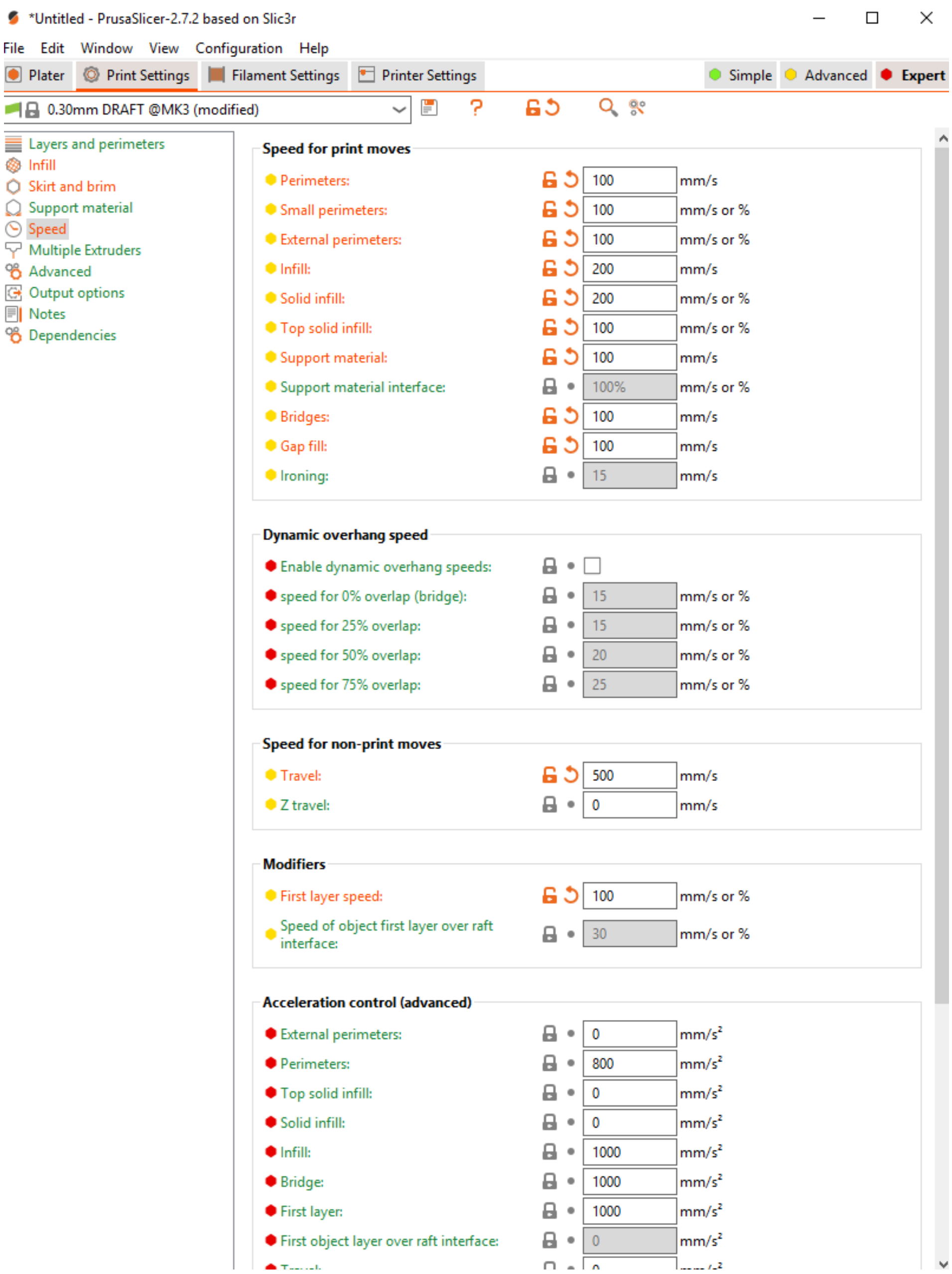

Fig. 1 – Printing speeds.

