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Computer-aided engineering: an innovative methodology for the design of agricultural tools for family farming

Ingeniería asistida por computadora: una metodología innovadora para el diseño de herramientas agrícolas para la agricultura familiar

Juan Martin Montoya Fernández[1], **PhD. Germán Leonardo García Monsalve**[1], **Ing. Mauricio Arango Correa**[1], **Santiago Parada Duque**[1]

[1] ***Universidad Nacional de Colombia****, Facultad de Minas, Departamento de Ingeniería Mecánica, Grupo de Investigación de Diseño Mecánico Computacional, DIMEC, Medellín, Colombia.*

Correspondence: *dimec_med@unal.edu.co*

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Abstract: In this study, a manual agricultural tool was optimized using computer-aided design (CAD), computer-aided manufacturing (CAM), and finite element analysis (FEA) technologies, which were carried out in different complementary design stages. The process began with an existing physical prototype, which, through reverse engineering processes, generated a detailed and scaled CAD model with functional design specifications. Subsequently, a low-cost additive manufacturing process (3D printing) was used to create a functional prototype from the previous CAD model. To estimate the mechanical performance and durability of the tool prototype, a Finite Element Analysis (FEA) was performed, simulating the loads it would be subjected to during use. The results obtained through the FEA simulation provided an optimal design for the tool and validated its performance. The tool prototype optimized by these FEA processes was again subjected to 3D printing to generate a functional model for the manufacturing of the agricultural tool through sand casting processes. The tools manufactured in the casting processes were used in conventional agricultural activities, closing the design cycle established in this study. It is concluded that the innovative approach, which combined the stages of computational design and additive manufacturing, offered multiple advantages due to the rapid and economical design iterations before constructing the first tool by casting. Additionally, it facilitated the optimization of the geometry, size, and weight of the tool prototype, considering ergonomic aspects and performance in the projected agricultural activities. Finally, the implemented methodology is viable for the creation of new agricultural tools, avoiding additional high-cost manufacturing processes, such as chip removal machining or mold manufacturing for forging or stamping processes, optimizing the design cost.

Keywords: Design optimization, Design methodology, Finite elements, Additive manufacturing.

Resumen: En este estudio se desarrolló una herramienta agrícola manual optimizada mediante el uso de tecnologías de diseño asistido por computadora (CAD), manufactura asistida por computadora (CAM) y análisis de elementos finitos (FEA) que se llevaron a cabo en diferentes etapas de diseño complementarias. Se partió de un prototipo físico existente que mediante procesos de ingeniería inversa generó un modelo CAD detallado y escalado con especificaciones funcionales de diseño. Posteriormente, se utilizó un proceso de fabricación aditiva (impresión 3D) de bajo costo para crear un prototipo funcional a partir del modelo CAD previo. Para estimar el desempeño mecánico y durabilidad del prototipo de la herramienta, se realizó un Análisis de Elementos Finitos (FEA) simulando las cargas a las que estaría sometida durante el uso. Los resultados obtenidos mediante la simulación FEA proporcionaron un diseño óptimo de la herramienta y validar su desempeño. El prototipo de herramienta optimizado por dichos procesos FEA se sometió nuevamente a impresión 3D con fines de generar un modelo funcional para la fabricación de la herramienta agrícola en procesos de manufactura por fundición en arena. Las herramientas manufacturadas en los procesos de fundición fueron utilizadas en actividades agrícolas convencionales cerrando el ciclo de diseño establecido en este estudio. Se concluye que el enfoque innovador, que combinó las etapas de diseño computacional y fabricación aditiva ofreció múltiples ventajas debido a las iteraciones de diseño de forma rápida y económica, antes de construir la primera herramienta por fundición. Además, facilitó la optimización de la geometría, tamaño y peso del prototipo de la herramienta considerando aspectos ergonómicos y desempeño en las actividades agrícolas proyectadas. Finalmente, la metodología implementada es viable para la creación de nuevas herramientas agrícolas, evitando procesos adicionales de manufactura de alto costo, como el maquinado por arranque de viruta o de fabricación de moldes para procesos de forja o de troquelado optimizando el costo de diseño.

