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Development of a Beehive Prototype to Produce Honey Through Digital Manufacturing Technologies

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Abstract

The objective of this research is to design and prototype a beehive using computer-aided design software, additive manufacturing technologies, and advanced materials, with the aim of innovating the Peruvian beekeeping sector and producing honey more efficiently, profitably, and sustainably. The Design Thinking methodology was selected due to its effective structure, focused on delivering value to the main users of beehives—beekeepers. As a result, the beehive manufactured through 3D printing matched the honey production performance of a traditional Langstroth hive during the testing period, reaching the established 10 kg per quarter. Advantages were identified in terms of ease of assembly, reduced transport effort, and greater material resistance. In conclusion, the prototype can address some of the current problems in beekeeping and represents a first step in Peru toward more innovative solutions.

Keywords
Beekeeping / Beehive / Digital Manufacturing / Design Thinking / Honey

1. Introduction
Beekeeping is a fundamental activity for both human and environmental existence: it provides food products (honey, nectar, pollen, etc.) with a wide range of health benefits and contributes to the ecosystem by ensuring the presence of many crops and wild plants through pollination (Pignagnoli et al., 2021).

Bees are raised in hives. In this regard, Crane (1994) mentions that in ancient beekeeping, various materials such as wood, tree bark, baked clay, fennel stems, dung, bricks, hollow logs, and pots, among others, were used to build hives. Currently, in Peru, Langstroth hives are used, which incorporate a wooden frame with embossed wax, held by fine wires, which the bees stretch following the hexagonal mold and then fill with nectar until it becomes ripe honey (Root, 2018).

According to MIDAGRI (2021), Peru produces around 2,314 tons of honey per year, placing it behind other Latin American countries. This disadvantageous situation is attributed to the fact that beekeeping in Peru is often combined with other economic activities, and most national beekeepers work with little application of technology.

Benyam Tadesse (2021) contextualizes that, although many basic beekeeping practices have remained similar since foundational studies, there have also been dramatic changes, such as the introduction of new pests, parasites, and pathogens, land use changes that affect bee productivity, and increased stress and pesticide exposure. Due to these factors, overwintering has become even more dangerous, and the loss of managed honeybee colonies poses major challenges for modern beekeepers.

1.1 Objectives
Beekeeping is no longer what it used to beat, faces new challenges. Therefore, this research aims to design and prototype a beehive using computer-aided design software, additive manufacturing technologies, and more efficient, cost-effective, and sustainable advanced materials, with the goal of innovating in the Peruvian beekeeping sector.

Digital manufacturing technologies were proposed to address these challenges by enabling the digitization of three-dimensional objects and their physical fabrication using 3D printers and CAD/CAM software that work in an interconnected manner. These tools feature user-friendly interfaces, intuitive design software, offer online tutorials, allow file sharing over the internet, and even use open-source programs (Fressoli and Smith, 2015). Likewise, innovation based on advanced materials can reshape traditional products (such as beehives), involving lower risk. Ultimately, innovation leads to an improved quality of life for people (Arciénaga et al., 2019).

2. Methods
This study involved applied research of a technological nature, aimed at understanding and improving the performance of traditional hives used in Peruvian beekeeping. Using a multimethod approach that sequentially integrates qualitative and quantitative techniques, the research began with an exploratory phase to identify little-studied issues in Peruvian apiaries, followed by a descriptive approach through data collection and analysis of improvement variables. According to Ñaupas (2013), this type of research does not generate pure knowledge, but is evaluated in terms of effectiveness and efficiency.

The methodology used to design and manufacture this new hive proposal was “Design Thinking,” a discipline that applies the designer’s sensitivity and methods to align user needs (beekeepers) with what is technologically feasible, adding value for both the customer and the market (Brown, 2008).

