

## APPLICATION OF THE FOUR-PHASE MODEL IN THE CONSTRUCTION OF A CNC MILLING MACHINE

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**Abstract:** This work applies the four-phase model—product definition, conceptual design, materialization design, and detailed design—to the construction of a CNC (computer numerical control) milling machine for machining medium-density fiberboard (MDF) parts 2.5–12 mm thick. The work contributes to demonstrating the methodological application established by Pahl & Beitz in a real example of engineering design. The CNC milling machine is constructed with a 20×40 mm and 20×20 mm aluminum structure, as well as 12 mm thick MDF, which makes it possible to machine models from 2D and 3D CAD designs. The effective workspace (x, y, z) is 270×270×50 mm. Parts are machined using the translational movement of the milling machine's movement system on the x-y plane and the height defined on the z-axis, as well as the rotational movement of the cutting system's spindle. Isometric views of the CAD design of the movement systems on the x, y, and z axes and the machining table are presented. The CNC milling machine is controlled by an Arduino Uno card, a CNC shield board for Arduino, stepper motor controllers, and 1.8° stepper motors. All components are commercially available, allowing for the development of a low-cost prototype. Finally, the machine's operating process is described, as well as the process sheet for machining parts.

**Keywords:** CAD design, CNC milling machine, four-phase model.

**Abstract:** In this work, the four-phase model is applied—product definition, conceptual design, materialization design, and detailed design—for the construction of a CNC (computer numerical control) milling machine for machining parts in medium-density fiberboard (MDF) 2.5–12 mm thick. The work contributes to demonstrating the methodological application established by Pahl & Beitz in a real example of engineering design. The CNC milling machine is built with a 20×40 mm and 20×20 mm aluminum structure, as well as 12 mm thick MDF, which provides the possibility of machining models from 2D and 3D CAD designs. The effective workspace (x, y, z) is 270×270×50 mm. The machining of parts is carried out from the translational movement that the milling machine movement system performs on the x-y plane and the height defined on the z axis, as well as the rotational movement of the cutting system spindle. Isometric views of the CAD design of the movement systems on the x, y, z axes and the machining table are presented. The CNC milling machine is controlled by an Arduino Uno card, a CNC Shield board for Arduino, stepper motor drivers, and 1.8° stepper motors. All components are commercial, which allows for the development of a low-cost prototype. Finally, the machine operation process is described, as well as the process sheet for machining parts.

**Keywords:** CAD design, CNC milling machine, Four-phase model.

## INTRODUCTION

The process of creating and developing a product or machine based on specific functions is one of the most complex and interesting tasks in the field of engineering. In this multidisciplinary process, the theory of machines and mechanisms, quality control, calculation and simulation, ergonomics, among others, are integrated to obtain a product that meets the needs of a project [1-5]. Product or machine design methodologies can be classified into two groups (Cross, 2021). The first corresponds to descriptive methodologies, some of which are those proposed by Cross (Cross, 2021), Ferrer Real (Ferrer Real, 2007), French (French, 1971), and Roozenburg & Eekels (Roozenburg & Eekels, 1995). These methodologies focus on describing the sequence of activities as they occur during the design process. The second group corresponds to prescriptive methodologies, which are characterized by being systematic or algorithmic and answering the question "How to do it?" (Romero, Martí, & Romeva, n.d.). Some of the best-known prescriptive methodologies for the product creation and development process are Pahl and Beitz's four-phase model (Pahl, Beitz, Feldhusen, & Grote, 2007), the

Ulrich and Eppinger's design method (Ulrich, 2013), German standard VDI 2222 (Guideline, 1977) and VDI 2221 (Guideline, 1987), among others.