The experimental parameters are the following:

- Printing material: PLA (Polylactic Acid)

- Filament size: 1.75 mm
- Nozzle diameter: 0.4 mm
- Nozzle temperature: 200°C
- Platform temperature: 60°C
- Layer height: 0.3 mm
- Printing speed: 500 mm/s (Fig. 1)
- Part size: 70 mm x 40 mm x 5 mm
- Filling density: 20%
- Filling patterns: Rectiliniar, Triangular, Cubic octagonal, Grid
- Software used: PrusaSlicer for G-code generation and fill pattern selection.
- 3D printer: Prusa i3 MK3S

The first step of the experiment was to create a 3D model to be used in all print tests. We choose a cubic model with dimensions of 70 mm x 40 mm x 5 mm (Fig. 2), a simple geometry, but representative enough to evaluate the impact of the filling pattern. The chosen dimensions allow fast and repeatable printing, essential to ensure data consistency (Wu *et al*., 2015).

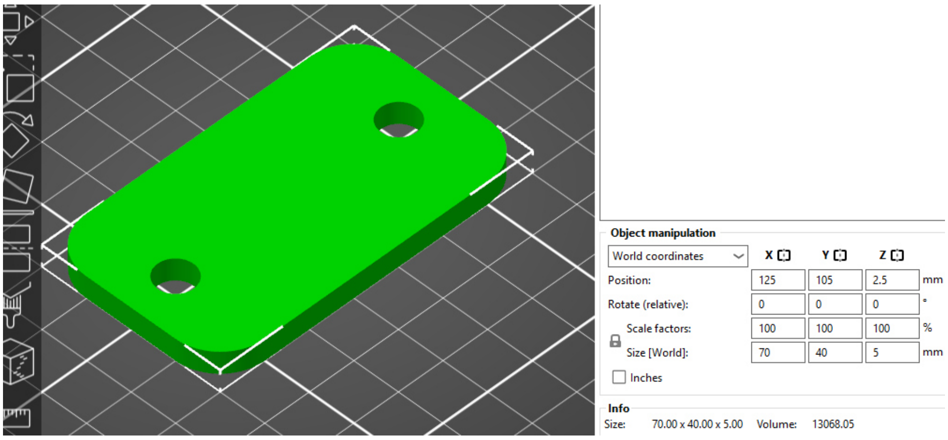

Fig. 2 – 3D model.

Once the CAD model was created, it was imported into the PrusaSlicing software, where constant print settings were applied for all tests. Standard settings included the use of 1.75 mm diameter PLA filament, a 0.4 mm nozzle, nozzle and platform temperatures of 200°C and 60°C, respectively, and a layer height of 0.3 mm. The printing speed was set to 500 mm/s, a compromise between print quality and production time (Lin *et al*., 2018).

These models were chosen due to their popularity in practice and their structural diversity, providing a wide range of options for comparative analysis (Jiang *et al*., 2017).

Each infill pattern was individually applied to the CAD model, and Prusa software generated the G-code for printing, ensuring consistency and accuracy of the process.

The collected data were statistically analyzed to identify significant differences between the filling models in terms of printing time and material consumption.

Comparative tables were constructed to visualize the relationships between these variables, highlighting the advantages and disadvantages of each filling model in the specific context of the experiment.

This analysis allowed clear conclusions to be drawn regarding the most effective infill models for various applications, thus providing a valuable guide for engineers and designers in selecting the optimal infill model for their specific needs (Afrose *et al*., 2016).

3. Fill Patterns and Internal Part Structure

Fill patterns are the internal support network of a 3D printed part, which is not visible from the outside, but plays a crucial role in determining the strength and stability of the part.

Each infill pattern has a unique geometric structure, which influences the stress distribution and how the part resists various types of forces.

Rectilinear Infill

Rectilinear infill (Fig. 3) is the simplest and quickest option, consisting of parallel lines laid out at a constant angle, usually at 45 degrees to the main axes.

The main advantage of this model is the reduced printing time, due to the simple path and the small number of changes of direction of the print head.

However, the linear structure is susceptible to delamination and provides low mechanical strength, especially at forces perpendicular to the direction of the layers (Wu *et al*., 2015).