This methodology consists of five stages, where, if the expected results are not achieved at any point, the process returns to the previous stage, making it an iterative cycle until satisfactory results are obtained. In this way, the process of materializing the beehive ensures that it concludes with a functional prototype that can be validated by the end users (beekeepers) (Mejía-López et al., 2019). The five stages of Design Thinking for the design and materialization of the beehive are described below:

Empathize: Empathy is the process of understanding end users (beekeepers) by analyzing their interests and observing their behaviors (Doorley et al., 2018). For this research, three activities were conducted: interviews, visits to apiaries, and the creation of an empathy map.

Define: In this stage, the empathy developed during the discovery process was interpreted and linked to the information gathered on user requirements (Pérez et al., 2020). This made it possible to identify the beekeepers' problems, which were represented in a cause-effect matrix.

Ideate: This stage focused on seven key aspects integrated into the SCAMPER technique, which encourages divergent thinking to generate a wide variety and quantity of ideas. It also promotes flexibility to reinterpret and reorganize pre-existing ideas, and the capacity to transform information and adapt it to new uses (Galindo, 2019).

Prototype: At this point, ideas become reality. First, the main ideas are designed using CAD software, considering the appropriate component dimensions based on required conditions. Then, the design materialized through the fabrication of components using 3D printing and carpentry. Finally, the beehive is assembled, and the technical features of each part, component, or equipment forming the final product are refined (Mejía-López et al., 2019).

Test: In the final stage, a field test of the beehive was conducted under natural conditions. Photographic evidence was collected, and the results were recorded in a report consolidating the entire process. The amount of honey produced was detailed, and it was determined whether a new test with modifications would be necessary (Mejía-López et al., 2019).

3. Results

Design Thinking methodology was developed to advance in the prototyping of the beehive, achieving its design and materialization. The Figure 1 below summarizes the steps and techniques used in this process.

3.1 Empathize

Information was collected through virtual interviews conducted via the Zoom platform with five specialists. These interviews, based on eight open-ended questions, addressed aspects such as the types of hives used, materials and dimensions employed, harvesting seasons, main challenges in the sector, honey production volumes, and experiences related to innovation in beekeeping.

To complement the interviews, field visits were carried out at two apiaries, which helped validate and enrich the collected information by providing visual and contextual evidence for the study. The first visit took place in the province of Oxapampa, with the collaboration of beekeeper Isaías Roca. The second was conducted in the district of Huarochirí, with the support of beekeeper Román Yacsavilca.

Based on the interviews with the beekeepers and the observations gathered during the field visits, an empathy map was created to better visualize and deeply understand the needs, desires, motivations, and frustrations of the beekeepers.