The four-phase model established by Pahl & Beitz for the design of a machine or product has been a benchmark in design engineering and has been applied in different contexts [2,14-22]. It consists of breaking down the design into a series of sequential steps to encourage the generation of multiple solutions, selecting the one that best fits the project objectives (Pahl et al., 2007). The first phase of the model is product definition, where the list of aspects and requirements of the final product is established. This stage is fundamental in the design process, and the result of this stage is a specification document. The second stage is conceptual design, where, based on the product specifications, initial solution alternatives are proposed and evaluated. This stage is also known as product concept. This stage is considered the most critical, as approximately 80% of the product's costs are determined during this phase (Mayda & Borklu, 2014; Pahl et al., 2007). The third stage is the realization design, also called design configuration, which presents an overview of the components, parts, dimensions, materials, among others, for the assembly process. The final stage is detailed design, which consists of defining the final configuration of the parts, such as shapes, dimensions, and design components, as well as the final selection of materials. Product documentation for manufacturing is also prepared, and the results of this activity are provided in the form of part drawings, component lists, and assembly diagrams (Pahl et al., 2007).

The four-phase model is flexible and can be easily adapted to different products and projects (Borges & Rodrigues, 2010; Çavdar, Börklü, Çavdar, & Sezer, 2019; Civelek, Brem, Fritz, & Zimmermann, 2024; Weiss & Hari, 2015), making it a valuable tool in design engineering, where the aim is to develop innovative and competitive products for the market (Civelek et al., 2024; Weiss & Hari, 2015). Different methodologies for product and machine development have been applied in the development and implementation of CNC machines [24-31]. These machines are widely used in industrial manufacturing processes and educational institutions, as they facilitate the precise machining of complex models of parts in materials such as metal, wood, plastic, among others [24, 32-34], increasing mass production by reducing operating times. The machining of parts can be carried out by chip removal through the movement of

mechanically driven rotating tools (Pelayo & Trejo, 2023; Rattat, 2017).

This work applies a four-phase methodology for the design and implementation of a three-axis CNC milling machine for 2.5–12 mm MDF. Control is performed using Arduino Uno (Arduino, 2024) and stepper motors. The CNC milling machine is focused on machining parts using 2D models and aims to meet the need to optimize time, economic resources, and infrastructure for micro-entrepreneurs, artisans, and entrepreneurs who work with low-density materials, such as MDF in thicknesses from 2.5 to 12 mm, improving the quality of the products they offer. Furthermore, the CNC milling machine presented here also aims to provide engineering students with a clear and concise procedure that allows them to develop their own low-cost CNC machine for machining parts based on designs created in computer-aided design (CAD) software that they develop in subjects such as computer-aided design, mechanisms, mechanical element design, and advanced manufacturing, to name a few.

## DEVELOPMENT

This work falls within the quantitative paradigm, with an applied approach that aims to implement a CNC milling machine by applying the four-phase model for product development. The general outline is shown in Figure 1, with the expected results for each stage set out in accordance with Pahl & Beitz (Pahl et al., 2007).



**Figure 1.** *Four-phase model for the design of a machine or product.*

**Source:** Own elaboration based on [7].

**Product definition.** The CNC milling machine must be capable of cutting, drilling, and roughing MDF from 2.5 to 12 mm through movements in space (axes  $x$ ,  $y$ ,  $z$ ), with a maximum cutting area of 27×27 cm. In order to easily transport the prototype, its final dimensions should not exceed 80x80x30 cm. The materials available for the development of the milling machine

These are: 1.8° step motors, 12 V power supply, 12 mm MDF, microcontroller, A4988 motor controllers that integrate two H-bridges (*A4988 Stepper User Guide*, 2024; *CNC/3-Axis Stepper Motor Shield User Guide*, 2024; Culda, Muncut (Wisznovszky), & Erdodi, 2021), toothed belt, worm screw. The CNC milling machine must operate with 120 V AC power and a frequency of 60 Hz with a maximum power consumption of 200 W.