Rectilinear fill pattern is a filling technique used in 3D printing that is based on straight or parallel lines arranged in a uniform direction.

This pattern is appreciated for its simplicity and efficiency in terms of printing time and material consumption.

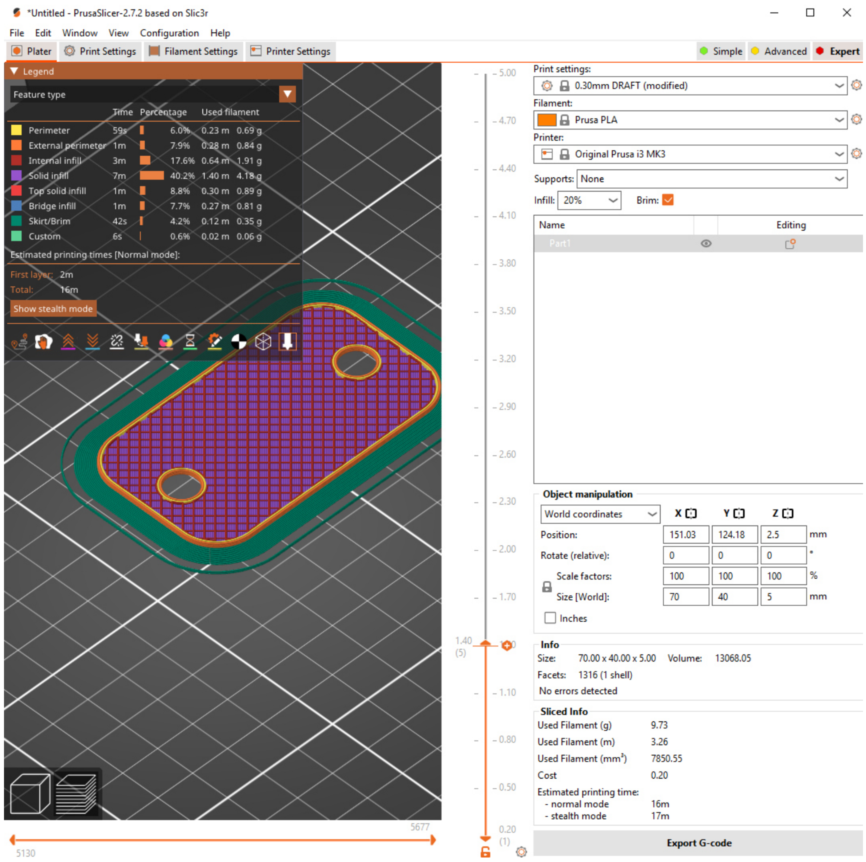

Fig. 3 – Rectilinear Infill.

Technical features of the Rectilinear Fill Pattern are the following:

1. Geometry and Structure:

   ○ Straight Line Structure: the Rectilinear Pattern utilizes parallel straight lines that are arranged in a uniform pattern on the horizontal plane. Depending on the orientation and density of the lines, they can be oriented in a single direction or alternate between two directions to form a grid of perpendicular lines (Gibson *et al*., 2015);

   ○ Simple and Regular: Rectilinear design is simple and easy to implement in the printing process, as straight lines are easy to control and apply by the printhead (Huang *et al*., 2017).

2. Impact on Printing Time:

   ○ Fast Printing Time: Rectilinear pattern is known for its efficiency in printing time. The parallel straight lines allow for uniform and repetitive print head movements, which helps reduce the time it takes to complete the print (Rouse, 2017);

o Efficient Movements: Due to the simple nature of the pattern, the print head movements are less complex and more direct, which contributes to faster print speed compared to more complex filling patterns (Zhang *et al.*, 2018).

3. Material Consumption:

o Material Efficiency: the Rectilinear Pattern is efficient in material utilization, as it requires less material to create an infill structure compared to denser infill patterns. This contributes to material savings and reduced printing costs (Lee *et al.,* 2019).

Optimization: Line size and density can be adjusted to optimize structural performance and material consumption, providing greater flexibility according to specific printing requirements (Zhang *et al*., 2018).