Palabras clave: Optimización del diseño, Metodología de diseño, Elementos finitos, Manufactura aditiva.

1. INTRODUCTION

Family farming (FF), which includes small and medium-scale producers, faces significant challenges due to the reliance on tools that, in many cases, are not adapted to the specific conditions of the land, climate, and crops. Moreover, important technical characteristics such as functionality, versatility, ergonomics, and soil care are often unknown. These tools, which are not widely commercialized with non-mass production methods, have been highly effective in addressing the particular challenges of farmers, as imported tools do not always fulfill specific functions [1].

The introduction of optimized agricultural tools using computer-aided engineering techniques not only predicts improvements in the performance of hand tools but could also assess the increase in productivity that small farmers would achieve without requiring significant investments in heavy machinery. For example, the use of lighter hoes with longer handles instead of traditional ones, considering the user's anthropometric dimensions, has significantly reduced the time required for agricultural tasks and the physical effort required. In situations of scarce resources, family farming households in FF make adaptations to worn tools to fulfill other functions, optimizing financial resources, but this does not necessarily protect the user or ensure soil sustainability. Additionally, the design of specific hoes (push/pull, tines or with wheels) for agricultural tasks such as weeding can save time and increase productivity, provided that the tools are culturally accepted and financially accessible. In the design of hand tools, there are international guidelines and some criteria for their selection in agricultural tasks that should be considered, such as: functionality; energy/power requirements; versatility; working period; costs and durability; maintenance; cultural and anthropometric aspects, among others [1].

Finite Element Analysis (FEA), widely used in mechanical and civil engineering, has been limitedly adopted in the agricultural sector. However, its use in agricultural engineering is relevant, as it allows for the evaluation of the stresses and deformations that a tool could be subjected to during agricultural tasks. This is fundamental for the continuous improvement of designs, as it guarantees the sustainability of the tools, respect for biomes, and an increase in agricultural productivity without expanding cultivated land, as studied by [16].

In the study presented by [5]., the use of CAD, CAM, and FEA technologies has demonstrated its effectiveness in evaluating and predicting the mechanical resistance and durability of manual agricultural tools, subject to fatigue studies. In this study, a detailed methodology is presented to evaluate the stresses and deformations that tools could be exposed to when subjected to real loads, using computational tools for the respective finite element simulations.

This work presents the optimization of an existing prototype of a manual agricultural tool using CAD, CAM, and FEA design tools. The reverse engineering process with a 3D scanner was key to generating the detailed CAD virtual prototype and the corresponding STL file that were used for 3D additive manufacturing processes and for FEA simulations. The reverse engineering process reduced the time required to improve the tool design before generating the final optimized tool prototype. Also, the mechanical resistance of the prototype was evaluated through finite element analysis, considering the soil conditions, functional, ergonomic, and performance aspects in agricultural tasks, validating the design methodology employed. Additionally, the optimized tool prototype, validated and verified in the field, has been manufactured using sand casting processes in small batches, as an alternative manufacturing option to commercial tools obtained through conventional processes. In this sense, the FEA technique allowed for continuous refinement of an existing product, as studied by [7].

2. METHODOLOGY

The following sections describe the stages of the optimization process for an agricultural tool prototype used for CAD/CAM/CAE computational modeling, starting from an existing functional prototype. Figure 1 illustrates the methodology used as a reference for the agricultural tool optimization cycle in a block diagram.

Reverse Engineering: Starting from an existing physical prototype, a reverse engineering process was carried out to generate a digital CAD model that captured the geometric and functional specifications of the tool. This model was validated using Finite Element Analysis (FEA), simulating real working conditions to identify and correct critical areas.

Additive Manufacturing Prototyping: Subsequently, a 3D printing process was used to generate a functional prototype of the CAD model, verifying dimensions and evaluating its physical functionality.

Field Testing: Tests were conducted under real agricultural conditions to verify the prototype's performance. Based on the results obtained, the tool's design was adjusted to optimize its functionality and ergonomics.

Final Manufacturing: Finally, the optimized tool was manufactured using materials that guarantee strength and durability, complying with quality standards for field use.

