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GENERATIVE DESIGN FOR REDUCING MATERIAL WASTE: A CASE STUDY ON FLANGES

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Abstract: *This article explores the use of generative design to reduce material waste in a case study applied to a basic flange design part, an important component in industry due to their structural and functional role, but also in basic applications where we require this kind of parts. In an industrial context where optimizing resources and reducing environmental impact are priorities, but also in custom projects made with the help of additive manufacturing such as FDM, generative design is an innovative method based on algorithms that allows the automatic generation of optimized configurations of the input design. By defining parameters such as basic start geometry, preserve and obstacle geometries, this process produces design iterations tailored for maximum performance with minimum material used. The case study examines the benefits of this approach in reducing the volume of material required to manufacture a flange part, analyzing and comparing the performance achieved against the traditional design. The results indicate a significant reduction in material waste, with potential for 3D printing implementation to improve sustainability and efficiency. The article also discusses the challenges and limitations in adopting generative design in the industrial environment, including the requirements for integration into current workflows and adapted to rigorous safety and reliability specifications.*

Keywords: *generative design, flange part, reduce material waste.*

1. INTRODUCTION

In an industrial context where resource efficiency and environmental protection are becoming global priorities, innovative solutions to reduce waste and optimize manufacturing processes are increasingly necessary. Generative design, a relatively new technology in the industry, offers huge potential for minimizing materials used and improving design processes, bringing significant economic and environmental benefits, with extraordinary possibilities of use in additive manufacturing, more precisely in three-dimensional printing. Generative design, based on advanced algorithms, has a different approach than the traditional one, by automatically generating solutions [1] in cloud that maximize the structural performance of a product while minimizing material consumption. This article aims to explore the applicability of this method in the design of a flange part, which can later be 3D printed using FDM (fused deposition modeling) technology.

By using generative design, engineers can define the critical parameters of a project, e.g. structural strength, weight limits, and material types. Thus, the software can automatically generate a multitude of possible configurations called iterations, each optimized to meet those criteria predefined by the user. The process involves continuous geometric modeling and structural analysis, enabling the identification of solutions that minimize the volume and mass of material required without compromising the quality and safety of the part [2]. Thus, besides cost savings, generative design allows a more rational use of resources and reduction of environmental impact, critical objectives in the transition to a circular and sustainable economy.

In this case, study, we will look in detail at the implementation of generative design of a flange part, examining how this method can significantly reduce waste from manufacturing processes, more precisely, to reduce the amount of filament used in the three-dimensional printing of this part.

Flanges are component parts with the role of connection between the various parts of a mechanical or hydraulic system and are often subjected to intense mechanical stress, but they are also used in other assemblies where they are not subject at very high external loads [3]. Besides materials such as stainless steel or aluminum, flanges can also be manufactured from plastic materials such as PVC (polyvinyl chloride) or nylon. Therefore, their design must ensure both maximum efficiency in the use of materials and adequate resistance to the forces and pressures encountered in use.

The main objectives of this article are to identify the benefits of generative design in reducing PVC or nylon material waste in the flange manufacturing process and

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to evaluate the impact on manufacturing costs or functional performance of the designed parts. We will also explore the challenges and limitations encountered in implementing this method, including the need to successfully integrate generative design into current industrial processes and ensure compatibility with stringent safety and reliability requirements [4]. The case study will include a comparative analysis between traditional and generative design for flanges, highlighting the practical advantages of this innovative methodology.

Thus, through this case study we want to make a relevant contribution to the understanding of the applicability of generative design in the optimization of the material used, especially if we are talking about customized projects, made with the help of three-dimensional printing, providing both a theoretical basis and specific examples.

2. METHODS

Fusion 360, developed by Autodesk, is one of the most popular CAD (Computer-Aided Design) modeling software used by engineers, designers and manufacturers to create accurate three-dimensional solid models and optimize complex structures [5]. One of the most innovative features of this software is the generative design module, which allows users to explore quickly multiple design iterations optimized according to specific parameters such as basic start geometry, preserve and obstacle geometry, boundary conditions, materials and the objectives that a user wants to achieve (e.g. reducing the mass/material). Generative design facilitates solutions that are more efficient by offering an approach that, through specific algorithms, enables continuous improvement and the automatic generation of innovative models based on predetermined criteria and constraints [6].