Triangular infill

Triangular infill (Fig. 4) utilizes a pattern of equilateral triangles, providing a uniform stress distribution throughout the internal structure.

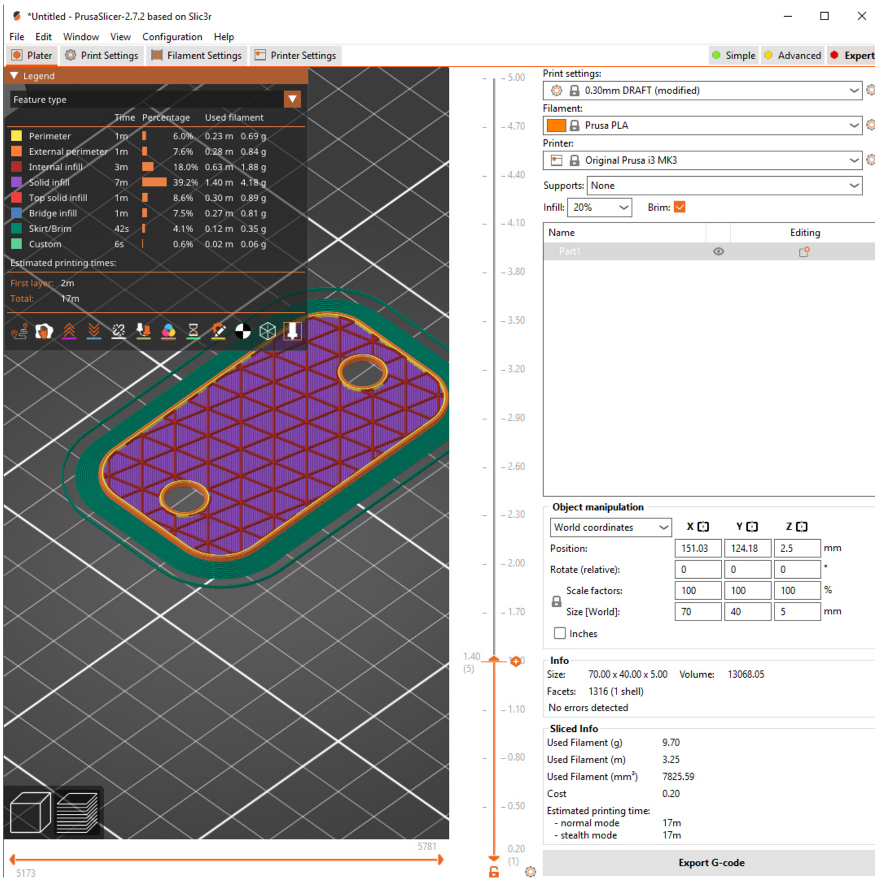

Fig. 4 – Triangular infill.

This filling pattern is known for its superior mechanical strength and is effective in applying multidirectional forces.

However, the printing time is longer than simple patterns and the material consumption is higher (Lin *et al*., 2018).

The Triangular fill pattern is a filling technique used in 3D printing that relies on a network of equilateral triangles or isosceles to fill the volume of printed parts. This model has an efficient structure and its ability to provide a balance between strength and material consumption.

Technical Features of the Triangular Filling Pattern are the following:

1. Geometry and Structure:

o Triangular Structure: The Triangular Pattern utilizes a pattern of triangular cells that are arranged in a uniform grid. Each triangle is connected to others to form a three-dimensional grid that fills the volume of the part (Gibson *et al*., 2015);

o Uniform Lattice: The triangular design is characterized by a uniform lattice of equilateral or isosceles triangles, which provides uniform volume coverage, facilitating an equitable distribution of forces and stresses (Huang *et al*., 2017).

2. Impact on Printing Time:

o Moderate Printing Time: Since the triangular model involves constructing a network of triangles, the printing time is moderate. Print head movements are relatively uniform but require precise execution of each triangle, which can add to the overall print time (Rouse, 2017);

o Movement Efficiency: The model allows for efficient and smooth print head movements, which helps reduce printing time compared to more complex fill patterns (Zhang *et al.*, 2018).