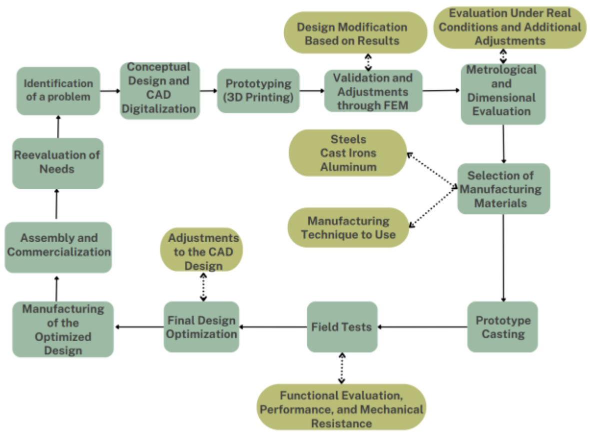

Fig. 1. *Design methodology CAD/CAM/CAE for the design and manufacturing of a manual agricultural tool. Adapted from [14]*

2.1. Stages

2.1.1. CAD Model Development.

The CAD model, a product of reverse engineering within the design phase, was instrumental in digitally reconstructing the physical prototype of the manual agricultural tool for design modifications prior to manufacturing. Leveraging technologies like CAD and FEA, this process enabled the identification and rectification of errors, optimization of geometric features, and assessment of the overall design feasibility, all crucial aspects of optimizing agricultural tool design [18]. Beyond visualization and geometric adjustments, the CAD model facilitated mechanical strength analyses using other CAE simulation techniques such as finite element analysis.

2.1.2. Analysis of the CAD Model in the Preliminary Reverse Engineering Stage.

The initial reverse engineering phase placed significant emphasis on digitizing the physical prototype. The CAD model was generated from physical measurements using reverse engineering techniques such as 3D scanning and manual calculations, resulting in a detailed CAD model (detail design). This digital representation enabled adjustments to tolerances and critical dimensions, ensuring manufacturing compatibility (design for manufacturing), adherence to specified requirements [19], and the prototype's precision and functionality [7]. Figure 1 depicts the digital CAD of the initial prototype serving as the reference for the reengineering process.

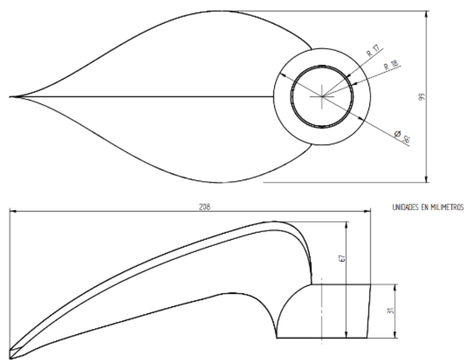

Fig. 2. *Initial engineering drawing of the furrower hoe before the reengineering process.*

2.1.3. Analysis of the CAD Model During the Design and Optimization Process

During the design process, the CAD model facilitated the optimization of the prototype's geometry. This analysis identified interferences and allowed for adjustments to the geometric constraints and dimensions of the prototype, aiming to optimize the design and ensure mechanical properties considering weight, material, and stress concentration zones on the tool, among other properties [8], [5].

2.1.4. Analysis of the CAD Model After Manufacturing.

Once the physical prototype is manufactured in materials such as aluminum or cast iron, it is essential to compare the digital model with the physical one through precise measurements. This comparison helps verify the accuracy of the manufacturing process and make adjustments to the CAD model if deviations in measurements are detected [10]. This approach allows for the correction of minor issues and optimization of mass production, which is crucial in the manufacturing of manual agricultural tools that must withstand severe working conditios [5].

2.1.5. Importance of CAD Model Analysis Throughout the Entire Process.

The analysis of the CAD model in all phases of the tool design process ensured accuracy, efficiency, and functionality. The transformation of the initial CAD model evolved through the design process with iteration, interaction, and collaborative work strategies into an optimized model and/or prototype for manufacturing (design for manufacturing), due to the support in computational modeling received by the integration of CAD and FEA design techniques. This CAD/FEA interaction allowed for the reduction of costs and development times of the prototype design of the agricultural tool [18]. Finally, evaluation by the finite element method allowed for validation and verification of the mechanical conditions of the prototype during the impact of the tip with the ground, simulating real operating conditions in agricultural activities for different materials [5].

