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Material Optimization, Reverse Engineering and Rapid Prototyping of a Handmade Shaver*

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Abstract: This study investigates the optimization of materials for a hand-crafted razor using innovative additive manufacturing techniques. It reviews previous patent designs to avoid replicating existing ones. Subsequently, a preliminary razor drawing was created based on hand biomechanics to determine compatible hand grips. This process culminated in a functional prototype, digitally rendered using a FARO Edge E09-05-17-32364 scanner supported by point cloud data. Various Computer Aided Design (CAD) software's were utilized to generate a digital model saved in an STL file format. Employing Fused Deposition Modeling (FDM) with ABS and PLA, alongside Stereo-lithography/Digital Light Processing (SLA/DLP) with resin technologies, the final prototype was produced, achieving a 45% material optimization in the handle. Additionally, gripping system for the razor blade was designed at the shaver's tip, ensuring secure closure a satisfactory performance.

Keywords: Additive Manufacturing; Industrial Design; Reverse Engineering

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Optimización de materiales, ingeniería inversa y creación rápida de prototipos de una afeitadora hecha a mano

Resumen: Esta investigación trata de la optimización del material de una navaja artesanal, mediante técnicas novedosas de manufactura aditiva. Se inició con la búsqueda de diseños con patentes, para no incurrir en copia de objetos similares. Se continuó con el boceto de la pieza tomando en cuenta la biomecánica de la mano para determinar los tipos de prensa a utilizar, para generar un prototipo funcional, el mismo que se digitalizó mediante un escáner FARO Edge E09-05-17-32364 apoyado en la nube de puntos y combinando *softwares* de diseño asistido por ordenador (CAD, por sus siglas en inglés), para generar un modelo digital en archivos STL. Mediante tecnología de modelado por deposición fundida (FDM, por sus siglas en inglés) con ABS y PLA, junto con tecnologías de resina estereolitografía/procesamiento de luz digital (SLA/DLP, por sus siglas en inglés), se fabricó el prototipo final con una optimización del 45% de los materiales en el mango. Mientras que a la punta de la afeitadora se le diseñ*ó* un sistema de agarre para la hoja de afeitar mediante un cierre firme y satisfactorio.

Palabras clave: Manufactura Aditiva; Diseño Industrial; Ingeniería Inversa

Optimização de materiais, engenharia reversa e criação rápida de protótipos de uma navalha feita à mão

Resumo: Esta pesquisa trata da otimização do material de uma navalha artesanal, utilizando técnicas inovadoras de manufatura aditiva. Iniciou-se com a busca de designs com patentes, para não incorrer na cópia de objetos similares. Continuou-se com o esboço da peça, levando em consideração a biomecânica da mão para determinar os tipos de prensa a serem utilizados, a fim de gerar um protótipo funcional, que foi digitalizado por meio de um scanner FARO Edge E09-05-17-32364, apoiado na nuvem de pontos e combinando softwares de design assistido por computador (CAD), para gerar um modelo digital em arquivos STL. Utilizando a tecnologia de modelagem por deposição fundida (FDM) com ABS e PLA, juntamente com tecnologias de resina estereolitografia/processamento de luz digital (SLA/DLP), foi fabricado o protótipo final com uma otimização de 45% dos materiais no cabo. Enquanto isso, na ponta da navalha foi projetado um sistema de fixação para a lâmina de barbear, garantindo um fechamento firme e satisfatório.

Palavras-chave: manufatura aditiva; design industrial; engenharia reversa

Introduction

Innovation in the industry aims to enhance product quality through material optimization and reduced production times, leading to decreased manufacturing costs and increased sales. The concept of optimization, originally rooted in mechanical design problem-solving, has now expanded to various physical disciplines. Topology optimization focuses on improving structures within defined constraints, to find an optimal geometry with maximum rigidity and minimal imprecision, disregarding manufacturing considerations. Various methods for topology optimization have been proposed, including density-based method, Evolutionary Structural Optimization (ESO), Level Set Method (LSM), and Bidirectional Evolutionary Structural Optimization (BESO). Density and evolutionary approaches use simple design variables, while the level set approach, being two-dimensional, combines topological derivatives and shape derivatives for optimization [1,2].

Topology optimization through numerical analysis can be resourced-intensive due to numerous iterations. Machine Learning (ML) algorithms have been developed to provide almost instantaneous solutions to various applications, including topology optimization [3].

Additive Manufacturing (AM) is a technology that facilitates this process, introducing new design structural constraints and manufacturing possibilities. AM optimizes, transforms, and innovates in product development, overcoming limitations of traditional subtractive manufacturing. It offers greater design freedom, enabling customized and environmentally efficient objects with complex geometries and lower energy consumption, leading to reduced carbon footprint. The cost structure differs due to reduced raw material usage and supply chain efficiency [4]. AM combines Mechanical Engineering for feasibility studies, CAD for Modeling, and CAM for 3D Printing, ensuring standardization across manufacturing methods [5]. A data flow is established from material selection to product manufacture, utilizing dynamic geometry and precise modeling for mechanical-structural analysis and material optimization [6,7].

AM fabricates parts layer by layer, enabling the production of complex structures, particularly for topology optimization. Consequently, it has become a standard technique for creating multifunctional, lightweight, and high-performance structures [8,9]. The complexity of components no longer a leading indicator of manufacturing costs, which has led to increased popularity in various sectors and industries [10,11].

Various polymers are commonly used in additive manufacturing, producing lightweight, functional, and cost- effective products faster than conventional processes. The promotion of low-cost 3D printers has facilitated more efficient procedures, particularly useful for decentralized manufacturing.