**Conceptual design.** Based on the specifications established in the product definition, the conceptual design is developed, presenting the solution principle and its functional structure (see Figure 2a). The inputs to the CNC milling machine are 120 V AC electrical power, an MDF plate

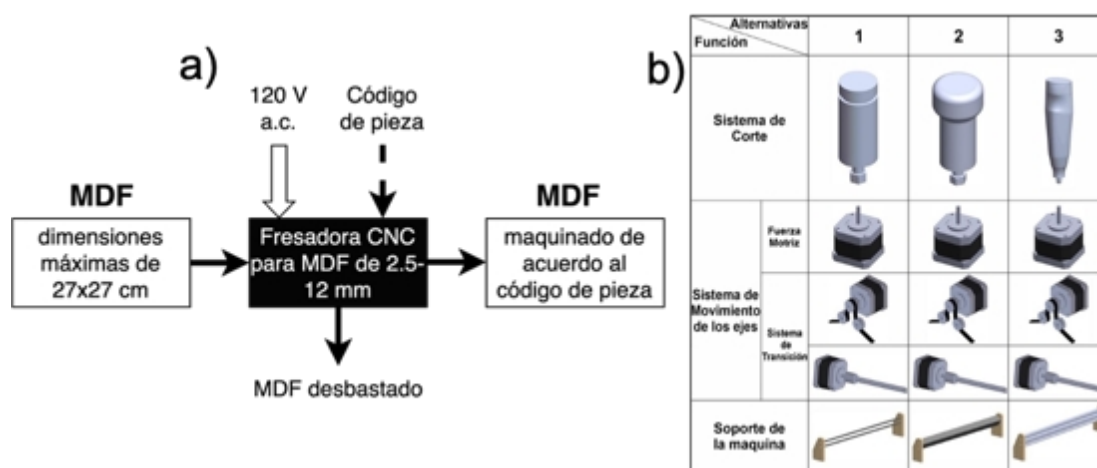
with maximum dimensions of 27×27 cm, and the code for the part to be machined. The outputs are the MDF Machining containing the CAD design and rough-cut MDF.

**Materialization design.** Figure 2b) shows the design alternatives created in SolidWorks (*3D CAD Design Software | SOLIDWORKS*, 2024) for the three main elements of the prototype: cutting system, axis movement system, and machine support. Three options were considered for the cutting system, each involving a particular type of tool. The first is a spindle with a mass of 1.2 kg and a power of 300 W, with an approximate price of \$184 ("300W Spindle Kit for CNC Router Masuter Pro & Masuter 3," 2024). The second is a 1.5 kg router with 550 W of power, priced at approximately \$75 ("Bosch - Router GKF 550 127V 550W with 2 collets: Amazon.com.mx: Tools and Home Improvement," 2024), and the third is a Dremel 3000 with

0.6 kg and 130 W of power, with an approximate price of \$60 USD ("Dremel 3000-N/10 Rotary Tool 3000PA with 10 Accessories: Amazon.com.mx: Tools and Home Improvement," 2024); in all three cases, it is possible to use cutters to make the cut. Regarding the axis movement system, we propose using a motor with a step angle of 1.8° per step and a belt system for the transition system in the three cutting system alternatives. Three design alternatives were also proposed for the machine support: the first considers the use of steel axes, the second is the implementation of square steel tubes, and the third uses aluminum profiles.

After analyzing the power and costs of each alternative for the cutting system, the Dremel 3000 was chosen, as it has the necessary power to cut MDF from 2.5 to 12 mm, is lightweight, affordable, and has the lowest power consumption (Wu, 2023). Furthermore, it is a tool that is no longer than 20 cm and 5 cm wide, making it a tool that optimizes the defined cutting area. Stepper motors are used for the movement system.