2.1. Project setup and parameter definition

To start generating design iterations, we must set the flange geometry and the most important parameters that must be considered further in this case study. These may include:

- *Base geometry* → first, the basic flange geometry was defined (*Fig. 1*);
- *Preserved geometry* → accessing the flange-editing mode, a copy of the initial *body* was generated on which the geometries that cannot be modified within the flange were defined. As *Fig. 2* shows, the four clamping holes have been defined as geometries that must not undergo changes, as well as the main central hole of the flange part;

Fig. 1. The flange part considered in this case study.

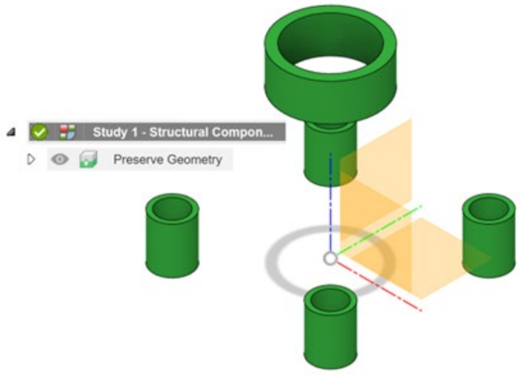

Fig. 2. The flange part preserved geometry.

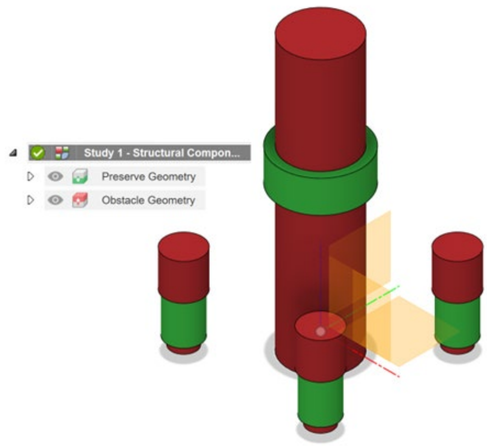

Fig. 3. Flange part obstacle (red colored shapes) and preserved geometry (green colored shapes).

- *Obstacle geometry* → to generate iterations of this flange part, is necessary to insert some other defined shapes such as obstacles, as we can see in *Fig. 3*, four simplified screw shapes were inserted in the fastening holes, and another geometry in the form of a cylinder in the central part of the flange;
- *The main case study objective* → the main objectives of this study are specified, namely the reduction of the material amount, and the safety coefficient of 1.5 (because we did not consider this flange to be used in extreme working conditions);
- *Materials* → material library allows the choice of several materials (e.g. aluminum, stainless steel, polymers) that directly influence the behavior and strength of the flange part, in this study we considered two materials nylon (polyamide) and PVC, both materials being widely used in three-dimensional printing;
- *Boundary conditions* → to generate iterations of the same design is necessary to define the loads and constrains that acts on the flange part, essential for the generative model to optimize the structure according to these conditions. In Fig. 4 we can observe how these boundary conditions were applied: a distributed internal pressure of 1 MPa on the internal flange part main hole was applied, an ~25 MPa hypothetical compensating pressure and a 200 N bolt pretension, with the flange bottom clamping holes fixed;

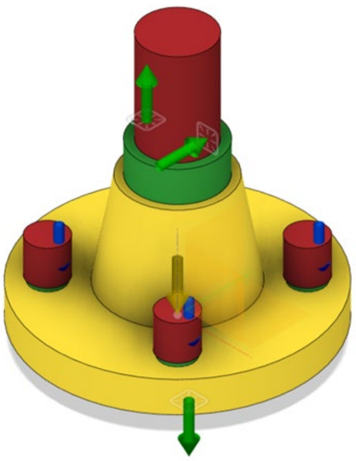

Fig. 4. Flange part boundary conditions.

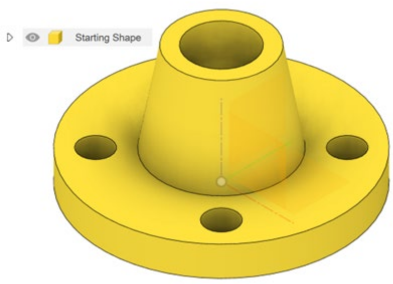

Fig. 5. Starting shape for the flange part generative design.

- *Starting shape* → the main part was divided into several *bodies* so that the part that intersects the preserved geometry can be modified (the yellow part is shown in Fig. 5).

These preconditions form the basis for the generative optimization process of the flange part, but depending on the complexity of the project and the number of desired iterations, this method can vary in accordance with the objectives that must be achieved.

3. RESULTS

Analyzing the generative design results from Table 1 and *2*, we can see how the iterative optimizations led to a significant mass reduction for the nylon and PVC-piping materials, while keeping the strength of the structure at acceptable levels. The safety coefficient did not undergo 1.5 value.