Digitalization and reverse engineering

Three-dimensional product design has undergone significant advancements through CAD, CAE, and visualization methods. These tools enable the creation and animation of images, while calculations can be perfomed, and object properties studied simultaneously with CAE, allowing for editing throughout the process. Achieving digitization requires providing relevant data for objects to be processed by suitable software. The nature of this technology determines the degree of processing effort and the suitability of results [12].

Reverse engineering (RE) has emerged as a primary solution to industrial design challenges, as it facilitates the acquisition of knowledge for reconstruction models used in design, making it one of the key areas of engineering today. RE enables the determination of principal characteristics and functions of processes, systems, or sets, thereby allowing for their reproduction through substitution, modification, inspection, documentation, or development of information for the manufacturing process (Londoño et al., 2012). It is a design methodology applicable to products, existing prototypes, or concepts, employing various techniques, guidelines, and theories to enhance understanding of the product in terms of shape, physical properties, and manufacturing and assembly methods.

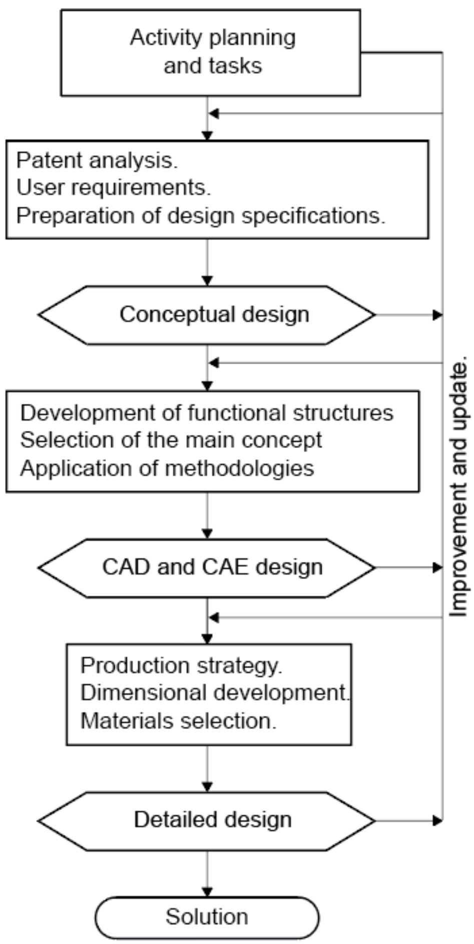
Multiple engineering disciplines converge to find solutions through CAD/CAM/CAE, which can then be developed rapidly, optimally, efficiently, and at low cost. Reverse engineering can extract design information from source code, recognizing that the complexity of the digital tool and its human analyst work together as a single unit, with the directionality of the process being highly variable [13].

Reverse engineering has become a primary solution to industrial design challenges, facilitating the acquisition of knowledge for reconstructing models used in design and positioning itself as one of the main areas of engineering today.

Materials and methods

The applied methodology is detailed in figure 1.

Figure 1. Methodology



Source: Authors.

Results and discussion

To determine the feasibility and level of innovation of the product under research focus, a search was conducted using the patent classifications B26B 21/00, B26B 21/02, and B26B 21/04 across the following databases: International Patent Classification, Google Patents, Espacenet, and Latipat. This search facilitated the discovery and identification of innovations, thereby enhancing knowledge and fostering constructive interaction among technology, businesses, research institutions, and projects [14].

The investigated object belongs to patent class B26, which pertains to hand-cutting tools, specifically subclass B for hand-cutting tools not otherwise specified, and levels numbered 21/00 to 21/56 for straight razors. The search yielded over 10,000 registered patents, which were then narrowed down to 523 active patents for further consideration.

Table 1 provides details of the patent codes and their description.

The proposed object must fulfill various functions tailored to the user's needs as dictated by the industry. This entails industrializing with suitable materials, such as plastic, due to its ease of manufacture and cost-effectiveness, while ensuring efficient ergonomics to provide an adequate grip. Additionally, considerations must be for asepsis, as the selected material will undergo different sterilization methods. Precision is paramount during modeling with specific tools like the bi-digital forceps specifically, the subterminal or fingertip opposition forceps, and the sub-terminal-lateral opposition forceps. Variations such as tetra-digital pulgotri-digital fingertip forceps will also be utilized based on necessity and working angle, given their requisite characteristics to meet user requirements.

Sketches creation

Currently, digital sketches are conducted using graphic tools as the primary means of product development. However, hand-drawn sketches and outlines remain superior in providing spatial representation while tapping into human creativity,