1.8° operating at 0.4 A (Jiang et al., 2023), these are sufficient to move each of the axes with good precision. The use of toothed pulleys is also considered for the axes and because they are more economical than a rod. The only additional parts needed are the tensioners to secure the belt and the tension pulleys. A threaded rod is used on the axis  $z$  due to the need to support the additional weight of the Dremel when it moves vertically. As for the machine support of the machine, options one and two use metal bearings that tend to wear out very quickly due to friction. For this reason, the aluminum profile was selected, where plastic wheels can be used, and it can be adjusted more easily compared to the other two alternatives. Based on the above, it is concluded that the best design alternative for the three main elements of the prototype is the one presented in column three (final design).



**Figure 2.** a) Block diagram of the conceptual design. b) Preliminary designs created in SolidWorks (3D CAD Design Software | SOLIDWORKS, 2024) for the cutting system, axis movement system, and machine support.

Source: Own work.

**Detailed design.** The prototype is made with MDF boards because it is an easy material to acquire and handle (Sütcü & Karagöz, 2012). It consists of three stages with the following functions ("Mechanical Design of the Structure for a CNC Router," n.d.): the first consists of providing the movements on the axes  $x$ ,  $y$ ,  $z$  together with the linear sliding system. The second function is to hold the cutting machine, which in this case is a Dremel 3000. The third function is to hold the MDF, preventing it from moving or oscillating when it comes into contact with the cutter. Figure 3a) shows the isometric view of the axis movement system  $x$ , which consists of a stepper motor, a pulley

20-tooth gear, two tension pulleys, 8 V-Slot wheels, 2 M3 screws, 4 M5 screws, 6 M5 nuts, 18 M5 washers, 8 wheel spacers. Linear movement in the horizontal direction involves the use of a sliding system, which provides movement along that direction.

direction. To perform the sliding task, a stepper motor is used, which is attached to plate 2 of the axis with two M3 screws and a 20-tooth pulley attached to its shaft in combination with a 6 mm open Gt2 toothed belt. The freely moving carriage consists of two 12 mm MDF plates joined by four M5 screws, on which the eight spacers with their respective wheels are placed. The four lower wheels use eccentric spacers to adjust the pressure that the wheels exert on the aluminum profiles.

Figure 3b) shows an isometric view of the shaft movement system, which consists of 2 stepper motors, 2 toothed pulleys with 20 teeth, 4 tension pulleys, 4 aluminum profiles 20×40 mm and 50 cm long. Also included are 8 V-Slot wheels, 4 M3 screws, 12 M5 screws, 20 M5 washers, 16 M6 screws, and 8 wheel spacers (not shown in the figure). The

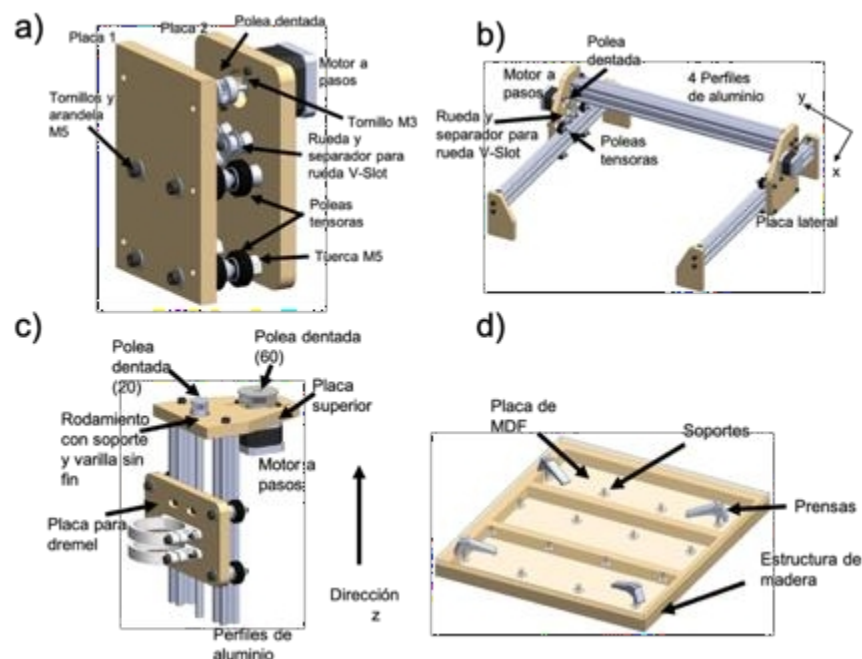
movement in this direction is similar to the movement in the x direction. The system is integrated with a series of V-Slot wheels, which allow translational movement in this direction without any obstruction, also provide stability during machining. The