2.2. FEM Analysis (Finite Element Method).

The Finite Element Method (FEM) analysis, as previously mentioned, using iterative, interactive, and collaborative strategies between CAD/FEM techniques, has been fundamental for optimizing the prototype in a digital environment through computational simulation processes, saving costs, processing times, and optimizing intermediate and final prototypes. The CAD/FEM computational integration allowed the generation of optimized prototypes/models for 3D printing with low-cost PLA filament (detail design) and those manufactured with metallic materials through aluminum casting, nodular casting, and other steels (design for manufacturing), predicting their behavior and mechanical performance [9] through operational environment simulation. The procedure carried out for the implementation of FEM in interrelation with the reverse engineering stage for the agricultural tool prototype is described below.

2.2.1. FEM in the Preliminary Stage (Reverse Engineering).

In the initial phase of reverse engineering a physical prototype, FEM identified the limitations and critical areas of the reference prototype. This identification guided the improvement and optimization processes towards a structural and functional perspective.

Physical prototype: Before modeling in CAD, the distribution of loads, stress concentration, and defo rmations on the initial prototype were analyzed, co nsidering real conditions, to more precisely establis h the boundary conditions for FEM analysis.

Critical areas: In the physical prototype, the areas subjected to wear and structural damage were analy zed, while the early use of FEM predicted the stres s concentration and deformation areas, directing th e prototype optimization process.

Design improvements: Once the analysis and mea surements of the physical prototype were carried o ut, the CAD model was adjusted, considering the cr itical areas. Subsequently, the improved CAD mod el was subjected to evaluations through iterative FE M processes [17].

FEM analysis in this advanced stage of reverse engineering validated and verified the behavior of the agricultural tool prototype more precisely at the moment of impact with the soil. [12] analyzed the behavior of a subsoiler in non-homogeneous soils with FEM computational modeling, which allowed for the prediction of design failures and adjustments in geometry, improving performance under real conditions.

2.2.2. FEM During the Design and Optimization P rocess.

During the CAD design phase, FEM analysis was used as an iterative and interactive computational technique to optimize the model's geometry, improving the mechanical resistance and durability of the tool. During this iterative and interactive cycle, the weight, size, geometry, and manufacturing cost of final prototypes of the agricultural tool were optimized, simulating severe operational conditions.

Tool materials: The materials defined for computational modeling are the same used in the prototype's manufacturing. The mechanical properties of the tool materials (Young's modulus, yield strength) influenced the FEM models, generating changes in the CAD models [20].

Boundary and load conditions: FEM simulation was carried out considering real conditions during operation, such as the distribution of impact forces, and the reliability of the results depended on the estimation of the same.

Analysis and redesign: FEM results (stresses, deformations, safety factors) were considered to reinforce or not the design of the areas depending on the higher or lower concentration of stresses and deformations according to the established failure theory, which in this case has been Von Mises. This stage was considered fundamental for finding the balance between resistance and efficiency. Topological analysis also played a crucial role, eliminating unnecessary material in areas that did not withstand considerable stresses [12] highlighted the importance of this optimization in the design of agricultural tools through FEM modeling to evaluate and improve the subsoiler's efficiency, ensuring effectiveness in agricultural work.

2.2.3. FEM After Manufacturing.

FEM analysis demonstrated its relevance once the prototype/tool was manufactured. It allowed for the verification and validation of the simulation's accu racy and facilitated adjustments before starting a pr oduction process.

Real tests: After initial manufacturing with materials such as aluminum or cast-iron alloys, for a manual agricultural tool like a hoe, impact tests were instrumented and the results compared with FEM analyses to verify, validate, and/or compare simulation conditions.

Safety factors: Selected safety factors must be validated under experimental conditions for critical areas, and if necessary, adjustments to the CAD model are made before the production process [7].