For the nylon material, the mass decreases steadily as the iterations progress, from 0.592 kg in the first iteration to about 0.149 kg in the final iterations. This shows that the software application has removed material from certain areas of the part, minimizing waste and streamlining the design.

Regarding the PVC-piping material, the mass decrease is smaller compared to nylon, but still we observe a similar optimization trend, the mass decreasing from 0.74 kg in the first iteration to about 0.343 kg in the final iterations.

Regarding the PVC pipe material, the mass decrease is smaller compared to nylon, but we still observe a similar optimization trend, with the mass decreasing from 0.74 kg in the first iteration to approximately 0.343 kg in the final iterations.

Table 1

Generative design study results of the flange part made of Nylon material

Iteration	Nylon		
	Mass [kg]	Max. Von Mises Stress [MPa]	Max. Displacement [mm]
1	0.592	28.501	0.853
2	0.599	25.366	0.761
3	0.570	24.281	0.713
4	0.506	25.756	0.709
5	0.438	27.856	0.705
6	0.378	31.522	0.710
7	0.337	34.443	0.742
8	0.290	39.777	0.795
9	0.251	45.161	0.860
10	0.265	37.398	0.786
11	0.264	36.915	0.768
12	0.258	37.272	0.765
13	0.249	38.051	0.770
14	0.241	38.461	0.776
15	0.233	38.853	0.783
16	0.225	39.573	0.790
17	0.217	40.092	0.800
18	0.210	40.582	0.809
19	0.202	41.365	0.822
20	0.191	43.250	0.850
21	0.180	44.837	0.882
22	0.169	46.103	0.916
23	0.161	46.933	0.948
24	0.153	46.933	0.982
25	0.148	46.933	1.002
26	0.146	46.933	1.000
27	0.146	46.933	0.991
28	0.147	46.933	0.980
29	0.148	46.933	0.967
30	0.149	46.933	0.960
31	0.149	46.933	0.951
32	0.150	46.933	0.945
33	0.150	46.933	0.944
34	0.149	46.933	0.943

The Maximum Von Mises Stress of the flange made of nylon increases as the mass decreases. This suggests that the material has been reduced in less stressed areas, but with a compromise in stress distribution. The maximum stress value remains below the yield strength of the material (46.933 MPa) in all iterations.

The maximum displacement for nylon gradually increases from 0.853 mm in the first iteration to about 1 mm in the final iteration. This displacement increase suggests greater flexibility of the part following mass optimization, but this value remains within acceptable deformation limits. Figure 6 shows some of the iterations automatically generated by the software.

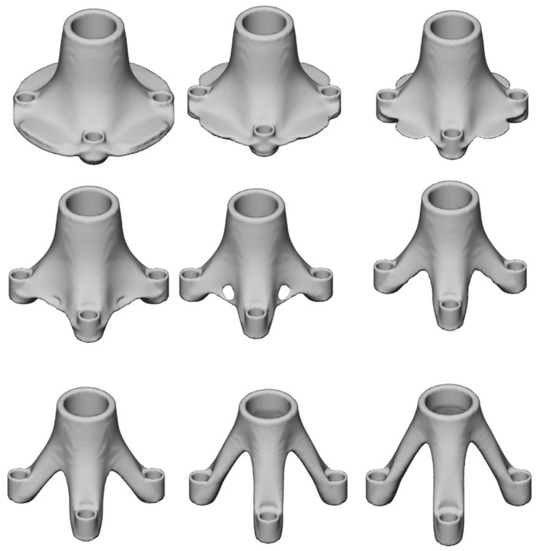

Fig. 6. Various iterations created with generative design.

This method demonstrates the effectiveness of using generative design to reduce component mass without significantly compromising structural integrity.

The Maximum Von Mises Stress of the PVC-piping material also increases about 31 MPa, but this value remains stable in the final iterations, indicating that the design has been optimized to a safe and stable stress level.

Maximum displacement for PVC-piping varies slightly, but stabilizes around 0.514 mm, which denotes a balance between strength and flexibility.

Figure 7 shows two iterations that would not be suitable for additive manufacturing due to residues around the clamping holes. In addition, Fig. 8 shows two iterations exported to the STEP file that can be used in other CAD software to generate other studies.

Fusion 360 software optimizes design by removing material from less demanding areas while maintaining safety margins.