y movement system is connected to the x movement system by means of two aluminum profiles attached to two 12 mm thick MDF plates called side plates. This axis moves through two profiles driven by two stepper motors with their respective belts. The motors at each end maintain the balance of the entire machine, preventing vibrations.

Figure 3c) shows an isometric view of the movement system on the z axis with the support for the Dremel. This consists of a stepper motor, a 20-tooth toothed pulley, a 60-tooth toothed pulley, a bearing with an internal diameter of 8 mm and another with a support, a worm rod, two 20×20 mm aluminum profiles, and two 25 cm long aluminum profiles. It also includes four V-Slot wheels, two M3 screws, 2 M4 screws, 18 M5 screws, 6 M5 "T" screws, and 2 M5 washers (not shown in the figure). The movement system in the z direction provides vertical displacement and is the responsible for carrying out the cutting depth on the workpiece. This system uses a worm screw that passes through the center of two bearings and its respective Acme nut with a support fixed with two M4 screws to the MDF plate located at the top. The rotational movement generated by the stepper motor is transmitted from the 40-tooth toothed pulley to the 20-tooth pulley attached to the

endless rod by means of a 228 mm closed band, producing a linear movement. The movement system atz is connected to the movement system atx by means of two 20×20 mm aluminum profiles

20×20 mm fixed to the plate known as the Dremel Plate (PpD). The connection is made with 6 screws. 16 mm M5 and 6 T-type nuts. In order to attach the Dremel to the PpD, 5 mm holes were drilled in the plate to attach the supports using 4 M5 screws. The brackets are manufactured using 3D printing and have a hole in the center the same size as the diameter of the Dremel. They also have a hole for a 2 cm M5 Allen screw that passes through the thickness of the brackets. These screws are tightened to secure the cutting tool.



**Figure 3.** a) Complete axis movement systemx . b) Complete axis movement systemy .  
c) Complete axis movement systemz . d) Complete machining table system.

**Source:** Own work.

Figure 3d) shows an isometric view of the machining table, which consists of a 12 mm thick MDF board measuring 44×50 cm that is attached to a wooden structure of the same dimensions. This structure is made of 20×30 mm wooden strips. The 16 insert nuts that form the supports for the material are also shown. The clamps are placed on these nuts to secure the material to be machined to the work table. The design of the machining table is intended to secure the materials to it so that they can be machined, as well as to connect the

y-axis movement system to it. In this way, the machining table also functions as an additional support for the CNC milling machine, helping to maintain the stability of the entire structure during the machining process.

## DISCUSSION AND ANALYSIS OF RESULTS

The CAD assembly process of the spatial movement system for each of the systems described is shown in Figure 4a). The physical assembly is made with MDF plates. For the x-axis, two

11×15 cm plates were cut for the y-axis, 6 plates were cut, 2 measuring 12×16.5 cm and 4 measuring 6×10 cm. For the z-axis,

one 11×13 cm plate and a second 10×15 cm plate were cut (see Figure 4b). The perforations and roughing of each plate were made with the help of a drill and a Dremel, respectively. The supports, spacers, toothed pulleys, V-Slot wheels, tension pulleys, and toothed belt were 3D printed with PLA filament. Screws, bolts, washers, nuts, bearings, aluminum profiles, and threaded rods with their respective acme nuts were also used (not shown in the figure).