Quality control: FEM analysis was used to predict fatigue life due to wear on hoes and analyze failures for an average operating time in agricultural work, to make modifications to ensure mechanical resistance to impact with the soil and the reliability of future prototypes/tools [12] evaluated FEM analysis results in identifying wear failures for specific soil conditions, allowing for design adjustments before mass production of tools.

2.2.4. Importance of FEM Throughout the Entire Process.

FEM analysis allowed for reducing the number of physical prototypes and destructive tests, decreasing optimization costs and times. On the other hand, identifying potential failures from the initial design ensured the manufacturing of a safer and more reliable prototype/tool, optimizing material, weight, and geometry.

2.3. Prototyping and Casting.

The manufacturing stage of a manual agricultural tool prototype was considered a critical stage in the development that directly influenced its performance and reliability. Several considerations were taken into account from the reverse engineering stage to the final manufacturing stage, ensuring that each stage of design optimization to production is carried out efficiently and precisely [15].

2.3.1. Initial Manufacturing Process.

3D Prototyping: In this research, the first step in manufacturing in the CAD/CAM interaction and iteration was the creation of a 3D printed prototype using low-cost PLA (polylactic acid). This prototype allowed for the verification of technical, functional, and performance specifications such as size, weight, geometry, ergonomics, mass distribution, contact and wear surfaces, among others, without affecting initial casting costs.

From the CAD design: From the optimized CAD model (final detailed virtual design), a 3D (virtual) prototype was generated, faithfully maintaining the dimensions, shape, weight, geometry, and ergonomics of the final design, yet unvalidated, unverified, and unoptimized. However, this step was key to identifying possible errors and misalignments in the phase prior to FEM modeling, just before its final manufacturing [6].

Prototype evaluation: The prototype was subjected to experimental tests in a controlled environment to verify its functionality and performance considering real operating conditions. This stage allowed for key adjustments and improvements in dimensions, shape, weight, geometry, ergonomics, performance, and mechanical resistance, just before moving on to the final manufacturing stage [3].

2.3.2. Initial Casting Manufacturing in Aluminum, Cast Iron, or Ductile Iron.

After validating and verifying the final 3D prototype, the next step was to carry out an initial functional casting (functional prototype) of the tool in aluminum alloy to evaluate in field tests. However, this initial tool was considered the prototype for casting other materials: ductile iron, cast iron, other cast steels, optimizing costs. This process in the functional prototype manufacturing stage allowed for the evaluation of the tool's real performance in agricultural tasks. It is worth noting that the prototype had been subjected in the previous stage to computational simulation tests to validate and verify its mechanical resistance and performance in a digital environment.

Sand mold casting: For the sand mold casting process, a sand mold was made for the pouring of the molten material to generate the functional prototype of the optimized design. For the aluminum casting prototype, the model corresponds to a 3D printed prototype with PLA filament. This intermediate step of prototype manufacturing (in aluminum casting) was used as models to generate other functional prototypes (cast iron, ductile iron, white cast iron, gray cast iron, steels, among others) for manufacturing manual agricultural tools. This casting technique was used as an economical manufacturing alternative in individual or small quantity molds given its availability [13].

Casting the material: The molten material is poured into the sand mold created in the previous step. Once the material poured into the mold has solidified, the piece or functional prototype is obtained by sand mold casting. The casting material is selected according to the mechanical property specifications to which the final design has been computationally modeled in a virtual environment. Aluminum casting allowed for obtaining pieces with a good weight-resistance ratio, cost-benefit, performance-efficiency, appropriate for manual use tools [2].

Tool finishing: Once the pieces were cast, burrs, defects, and imperfections were removed, and necessary adjustments were made to optimize the tool's geometry. The tool was subjected to initial resistance and performance tests to ensure functionality and reliability in real agricultural tasks [15].

2.4. Design Optimization of the Tool for Small Batch Production (Steel, Cast Iron, White Iron, or Ductile Iron Casting).

Once the functionality and performance of the cast tool were tested, validated, and verified under real conditions, the tool was manufactured in steel or cast iron, with high mechanical properties, reliability, performance, and prediction of infinite fatigue life, suitable for use in high-demand agricultural tasks. The cost of these tools was higher than those made from aluminum casting, more complex to cast, but still competitive with tools produced by traditional processes (forging, bending, stamping) and in mass production.