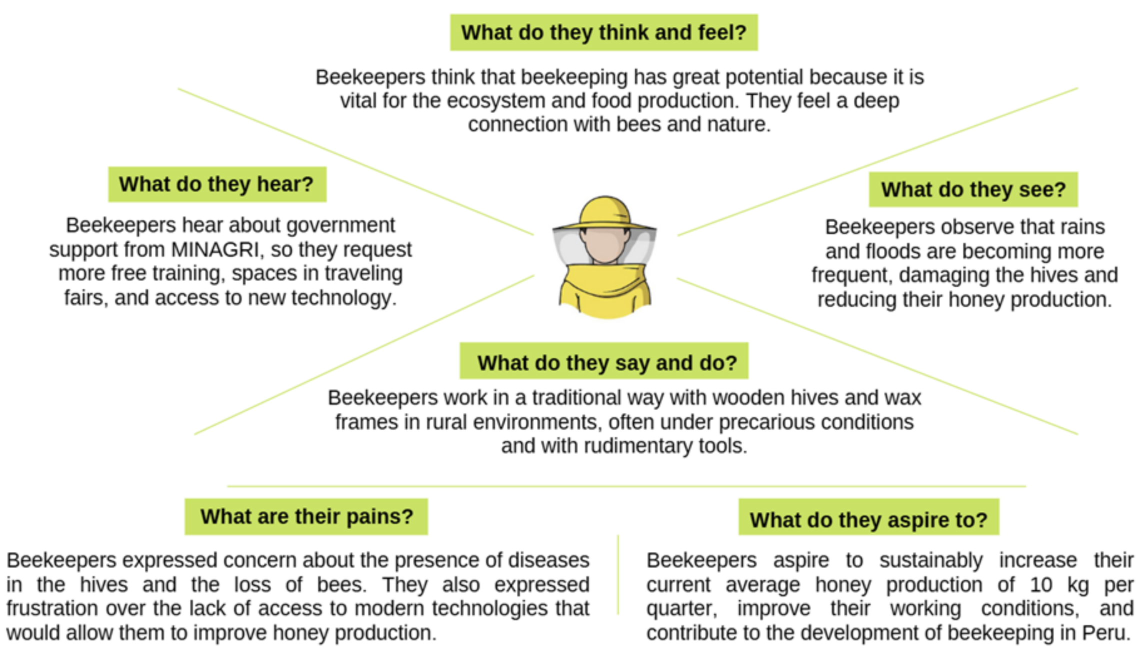

Figure 1. Empathy Map of the Interviewed Beekeepers

3.2 Define

This step aims to identify the core problems and needs of Peruvian beekeepers. These findings will be graphically presented in a cause-and-effect diagram, known as an Ishikawa diagram.

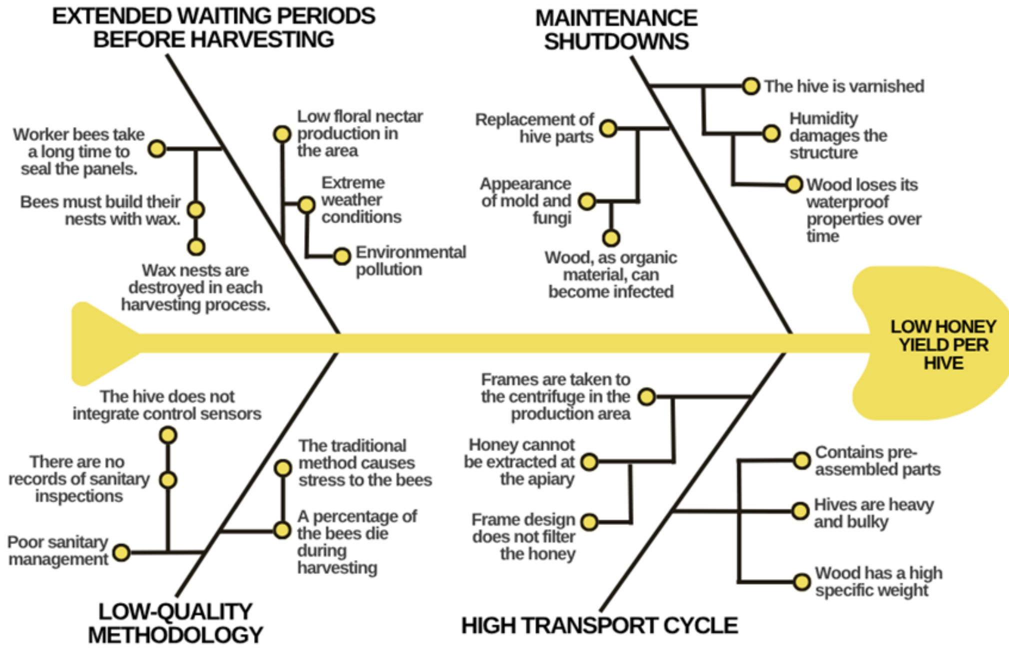

Figure 2. Ishikawa Diagram Applied to the Traditional Beekeeping Production Process

These identified causes have a direct impact on honey production and the well-being of beekeepers (Figure 2). Defects resulting from a low-quality methodology can affect the final product's quality and customer satisfaction. Therefore, it is essential to consider these causes in the design of the prototype to be manufactured.

3.3 Ideate

Based on the problems and needs identified in the previous section, the SCAMPER technique was applied. This technique, through a series of guiding questions, stimulates innovative ideas to design a beehive that is user-friendly, cost-effective, and environmentally friendly, benefiting both beekeepers and the Peruvian beekeeping sector.

The improvement actions to innovate the beehive focused on addressing the root causes. Below, the SCAMPER technique is presented in a structured format, using specific steps to tackle and question the identified issues (Table 1).