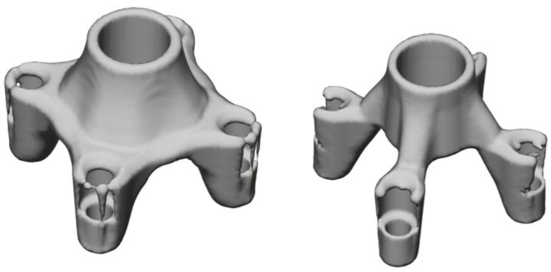

Fig. 7. Iterations not suitable to be manufactured.

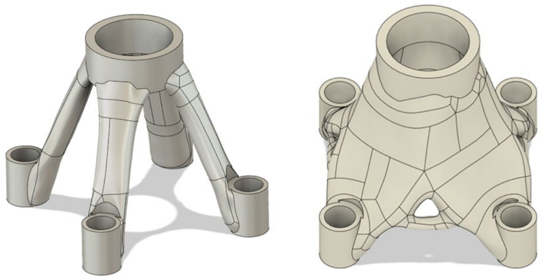

Fig. 8. Exporting models in STEP formats.

Table 2

Generative design study results of the flange part made of PVC material

Iteration	PVC - Piping		
	Mass [kg]	Max. Von Mises Stress [MPa]	Max. Displacement [mm]
1	0.740	28.240	0.64
2	0.701	23.563	0.571
3	0.615	24.464	0.589
4	0.521	26.809	0.623
5	0.441	30.588	0.663
6	0.445	29.246	0.625
7	0.432	29.164	0.606
8	0.425	29.272	0.587
9	0.408	29.565	0.576
10	0.397	29.628	0.564
11	0.380	29.818	0.558
12	0.367	30.420	0.551
13	0.355	31.020	0.546
14	0.351	31.020	0.538
15	0.345	31.020	0.534
16	0.346	31.020	0.528
17	0.348	31.020	0.524
18	0.345	31.020	0.522
19	0.343	31.020	0.522
20	0.341	31.020	0.521
21	0.346	31.020	0.561
22	0.351	31.020	0.512
23	0.352	30.803	0.510
24	0.349	31.020	0.511
25	0.346	31.020	0.512
26	0.342	31.020	0.515
27	0.342	31.020	0.515
28	0.343	31.020	0.514
29	0.344	30.808	0.513
30	0.343	31.020	0.514
31	0.344	31.020	0.513
32	0.342	31.020	0.514
33	0.343	31.020	0.514
34	0.343	31.020	0.514

The results are consistent with the help of this case study, which aimed to reduce material waste through generative design, providing lighter and more sustainable components. In Fig. 9, one can see the Von Mises Stress distribution along two software generated iterations.

FDM printing enables the creation of optimized parts with complex shapes and lightweight structures through careful substrate preparation, part orientation and infill density adjustment, thus ensuring efficient and sustainable manufacturing.

To print generative flange designs on an FDM three-dimensional printer such as those provided by the Creality company, is essential to optimize both the model and the print settings to save material and time while maintaining the final quality of the part. Before printing

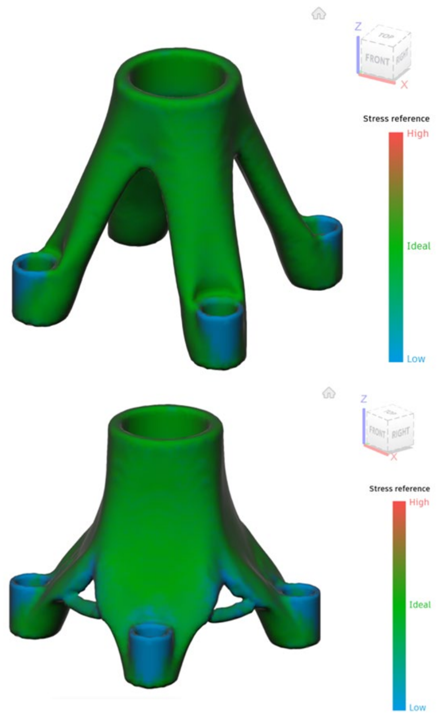

Fig. 9. Von Mises Stress distribution of two design iterations.

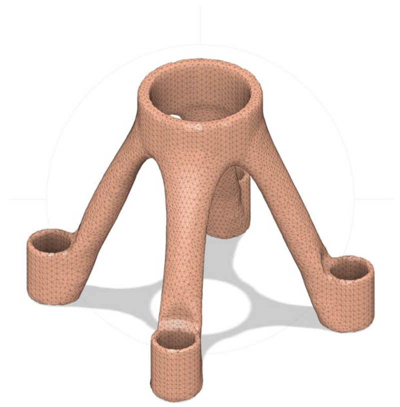

Fig. 10. Preparing the model for 3D printing with FDM technology (exporting the CAD model in STL file).

begins, the model must be strategically oriented in the Creality Print 5.1 slicer to reduce the supports required (if necessary) and choose the angles that allow optimal support without adding extra material. Also, the infill density can be reduced to about 15–20%, enough for a strong but lighter flange, and by using *gyroid* or *triangular* patterns, stiffness can be maintained without excessive consumption of filament.