Field tests: With the results from the aluminum cast prototype tests, the first detailed adjustments were made to the virtual CAD model to improve the tool's resistance, ergonomics, and efficiency, stress and deformation concentration, and some design details such as the edge angles, according to the agricultural application [6].

Production in final materials: Once the final prototype was improved, tested, validated, verified, and enhanced, with some computational CAD/FEM iteration and interaction in its mature final stage, if necessary, the tool is cast in steel or cast iron alloys using sand molds for these materials. This process included rigorous quality control to ensure the tool design specifications were met [13].

Post -casting and finishing: After casting in the final materials, the tool underwent a rigorous surface finishing process to remove burrs, imperfections, flaws, and properly adjust all tools. In critical situations of defects and/or failures, the tools were corrected; however, if the design did not meet these specifications, the tool was rejected [2].

2.5. Importance of the Manufacturing Process in Manual Agricultural Tools.

The manufacturing stage in this agricultural tool optimization process was the final step to consolidate the design of a manual agricultural tool. The process showed that the design developed during the previous stages (CAD/CAM and FEM analysis) generated a tool design that meets the requested requirements of ergonomics, performance, and reliability for demanding work on slopes in AF. FEM computational simulations predicted the functional and reliable mechanical behavior and performance for different materials (aluminum castings, steels, ductile iron, gray cast iron, among others) when the tool tip impacts the ground. Von Mises simulations were used to determine and evaluate critical areas where the highest stresses and deformations concentrate, ensuring that the stresses do not exceed the elastic limits of the selected materials, avoiding premature failures during use [5].

The correct selection of materials, the quality of the casting, and the subsequent adjustments made to the final CAD models and the functional prototypes tested, manufactured by casting processes, validated, tested, and verified through iterative, interactive, and cyclic integration strategies of CAD/CAM/FEM computational tools demonstrated their effectiveness in optimizing the design of agricultural tools. Optimization can perfect the design so that it reduces the physical load on farmers and increases productivity [15].

3. RESULTS AND ANALYSIS

3.1. CAD Model.

Based on an existing physical prototype corresponding to a manual agricultural tool, manufactured through a casting process, reverse engineering techniques were used to scan the tool, generating a virtual 3D CAD prototype, allowing for the detailed parameters of its surface to be obtained. The standardized CAD model taken as the initial reference was used for the analysis and optimization of the tool. Figure 3 shows the resulting 3D CAD model once reverse engineering by scanning has been applied.

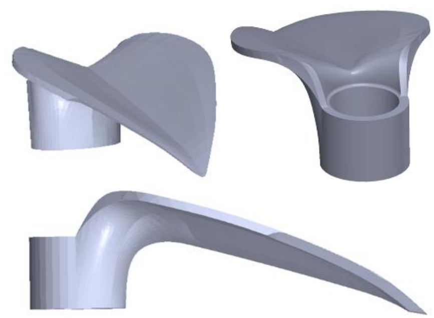

Fig. 3. *Standardized CAD Model [11].*

Based on the generated CAD model, the tool's drawings are obtained. This reverse engineering process saved time in the design optimization cycle, facilitated model adjustments, and reduced the margin of error. After scanning, measurements were corroborated, and necessary adjustments were made, including changes and geometric improvements to the dimensions of the bushing hole where the handle is assembled for standardization. In this case, the internal cone dimension and geometry were modified to a commercial standard size to facilitate the assembly of the commercial handle with the tool, optimized to avoid a negative cultural impact by simply changing a diameter. However, following a guideline for the design of agricultural tools, the handle diameter plays an important role in its design, related to ergonomics when providing an adequate grip according to the farmer's anthropometric dimensions.

3.2. Additive Manufacturing.

The tool's CAD model was used to generate a physical prototype through 3D printing. This prototype allowed for the validation of the tool's dimensions and geometry before proceeding to its final manufacturing. The precision of 3D printing was vital to detect possible inconsistencies or errors in the measurements, which facilitated adjustments in the early stages of the agricultural tool optimization process. Figure 4 shows some prototypes obtained through 3D printing with geometric and dimensional differences that illustrate changes incorporated when computationally interacting with CAD/CAM/CAE computational tools in the optimization stage of a prototype.