Table 1. Patents

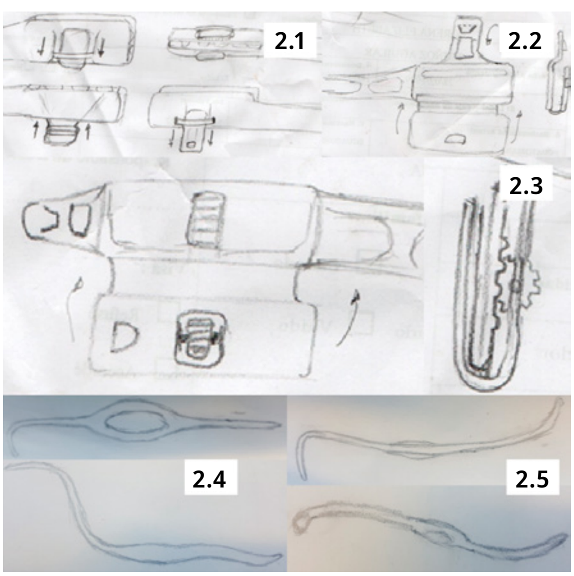
Patent number	Description
US08572953	The invention features tubular elastic handles, such as helical elastic wire springs, and a disposable razor blade. This blade consists of a handle, a blade unit containing at least one blade, and an elastic connection linking the handle to the blade unit.
WO1997044164A1	The invention includes an elastic connection to assist the user in maintaining the hold or head part at a predetermined angle or inclination during use. Additionally, it combines the adjustment of the tool or the head portion with the handle, providing a grip that enables the user to alter their grip during operation.
FR2935920 (A1)	The invention features a system with a V-shaped blade support head, where each branch of the blade support head is equipped with adjustable blades. Additionally, the angle of inclination of the knife-supporting head relative to a handle is adjustable.
EP2962816A1	The invention comprises a fluid extraction and application device, incorporating a hair removal mechanism, a fluid distribution system, a fluid reservoir, and a supporting body. Notably, the supporting body is constructed from cardboard.
WO2017034542 (A1)	The invention is a shaving device featuring a planar body with a groove carved into its contact surface. This groove accommodates a blade bearing surface designed to receive a safety razor blade. Importantly, the blade bearing surface opens into the groove, exposing the cutting edge of the razor blade.
CN106426310 (A)	The invention is a razor with a body featuring a rounded outer surface and an interior rectangular channel with flat walls. These walls define the rectangular channel, extending from the first end of the body to the second end. Additionally, there is a slot through the body in an axial direction relative to the central axis, starting from the first ending at the second end of the body.

Source: Authors

as they tend to inherit certain characteristics from creators [15].

During the preliminary stage, sketches are created by hand. Figure 1 illustrates sketches of the pressure coupling system between two surfaces (1.1, 1.2, 1.3), alongside alternative razor grip designs (1.4,1.5).

Figure 2. Systems for gripping between two surfaces (2.1, 2.2, 2.3, 2.4 and 2.5)



Source: Authors.

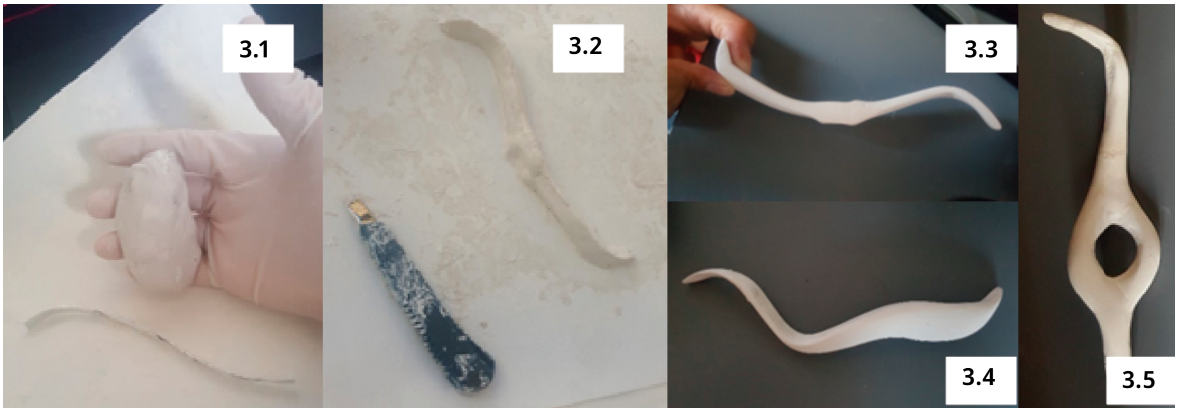
These models were crafted using modeling paste. Figure 2 depicts each steps: 2.1 and 2.2 showcase the aluminum structure crafted for enhanced rigidity; while 2.3 presents one of the models from two different angles, and 2,4 and 2,5 display a second and third model, respectively.

Digitalization and reverse engineering

Prototypes were developed with the main characteristics to arrive at the best working model (figure 3). Options 3.1 and 3.2 display models with a more basic gripping system that do not meet the requirements of an adequate clasp. Option 3.3 meets these requirements in both form and function in terms of the use it is to be given and what is expected from the design.