Table 1. SCAMPER Idea Generation Technique

Verb	Question	Proposal	Benefit and reference
Substitute	Can a specific part of the beehive be replaced with a new one?	Replace the wax-printed frame with a food-grade PETG frame with pre-formed cells.	Aims to reduce the time needed for comb construction in the hive. (Van Der Zee et al., 2021)
Combine	Can new materials be implemented together in the same beehive?	Wood can remain as the structure while the walls are lined with polypropylene.	Preserves the bees' habitat and shields the wood from weather. (Van Der Zee et al., 2021)
Adapt	Could changes be introduced to meet new	Integrate fragments of bioplastics derived from mycelium in the	Helps suppress parasitic effects on bees. (Ilgun and Schmickl,

	beekeeper preferences?	brood chamber.	2022)
Modify	Could the appearance of a beehive be changed?	Change the square shape of the hive to a cylindrical one.	Creates biomimicry by raising bees in a semi-natural shaped hive. (Gorrochategui et al., 2022)
Put to Other Uses	Is it possible to use a hive for something it was not originally designed for?	Integrate temperature and humidity control sensors into the hive.	Turns the hive into a tool for monitoring local flora conditions. (Ntawuzumunsi et al., 2021)
Eliminate	What non-essential parts could be removed from a beehive?	Eliminate the metal roof, as it could be integrated into the dome-shaped super.	The dome shape resists environmental conditions better due to its aerodynamics. (Pérez et al., 2022)
Rearrange	Is it possible to deconstruct the hive and its main components?	Innovative spiral-shaped frames can be designed, incorporating a filtration system based on gravity and movement.	Innovates traditional beekeeping by redesigning conventional hives. (National Geographic, 2017)

3.4 Prototype
At this stage, the design and materialization of the beehive were carried out, using as a reference the technical report by Besora (2016), which details the construction of a Langstroth-type hive. Below are the parts of the new beehive to be designed and prototyped:

Brood chamber: This is the part where the queen bee lays her eggs. An improvement was implemented by integrating the base and entrance at the bottom. Structural construction included components such as supports, center, rings, bases, and rails.

Queen excluder: A grid with a spacing of 4.1 to 4.4 millimeters between the bars or support lines is placed, allowing only the worker bees to move up into the super and preventing the queen from laying eggs in that area.

Super: In this section, the worker bees store the honey. It is placed above the brood chamber and is the same size and material. A dome was integrated into the upper part to improve aerodynamics and provide protection from rain.

Frame: A set of hexagonal cells made of wax by the bees. In the study by Smith et al. (2021), a 3D scanner was used to analyze over 19,000 cells, concluding that bee architecture is not perfect, showing three average dimensions of separation between the hexagonal cell walls. The first, 5.4 mm, is intended for storing honey for bee consumption; the second, 6 mm, for worker development; and the third, 6.6 mm, for drone growth.

3.4.1 2D and 3D Modeling
By integrating the solutions proposed through the SCAMPER technique and applying the principle of biomimicry, the 2D and 3D design of the beehive was developed. Inspired by the natural spiral patterns that some bees create in their hives, these structures were replicated in the frames of the super, and the brood chamber cells were adjusted to the dimensions of 5.4 mm, 6 mm, and 6.6 mm, optimizing space and improving honey production efficiency. This biomimetic approach not only aligned the design with the bees' natural processes but also resulted in a stronger and more functional beehive for beekeepers, achieving synergy between nature and innovation.

Below is the 3D design of all the components that make up the beehive, developed using Inventor and AutoCAD software. These tools enabled complete modeling, detailed part breakdowns, and precise drawing management, providing a clear view of both the dimensions and technical specifications of each component, thereby facilitating more accurate manufacturing and assembly (Figure 3).