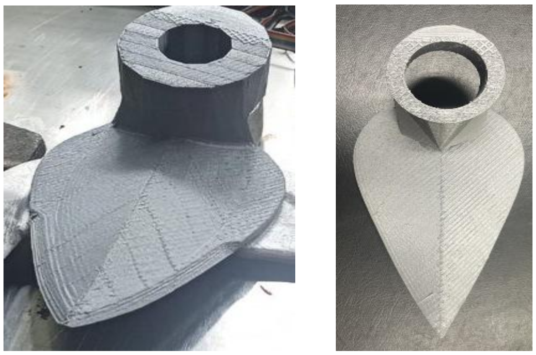

Fig. 4. Initial prototypes through 3D printing (authors).

During the review of the printed prototype, key aspects such as ergonomics and the fit between parts were corroborated, particularly in areas like the bushing hole for the handle assembly, the geometry according to the design specifications, size, dimensional verification, among others. The use of low-cost 3D additive manufacturing with PLA filament allowed for obtaining a physical representation of the design that facilitated the visualization and handling of the tool in simulated use conditions, which helped foresee the tool's behavior in the field.

***Figure 5.** Prototype through 3D printing with corrections in the eyelet dimensions (authors).*

The printed prototype was essential to confirm that the design features met the functional requirement, allowing necessary adjustments before moving forward with manufacturing in final materials, such as changes in the diameter of the bushing hole or the ergonomic geometries that arose after initial changes as illustrated in figure 5.

Figure 6 illustrates a more optimized final design compared to the illustrations of the 3D prints in figures 4 and 5. In particular, the design presents improvements in its geometry, the bushing diameter, and the body. The stress concentration areas have also been improved since figures 4 and 5 have areas near the bushing and the body with high stress concentration because they do not have smooth fillet surfaces according to the section changes. All these improvements were made on the CAD before moving again to 3D printing processes.

***Fig. 6.** Final prototype through 3D printing (authors).*

3.3 Verification through FEM.

Computational analyses indicated that in the prototype of figure 6, the geometry at the tool's tip prevents concentration and favors the distribution of stresses over larger areas, ensuring adequate dissipation of deformation energy during operation. This ensures that the materials remain mainly within their elastic ranges [5].

FEM simulations during the advanced stage of the tool's optimization facilitated the comparative evaluation of the maximum Von Mises stresses that occurred under the same operating conditions in agricultural tasks with tools made from different materials. In the table illustrated in (Figure 7), the maximum stress concentrated on different areas of the tool, applying Von Mises failure theory, does not exceed the elastic stress for any of the evaluated materials.

Material	Von Mises Stress (MPa)	Elastic limit (MPa)
AISI/SAE 4140	16.30	675.00
AISI/SAE 4130	16.30	460.00
AISI/SAE 1060	16.30	427.00
Annealed nodular cast iron	15.17	275.79
Normalized nodular cast iron	15.17	482.63
Aluminum A356 permanent mold cast	8.39	179.01

Fig. 7. *Von Mises elastic stresses for different materials evaluat ed by FEM [5].*

In (Figure 8), using FEM modeling, the areas of maximum stress concentration in the body for a ductile cast iron tool are illustrated, evaluated using Von Mises failure theory. The maximum stress value corresponds to 15.17 MPa, while the yield strength value for that ductile iron casting is 482.63 MPa, indicating that the stresses concentrated in some localized areas on the central rib of the tool and near the bushing where the handle is housed are completely elastic and significantly lower than the yield strength value of the tool material. Therefore, the tool is only exposed to minimal elastic stresses that do not exceed the material's yield strength.