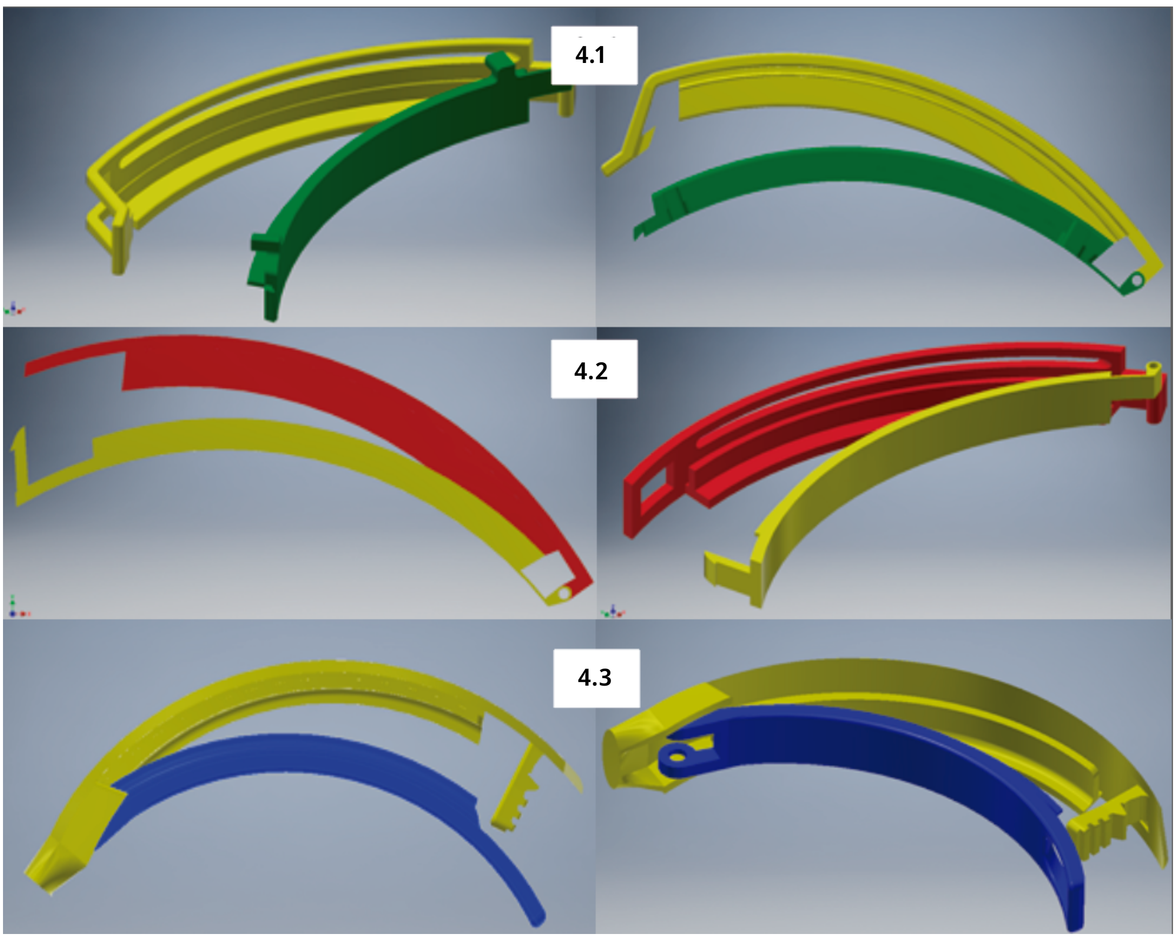
With the aid of a FARO Edge E09-05-17-32364 scanner, the tool was rendered in a digital format with a point cloud, as shown in figure 4 (4.1). The digital model initially presented various imperfections, as shown in 4.2. Following processing with the CAM program, an improved version was obtained, as shown from two perspectives in 4.3.

Figure 3. Experimental models of the prototype (3.1, 3.2, 3.3, 3.4, and 3.5)



Source: Authors

Figure 4. 3D razor-tip models (4.1, 4.2, and 4.3)



Source: Authors.

Razor design

The digitalized object and the specifications for curvature, ergonomics, and anthropometry were divided into three components: handle (1), blade holder (2), and blade holder clasp (3). The handle's curved silhouette is demonstrated in 5.2.

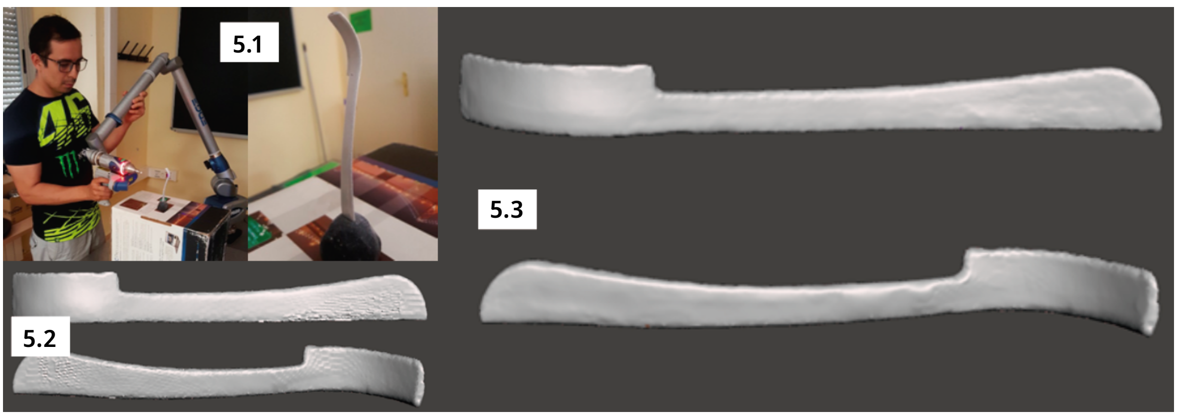
For optimization, we evaluated specialized software to determine the most suitable shape for the razor handle under various loads and fixed supports. We conducted an analysis of all components, including the pivot pin, which serves as the point of union between the two components the razor components. To establish tolerances, Equation (1) was applied:

$$ITn = k(0{,}45\sqrt[3]{D} + 0.\,001D) \qquad (1)$$

Where ITn represents the tolerance in micrometers for quality "n", D represents the extreme values of the geometric measurement of each group of nominal diameters expressed in millimeters, k is a dimensional multiplying factor, and 0.001 D accounts for irregularities measurements that increase in proportionally with the diameter and are noticeable in diameters exceeding 80 mm.