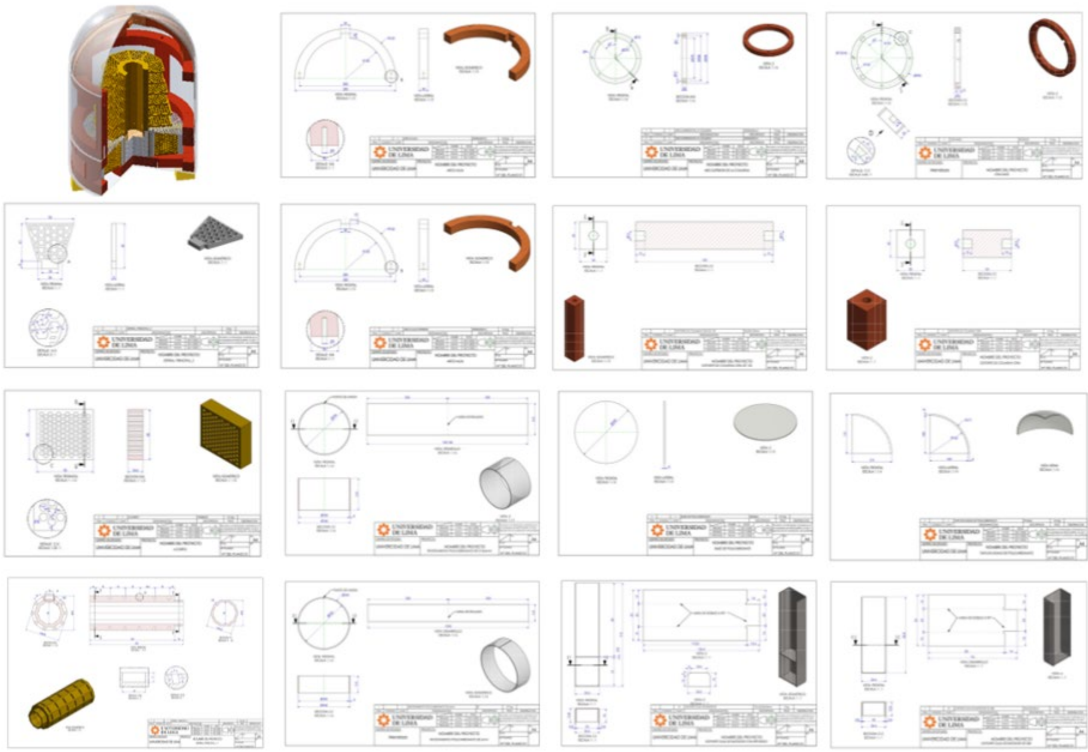

Figure 3. Blueprints of the components that make up the hive process

3.4.2 Manufacturing

This section describes the hive manufacturing process, which involves various materials and technologies. The main steps are detailed below:

Construction of the wooden structural part: Tornillo wood was selected, as it is the most used material in hive construction due to its durability, natural insulation capacity, and ease of woodworking. The wooden pieces were cut according to the dimensions specified in the DXF-format blueprints using a CNC router. Finally, the surface was sanded, and a waterproof treatment was applied to the wood to prevent splinters and improve resistance to moisture.

Polypropylene sheet cladding: TR4 polypropylene sheets with a thickness of 1.5 mm were sourced from the local market, selected for their weather resistance, low weight, and UV protection. The sheets were precisely cut to match the hive structure dimensions.

Manufacturing components by additive manufacturing: To proceed with 3D printing, the main requirements for the filament had to be identified based on the needs of the interviewed. First, it must be suitable for use in the beekeeping industry, requiring food-grade certification. Second, it must be weather-resistant, capable of withstanding high temperatures. Finally, it must be readily available in the Peruvian market and be cost-effective. The PETG filament met all the requirements outlined by the beekeepers. A more specialized operator was also considered necessary, as PETG presents greater printing difficulty compared to PLA and ABS.

Using a 3D printer, the brood and super frames were reproduced as solid three-dimensional objects in STL format by adding PETG filament, layer by layer, extruded through a stainless-steel nozzle. As a result, producing all the parts required 579.40 meters of filament (1.75 rolls) and 105.60 hours of slicing/printing time.