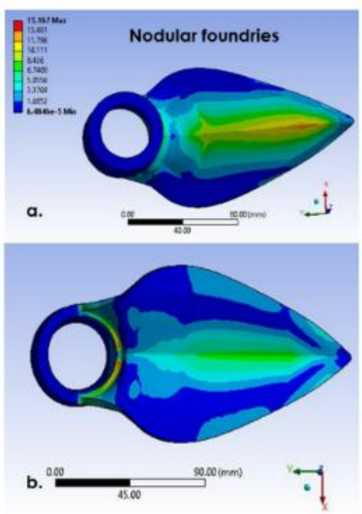

Fig. 8. *Von Mises stresses for a ductile iron casting [5].*

On the other hand, by evaluating the geometry of the tool in (Figure 8) using FEM analysis, it can be verified how the stresses are distributed in certain materials, considering that an operator can apply up to 300 W of power to an agricultural tool at certain times [5]. The results show that the geometry meets the established requirements, confirming the success of the reverse engineering process, from the creation of the CAD model and the 3D prototype to the first manufacturing of the model in an initial material like aluminum.

3.4. Aluminum Casting

Once the final model was obtained from the 3D printing, this prototype was used as a basis for aluminum casting shown in (Figure 9). This step was vital to validate the geometry and specifications of the printed model. The casting allowed for evaluating the design's behavior in a more resistant and suitable material for field use.

Fig. 9. *Aluminum casting prototype, with 3D printed mold (authors).*

The casting process was carried out using a mold created from the printed prototype, thus ensuring that the dimensions and characteristics of the model were maintained in the final piece. This methodology allowed for the confirmation that the design was viable not only in a digital environment but also in real manufacturing conditions. The cast piece was analyzed to verify the accuracy of the dimensions and structural integrity, ensuring it met the necessary requirements for its performance in agricultural work. This validation is fundamental to ensure that the ridging hoe is effective and durable under intensive use conditions.

3.5. Iron Casting

After field tests with the aluminum model, crucial aspects such as ergonomics and the tool's measurements were verified. These tests allowed for the evaluation of the design's performance under real agricultural use conditions, ensuring that the ridging hoe met the functional and comfort requirements necessary for fieldwork.

The results confirmed that the aluminum model was adequate in terms of dimensions and ergonomics. However, to ensure greater durability and resistance, it was decided to perform the final casting in iron, as shown in (Figure 10). This material change responds to the need for a tool that withstands intensive and prolonged work conditions, common in agricultural tasks.

Iron casting will ensure that the ridging hoe maintains its structural integrity, minimizing wear and extending its useful life. This decision aims not only to improve the tool's functionality but also to offer a more robust and efficient solution for farmers.

Fig. 10. *Final casting in ASTM A536 cast iron (authors).*

3.6. Field Tests.

The tool manufactured using nodular casting processes was used in field tests to validate its functionality, performance, and ergonomic posture. The results, according to the soil conditions, showed positive outcomes, which have allowed for final design adjustments, such as handle tightening, scaling, and weight to facilitate specific field tasks. Additionally, the tool was tested by a female community, which has accepted it for processes like fertilizer distribution, soil tillage homogenization, and vegetable cultivation, among others.

Fig. 11. *Farmer woman using the ridging hoe (authors).*

4. CONCLUSIONS

The application of reverse engineering allowed for the efficient development of the CAD model, accurately capturing the dimensions and characteristics of the agricultural tool. This approach optimized the design process, reducing time and margin of error compared to traditional design methods.

The fabrication of a prototype through 3D printing is a crucial stage to validate the design's ergonomics and functionality. Conducting tests on a 3D printed prototype helps identify and correct deficiencies before final manufacturing, ensuring a more effective tool for the target population.

Field tests with an aluminum fabricated prototype confirmed the need to use more robust materials for the final tool. Opting for iron casting ensured greater durability and resistance, aligning with the agricultural sector's requirements.

Finite Element Analysis (FEA) and field tests proved fundamental to guarantee the tool's functionality and safety, ensuring its performance under intensive agricultural conditions. This methodology not only enables the development of more efficient agricultural tools but also establishes a replicable protocol for the design and manufacturing of other manual tools, contributing to improving the productivity and working conditions of farmers.

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Grupo de Investigación de Diseño Mecánico Computacional (DIMEC)
Correos: dimec_med@unal.edu.co; glgarcia@unal.edu.co
Director DIMEC: Germán Leonardo García Monsalve
Teléfono: (+57) 3017215804: (+57) 6044306204

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