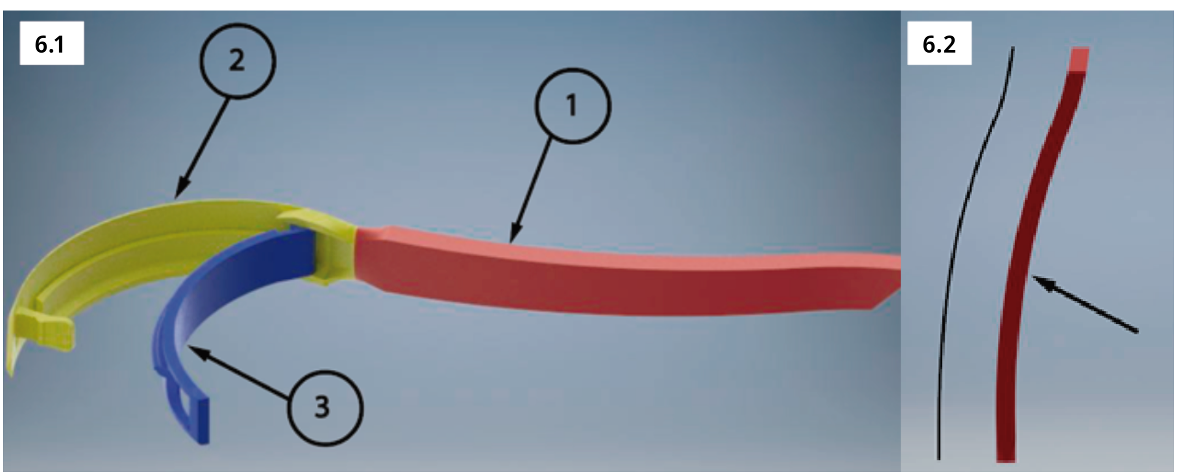
The development of the blade holder was divided into two parts for ease of analysis (*see Fig.* 6): *Fig.* 6.1 illustrates the snap-fit mechanism, which functions as a clasp for the blade, while 6.2 displays the system for embedding the blade and limiting its movements. Additionally, *Fig. 6.3* provides a detailed view of the pivot pin.

Figure 5. Scan of the tool and improvement of imperfections (5.1, 5.2, and 5.3)



Source: Authors.

Figure 6. (6.1 and 6.2) Parts of the razor and silhouette



Source: Authors.

To assess the durability of the component, we calculated the tolerances for the pivot pin and pinhole using Equation (1), resulting in a value of ITn=10.43, as shown in table 2.

Table 2. Pin tolerance quality

Pin (mm)	Hole (mm)
DMax = 2.004	dmax = 2
DMin = 1.994	Dmin = 1.99

Source: Authors.

For the diameter of the pivot pin and hole, Equation (2) was utilized to derive the results:

$$\left.\begin{array}{l} J_M = D_{máx} - d_{min} \\ J_m = D_{min} - d_{máx} \end{array}\right\} \quad (2)$$

The tolerance quality was calculated as IT-7= 16 since the pivot pin diameter was approximately 2 mm. Following the position of the pinhole J was selected as J7 by the tolerance quality. The pivot pin position was set as h = 0 since, in this system, the pin serves as a fixed axis with a movable hole. A statistical study was conducted using pin and hole tolerances of h7 and J7 as variables.

The degree of tightness was not precisely determined but approximated a tightness range of 0.006 and looseness 0.014. Figure 6.4 illustrates the handle component joining to the blade holder. The blade support, depicted in figure 6.5, is where the blade rests, and the angle shown in figure 6.6 describes its usage by barbers (60°).

To facilitate study and description, this part was divided into two sub-components (see Fig. 7). Figure 7.1 illustrates the pinhole, serving as a pivot, with dimensions determined by the tightness calculation outlined in table 1. Figure 7.2 displays the fastening track, exerting pressure on the blade to prevent movement or sliding. Figure 7.3 shows the clip orifice securing the entire component in place.

Figure 8. Razor clasp (8.1, 8.2 and 8.3)

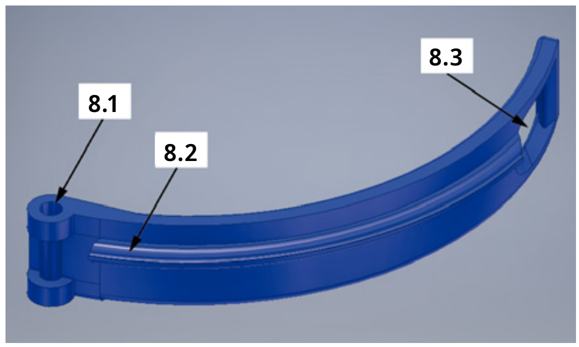


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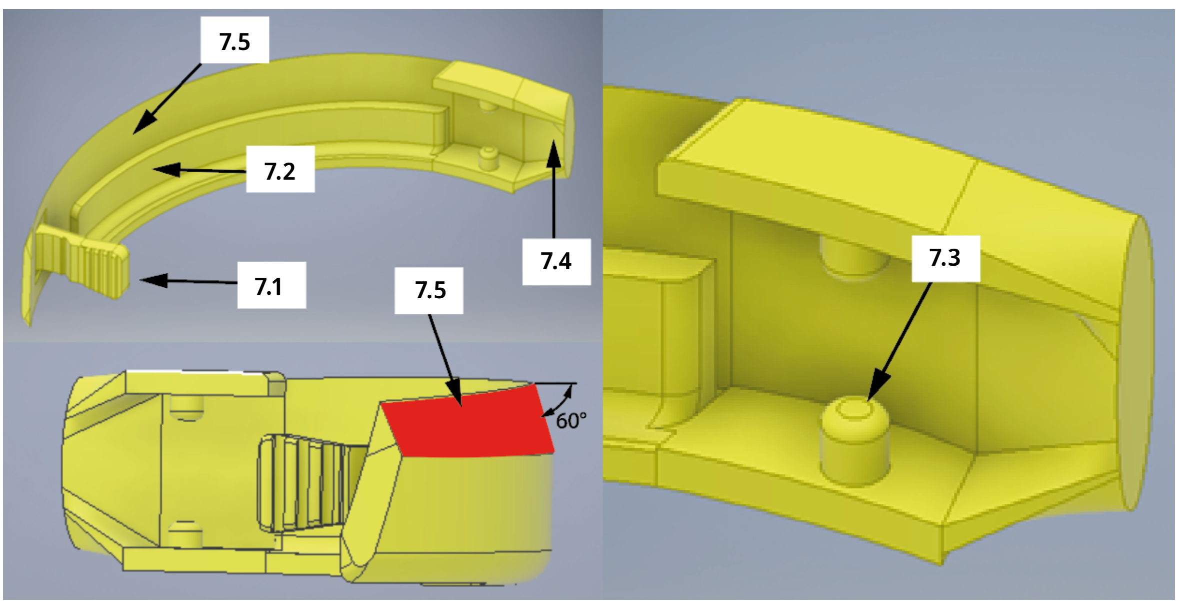
Figure 7. (7.1, 7.2, 7.3, 7.4, 7.5, and 7.6) Detail of the design of the blade holder