3. Material Consumption:

o Material Efficiency: The Triangular Design is efficient in material utilization as the triangular structure saves material compared to solid or very dense fillers. The triangular cells help maintain proper material density within the part (Lee *et al*., 2019);

o Optimization: the size and density of triangles can be adjusted to optimize material consumption and structural performance, providing flexibility according to specific printing requirements (Zhang *et al*., 2018).

Cubic infill

Cubic infill (Fig. 5) creates a network of superimposed cubes, providing uniform mechanical strength in all directions.

This pattern is useful for parts that will be subjected to variable and unpredictable forces.

Although it provides good structural stability, the printing time is considerably longer and material consumption is relatively high (Jiang *et al*., 2017).

Cubic fill pattern is a popular technique used in 3D printing that relies on a three-dimensional cubic structure to fill the interior of printed parts.

This model is valued for its ability to provide a balance between material efficiency and structural performance and is commonly used in engineering and rapid prototyping applications.

Technical features of the Cubic Fill Pattern are the following:

1. Geometry and Structure:

   o Cubic Structure: The Cubic model utilizes a three-dimensional grid of cubes that extend uniformly in all directions. This lattice consists of a series of cubes aligned in a 3D matrix, creating a fill pattern with uniform spacing between cubes (Gibson *et al*., 2015);

   o Modularity: The cubic design is modular and repeatable, which allows for simple and efficient pattern implementation in the printing process. Each cube is typically of equal size and aligns with the other cubes to form a uniform volume (Huang *et al*., 2017).

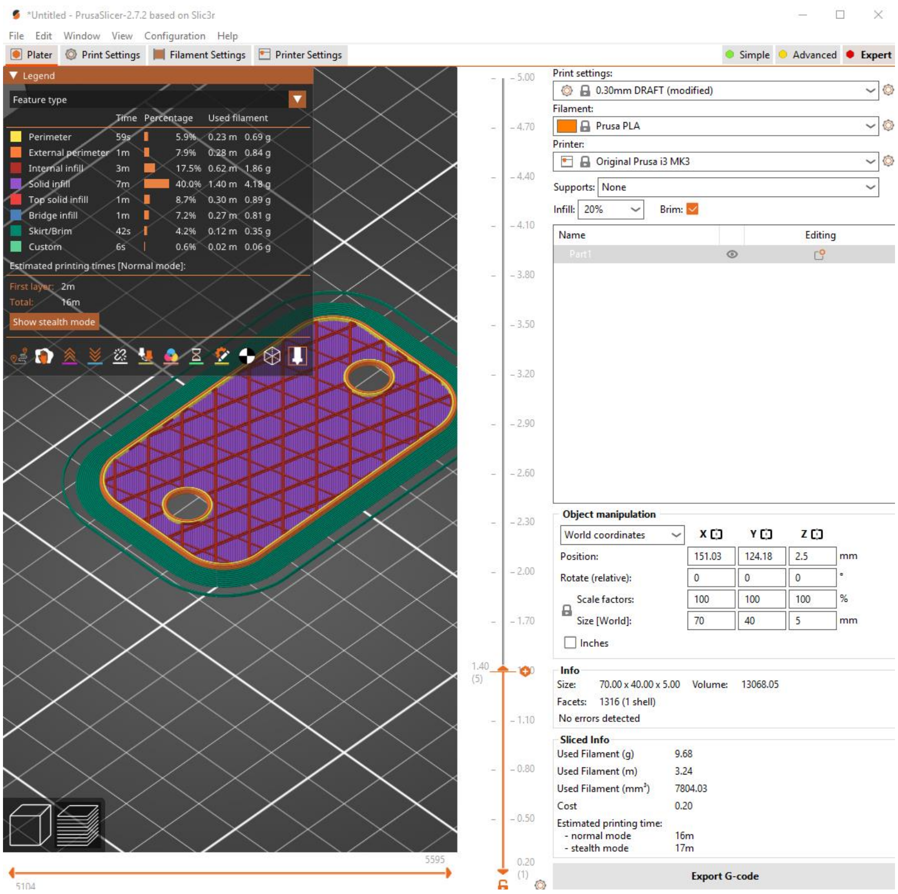

Fig. 5 – Cubic Infill.