3.4.3 Assembly and Validation

The hive assembly process begins with the integration of polypropylene sheets into the wooden structure using H-profiles that allow for a precise and secure fit through a sliding system. This facilitated the installation, ensuring stable and resistant fastening. This design not only optimizes assembly but also enables interaction between the beekeeper and the internal components of the hive. Subsequently, the brood and super frames previously printed 3D using PETG filament are incorporated. Each frame is fitted and fixed at specific points to ensure its stability within the hive. Finally, a visual and precision inspection is conducted to confirm the dimensional stability of each component and to verify the integrity of the joints.

3.5 Testing

3.5.1 Field Test

An apiary was established to conduct an experimental trial using the following hive configurations: one traditional Langstroth hive; one hive with a traditional honey super and a 3D-printed brood chamber; one hive with a 3D-printed honey super and a traditional brood chamber; and one hive entirely 3D-printed. The field test was conducted from December 2024 to May 2025 in the district of Callahuanca, Huarochirí Province, under the following real climatic conditions reported by the National Service of Meteorology and Hydrology of Peru (SENAMHI):
Temperature: Maximum of 25–27 °C, minimum of 15–17 °C.
Relative humidity: 80%
Precipitation: 3–5 mm, showing a slight increase toward the onset of the rainy season.
UV index: Very high, close to 12, due to greater solar exposure during the summer months.
Wind: Average speeds of 10–15 km/h, with occasional gusts.

3.5.2 Recording and Report

Key factors for bee development were identified in the test hives, such as wax elasticity, thermal variations, and pheromone activity. In the fully 3D-printed hive, the PETG frames initially facilitated oviposition; however, the lack of adequate natural conditions prevented larval development, which, over the course of several weeks, led to a progressive population decline and the eventual abandonment by the queen. This phenomenon was not observed in the hybrid hives—those combining traditional and 3D-printed components—where more favorable outcomes were achieved. A summary of the findings is presented below in Table 2.

Table 2. Prototype Comparison

Variable	**Traditional Hive**	**Traditional Super + 3D-Printed Brood Chamber**	**3D-Printed Super + Traditional Brood Chamber**	**Fully 3D-Printed Hive**
Honey production (kg per quarter)	9.8kg	6.6kg	10.1kg	4.5kg
Weather resistance	Slight moisture accumulation and wood cracking	Slight moisture accumulation and wood cracking	No visible damage; good waterproofing and cleanliness	No visible damage; good waterproofing and cleanliness
Empty hive weight (kg)	16 kg hive	13 kg hive	13 kg hive	7kg hive
Maximum internal temperature (°C)	31,2 ± 1	31,0 ± 1	30,9 ± 1	29,5 ± 1
Minimum internal temperature (°C)	25,9 ± 1	25,6 ± 1	25,4 ± 1	25,0 ± 1

Internal humidity (% RH)	56	57	55	53
Photographic evidence				

4. Discussion

The hive prototype developed in this research demonstrated a productive performance equivalent to that of traditional hives, while also exhibiting qualitative advantages such as greater resilience to adverse conditions and easier handling for beekeepers. These findings are supported by the study conducted by Ishak et al. (2024), who evaluated 3D-printed hives for stingless bees and reported structural improvements in the external box, including increased lightness and strength. Together, both studies validate the potential of prefabricated structures to support proper bee development in artificial environments. However, to consolidate their applicability, it is necessary to extend testing over a complete apicultural annual cycle.

5. Conclusions

The choice of polypropylene as a cladding material proved to be appropriate, as its insulating properties helped maintain stable environmental conditions within the hive, ensuring optimal levels of temperature and humidity. Additionally, its application contributed to a reduction in structural weight, with the 3D-printed hive weighing 8 kg less than the traditional hive—representing a 56.25% decrease in total weight. Favorable results were obtained with the use of prefabricated frames in the honey super, as worker bees were able to successfully deposit honey. This positive response was consistent across all four hives evaluated, supporting the conclusion that it is feasible to implement these frames in hybrid hives composed of both natural and prefabricated elements. The main benefit observed was the reusability of the prefabricated frames in the honey super after honey extraction through centrifugation.

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