Source: Authors.

Optimization and analysis

Effort distribution was obtained through effort analysis (Fig. 8). A 10 N force was applied for effort distribution, following Von Mises guidelines, depicted in the colored scale, with blue representing the fixed area (8.1). This zone functions as a beam, with a maximum value of 34.328 MPa falling within the resistance range of polypropylene (31.3 - 35.9 MPa). The safety factor was also developed based on the characteristics of polypropylene, resulting in values greater than 1 and 4.

Static safety factor analysis relied on the characteristics of polypropylene. Detail in figure 8.2 shows an orange area indicating values between 1 and 4, exceeding the requirement outlined in the LM Guide, Spanish Edition. Figure 8.3 displays the results of the study to determine the lifespan of the snap-fit component. A constant of 10^9 cycles was used with failure occurring at the 3.11^7 time of usage, assuming normal employment of the component.

Using optimization software, loads and supports were placed in various positions along the razor handle. Figure 10 (10.1, 10.2, and 10.3) indicates the placement of loads of 1 MPa on the upper side of the handle, with four points of support shown on the lower side. After running the optimization program, a 33.3% material saving was achieved compared to the original design. Finally, Figs. 10.4 and 10.5 depict the placement of applied forces and supports aimed at improving the derived geometry of the handle. This resulted in a 45% optimization, enhancing the design aesthetic.

Figure 9. (9.1, 9.2, 9.3) Resistance analysis by effort distribution, static security factor and life cycle fatigue

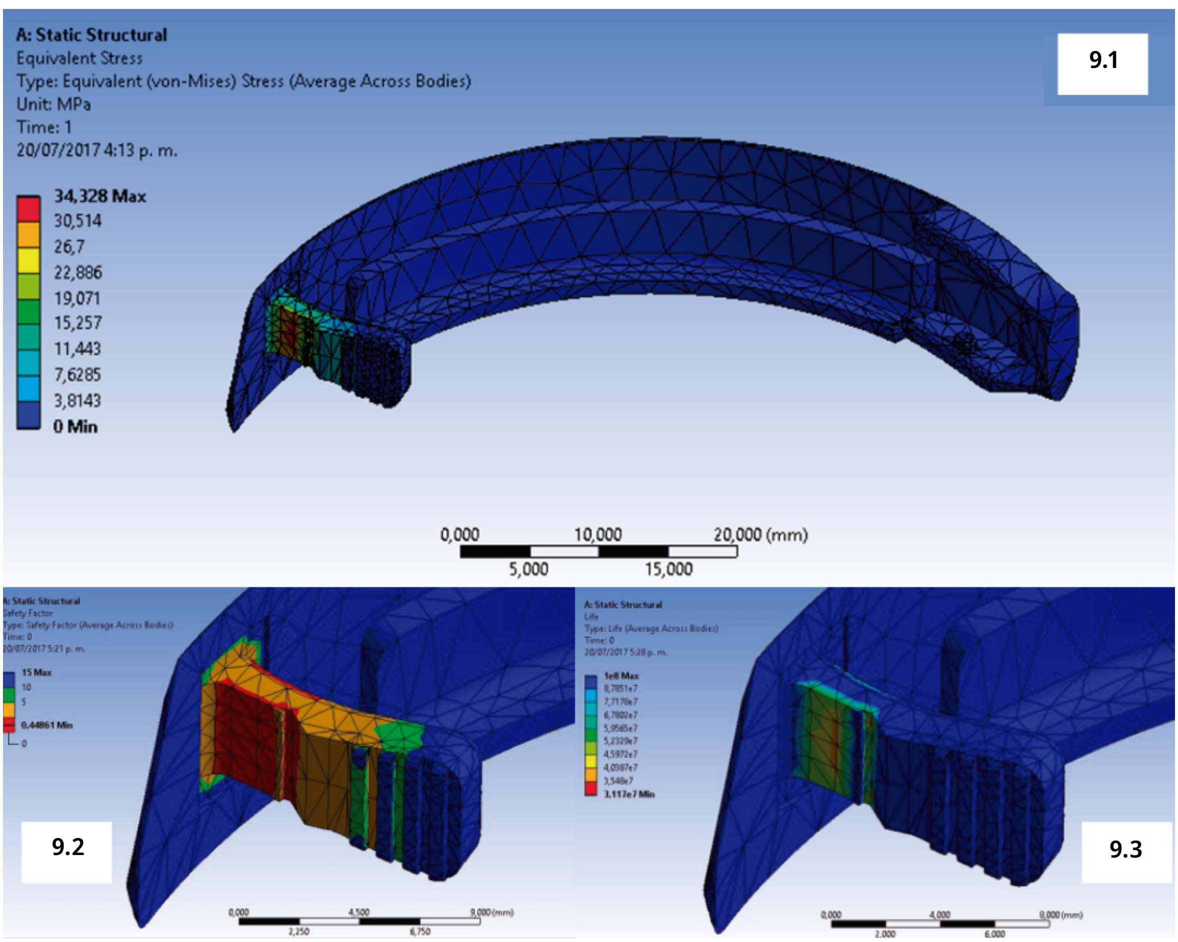


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Figure 10. Process of material optimization of (10.1, 10.2, 10.3, 10.4, and 10.5)