1. Impact on Printing Time:
   - Moderate Printing Time: Because the cubic pattern involves building a volume of cubes, the printing time is longer compared to simpler fill patterns, but shorter than highly complex patterns. Print head movements are relatively uniform without sudden changes in direction, but require multiple layers and passes to complete the fill (Lee *et al*., 2019);
   - Accuracy and Efficiency: the cubic pattern allows for precise and efficient print head movements, contributing to a manageable print time compared to more elaborate fill patterns (Rouse, 2017).
2. Material Consumption:
   - Material Efficiency: the Cubic pattern is moderate in material utilization, offering a trade-off between filling density and material consumption. Although denser than simple filling patterns, material consumption is lower compared to very dense filling patterns (Lee *et al.*, 2019);
   - Optimization: Printing parameters, such as cube size and mesh density, can be tuned to optimize material consumption and part structural performance, providing flexibility according to specific printing requirements (Zhang *et al*., 2018).

Grid filling

Grid filling (Fig. 6) consists of a series of perpendicular lines arranged in a grid pattern.

This pattern provides good strength in both horizontal and vertical directions and is relatively efficient in terms of material consumption and printing time.

However, stress concentration at the intersections of the lines can lead to weak spots in the internal structure (Jiang *et al*., 2017).

Grid fill pattern is a popular pattern used in 3D printing to provide internal support structure in an efficient and simple way.

This pattern is characterized by a grid of parallel lines that intersect to form a uniform array of squares or rectangles, providing structural support to the printed part.

It is often preferred for applications requiring a compromise between durability and efficiency in material utilization.

Technical Features of the Grid Fill Pattern are the following:

1. Geometry and Structure:
   - Grid of Parallel Lines: the Grid pattern utilizes parallel lines arranged in an orthogonal grid, forming squares or rectangles. These lines are typically oriented at a 90-degree angle to the principal axes of the part (Gibson *et al*., 2015);
   - Simplicity: the Grid model's simple structure is easy to implement and adjust, making it a practical choice for many types of 3D printing (Huang *et al*., 2017).

2. Impact on Printing Time:

o Moderate Printing Time: Because the Grid model involves simple parallel lines, the printing time is moderate compared to more complex fill models, such as Hilbert curve or octagonal fill. However, it is longer than very simple patterns such as linear or zigzag (Zhang *et al.*, 2018);

o Trajectory Efficiency: the print head movements are relatively efficient and uniform without sudden changes in direction, which contributes to a more predictable and manageable printing time (Rouse, 2017).