Figure 10 shows the STL model format exported to be prepared in the Creality Print 5.1 slicer software.

The number of outer perimeters can be adjusted to 2–3, which gives part stability without adding unnecessary layers. The Creality three-dimensional printers can also print at high speeds, thus preserving the quality of the outer surface. The rafts should be used minimally and placed only where strictly necessary (as shown in Fig. 11). Some slicers, such as Cura, allow the use of tree-like rafts, which effectively support the part, while consuming less material than traditional straight rafts.

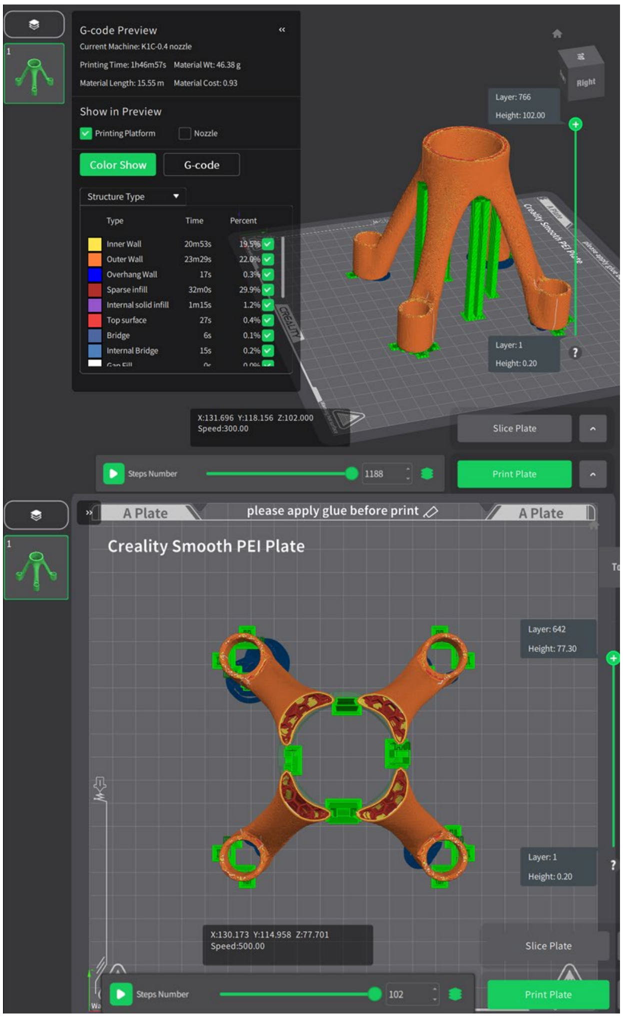

Fig. 11. Preparing the flange design gcode in Creality Print software.

Regarding the layer height, users can select a higher value, for example 0.3 mm, for sections that do not require fine details, thus saving time and material, while layers of 0.1–0.2 mm can be used for portions that require precision.

Another parameter to adjust is the extrusion rate (extrusion multiplier), because setting it to a lower value (about 90–95%) will prevent excessive extrusion and help reduce material consumption. Post-processing, such as raft removal and surface finishing by sanding, can be used to improve the appearance of the part. Also, applying a layer of resin or special paint can strengthen the part without adding material to the printing process.

With these adjustments, the Creality three-dimensional printers will be able to produce a generative flange design with efficient filament consumption, reducing production costs and time without compromising the performance of the final part.

4. CONCLUSIONS

This case study demonstrates the potential of generative design in optimizing mechanical structures to reduce material waste, improving the efficiency and sustainability of the manufacturing process. By using software applications such as Fusion 360 to design flanges from plastics such as nylon and PVC, a significant reduction in the part's mass was achieved while maintaining their strength and functionality. Through successive iterations, the software removed material from less stressed areas and optimized the structure to balance stress and displacement within safe limits.

The results highlight the advantages of using generative design in industrial design: reducing costs, decreasing material consumption and promoting sustainability through lighter and more efficient parts, being an extraordinary solution for additive manufacturing such as FDM technology. Thus, generative design represents a promising methodology for the future of engineering, offering innovative solutions to the economic and ecological challenges of the modern manufacturing era.

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