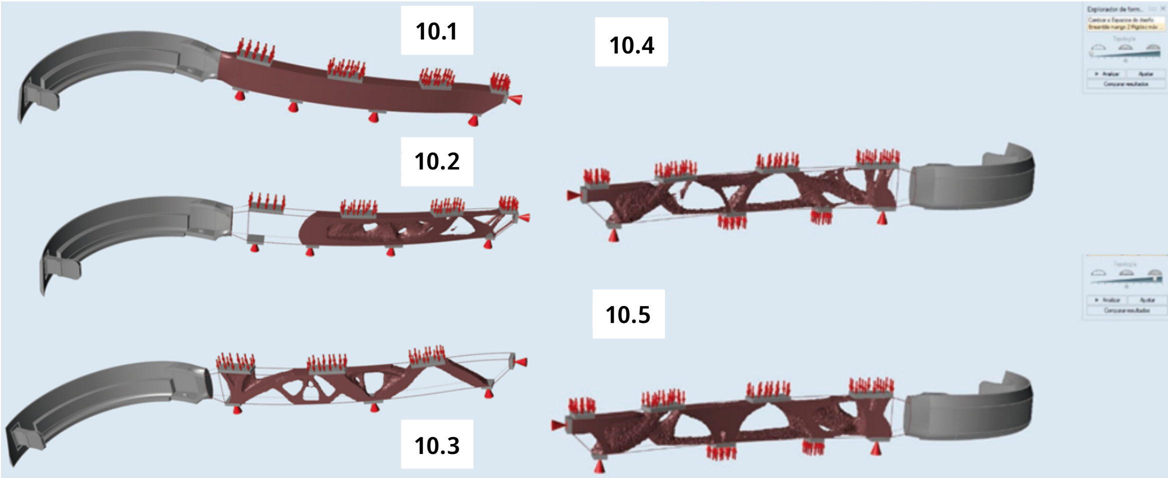

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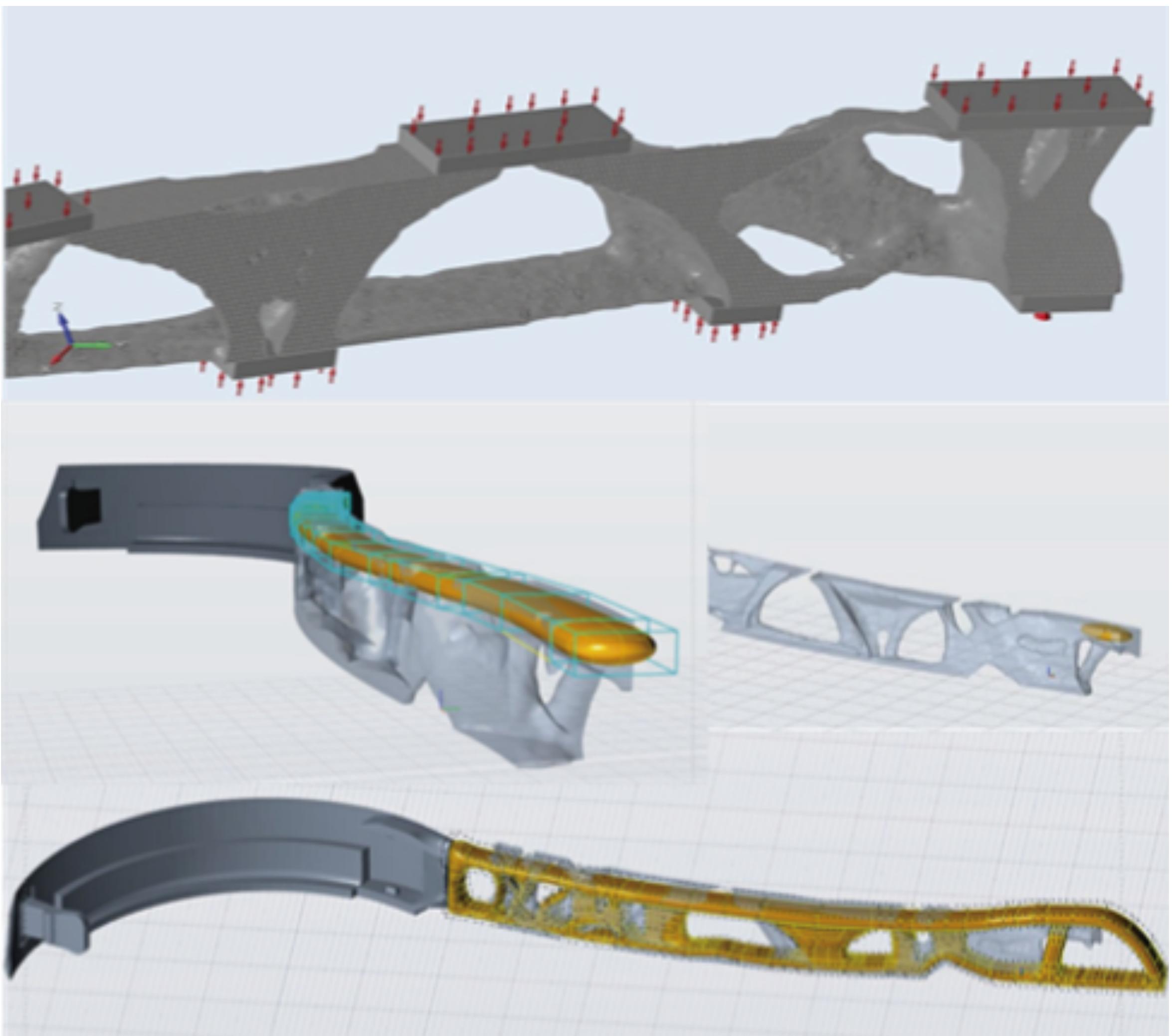
Figure 11. Design based on PolyNURBS