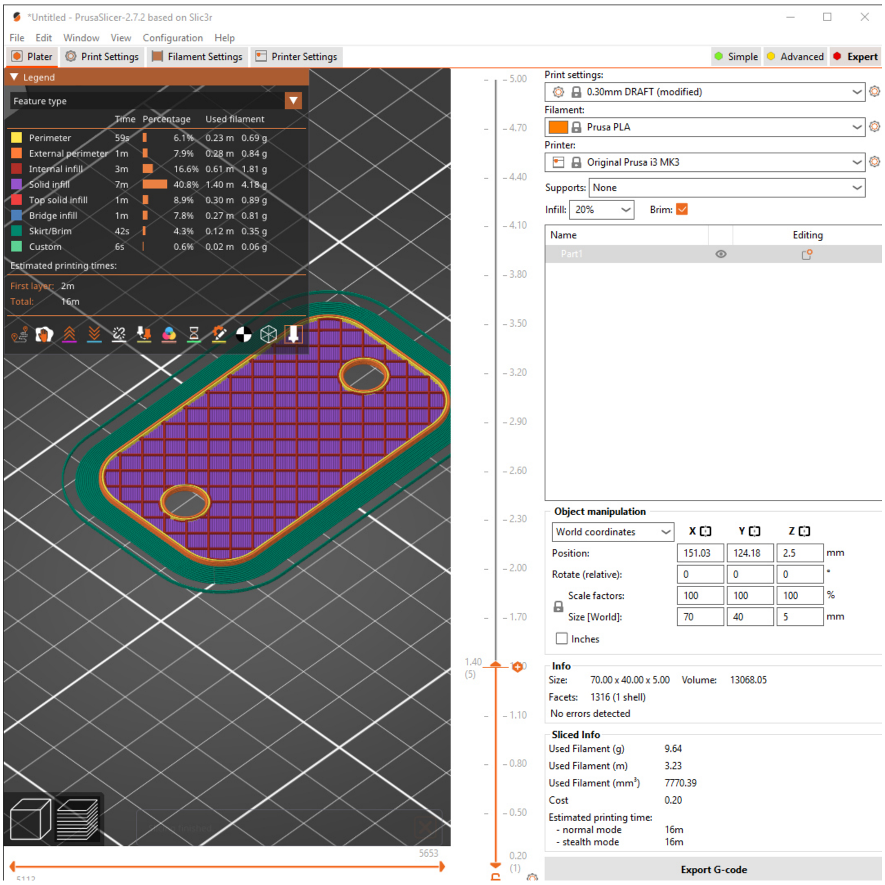

Fig. 6 – Grid Infill.

3. Material Consumption:

o Material Efficiency: The Grid model is relatively efficient in material utilization compared to dense and complex infills. However, the material consumption is higher than in very simple models, but lower than those involving very dense structures (Huang *et al.*, 2017);

o Optimization: grid density and size can be adjusted according to specific part requirements, providing a balance between material consumption and structural performance (Zhang *et al.*, 2018).

4. Impact on Printing Time and Efficiency

Printing time is a crucial factor in any manufacturing process, influencing both cost and delivery time (Table 1).

Filling patterns involving simple trajectories, such as linear or grid infill reduced printing times, making them ideal for rapid prototyping and non-critical parts.

On the other hand, complex patterns such as honeycomb or gyroid require more time and resources due to their elaborate structure, but offer significant advantages in terms of strength and durability of the final part (Ning *et al.*, 2020).

In the comparative analysis, it was found that the choice of the filling pattern has to be made based on a balance between the mechanical requirements of the part and the time available for production.

For example, for applications where speed is of the essence, rectilinear or grid filling might be preferred, even if this implies reduced mechanical performance.

In contrast, for industrial parts where durability is crucial, the use of more complex patterns might be justified, even if this implies longer production time and higher material consumption (Lin *et al.*, 2018).

Table 1
Time and material consumption distribution over the infill pattern

Infill Pattern	*Time (min)*	*Material consumption (g)*
Rectilinear	16	9.76
Triangular	17	9.7
Cubic	16	9.68
Grid	16	9.64

4. Conclusions

In 3D printing, the decision to choose a filling pattern is a critical decision that directly influences the efficiency of the process and the quality of the final part.

Choosing a filling pattern in 3D printing has to be made taking into account the specific requirements of the part in question.

While more complex patterns, such as octagonal and cubicoctogonal, offer superior mechanical strength, they come with increased printing time and material consumption.

On the other hand, simple patterns, such as linear and zigzag, allow for shorter production time but sacrifice part strength. The final decision depends on the desired balance between these critical aspects of 3D printing.

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INFLUENȚA MODULUI DE UMPLERE ASUPRA TIMPULUI DE IMPRIMARE ȘI CONSUMULUI DE MATERIAL LA IMPRIMAREA 3D

(Rezumat)

Imprimarea 3D a devenit o tehnologie de bază în mai multe industrii, permițând crearea rapidă de obiecte complexe, personalizate și rentabile.

Un aspect crucial al procesului de imprimare 3D este modelul de umplere, care nu numai că influențează rezistența și greutatea produsului final, dar are și un impact semnificativ asupra timpului de imprimare.

Acest articol explorează relația dintre timpul de imprimare și diferitele tipuri de modele de umplere utilizate, oferind o analiză detaliată a compromisurilor implicate între viteza de producție și caracteristicile fizice ale obiectelor imprimate.