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Utilizing PolyNURBS modeling on appropriate software, a model was developed based on the optimizations obtained in Figure 10. Figure 11 presents various views of the resulting model after considering the optimization limits.

Upon finalizing the optimization process and comparing it with the initial design proposal, the degree of handle optimization was established. This resulted in a reduction of the object's volume, as illustrated in Figure 11. Table *3* details the volume optimization.

Table 3. Material Optimization

Part	Volume (mm³)	%
Handle without optimization	2977,379	100
Handle without optimization	1640,759	55
Optimization	1336,620	45

Source: Authors.

Conclusions

Through patent analysis, the general and specific category of the tool was determined.

By investigating hand biomechanics, the design was adapted to the methods used by the hand to hold objects.

A snap-fit safety clasp was studied to determine the grip of the blade and the type of pivot to be used. The best method was determined to be a hole with a fixed axis pivot, each with a respective tolerance variable of J7 and h7.

Material optimization achieved a 45% reduction in materials used in the handle without affecting the properties and rigidity of the razor.

The model underwent subjected to a structural static analysis with forces higher than those typical use, testing its functionality and resistance. The safety factor (figure 9.2) was found to be greater

Figure 12. Result of handle optimization

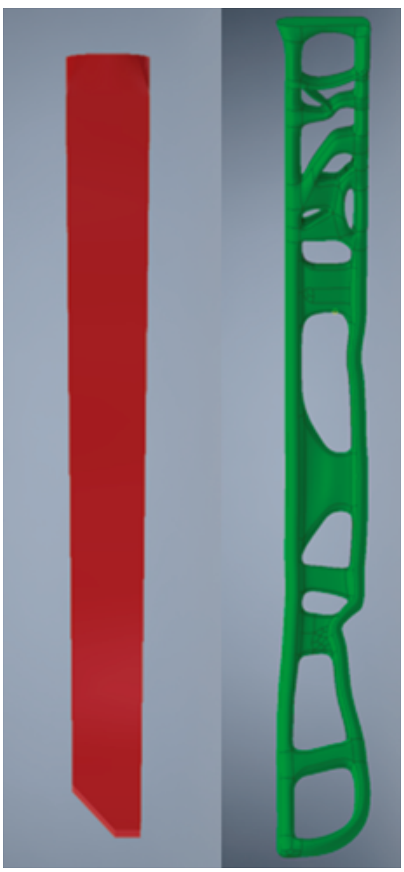

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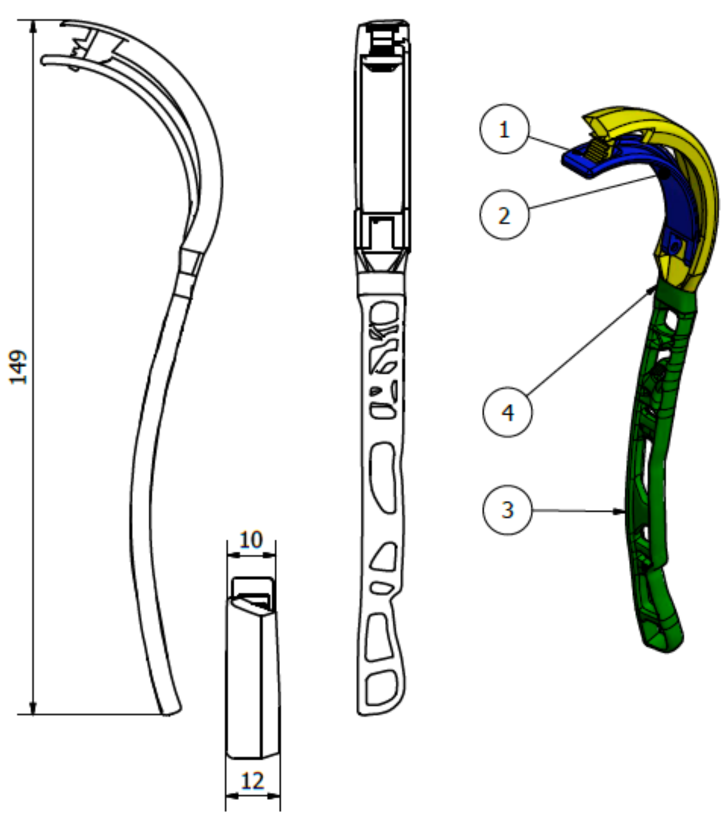
Figure 13. Result of the handle optimization



Source: Authors.

than unity, and the useful life of the model is of adequate duration, greater than 1, as indicated in the LM Spain Guide (2024), classifying it into machine and tool with no vibration or impact..

Utilizing reverse engineering, outstanding attributes were obtained for this hand-crafted razor, forming the basis of a product to be later developed by AM, thereby serving as a real and functional prototype.

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