An Arduino Uno board (Arduino, 2024) was used in the development of the project, a CNC shield board for Arduino (*CNC/3-Axis Stepper Motor Shield User Guide*, 2024), stepper motor controllers (*A4988 Stepper User Guide*, 2024), commercial 1.8° stepper motors corresponding to 200 steps per revolution, a 12V DC power supply, and connectors. The stepper motors were used in

a 1/8 step configuration for the axes x and y and a 1/2 step configuration for the axis z. A 4-wire rod with a displacement of 8 mm. The steps per millimeter on this axis are calculated as follows (Conti, 2013):

$$PP_{mm} = \frac{p_m \cdot \mu_p}{r_{vv}} \quad (1)$$

Where  $PP_{mm}$  are the steps per millimeter,  $p_m$  are the motor steps,  $\mu_p$  is the number of microsteps, and  $r_{vv}$  is the rod travel per revolution. Substituting the values  $p_m = 200$ ,  $\mu_p = 2$ , and  $r_{vv} = 8$  gives

$PP_{mm} = 50$ . Because a 60-tooth pulley is used on the motor shaft and another 20-tooth pulley on this shaft. The ratio between the teeth on the threaded rod and the motor is 3:1, meaning that for every 50 steps taken by the motor, the threaded rod moves three millimeters. Sixteen steps are required for the rod to move one millimeter.

For the x and y shafts, a Gt2 toothed belt and 20-tooth pulleys are used. The formula for calculating the steps per millimeter is (Conti, 2013),

$$PP_{mm} = \frac{p_m \cdot \mu_p}{p_c \cdot N_d} \quad (2)$$

Where  $pp_{mm}$  are the steps per millimeter,  $p_m$  are the motor steps,  $\mu_p$  is the number of microsteps,  $p_c$  is the belt pitch, and  $N_d$  is the number of pulley teeth. By substituting the values  $p_m = 200$ ,  $\mu_p = 8$ ,  $p_c = 2$ , and  $N_d = 20$ , we obtain  $pp_{mm} = 40$ . The values obtained are used to configure the Universal G-Code Sender (2023) software that controls the CNC milling machine.

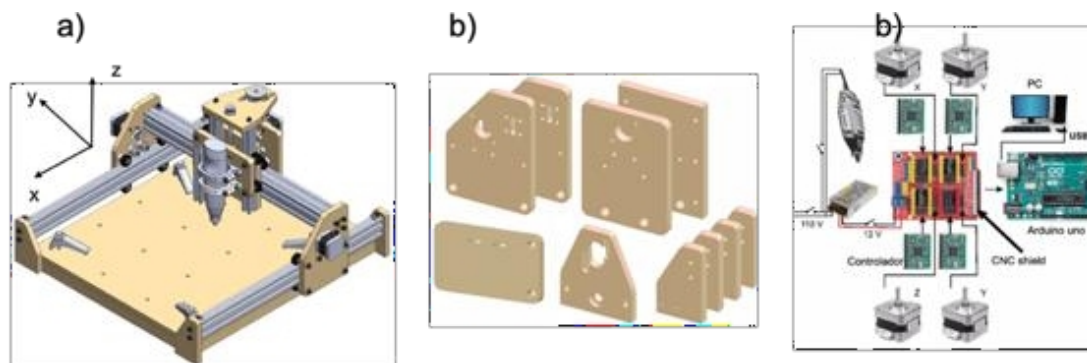
On the other hand, it is necessary to calculate the reference voltage for the correct movement of the motor using the A4988 controller and an H-bridge. The controller incorporates PWM current control for the H-bridge, which limits the load current  $I_{TRIP}$  to a desired value. The maximum value for the current limitation is identified as  $I_{TRIPMAX}$  and is related to the input voltage of the REF pin of the controller,  $V_{REF}$ , using the equation ("DMOS Microstepping Driver with Translator and Overcurrent Protection," 2024),

$$V_{REF} = I_{TRIPMAX} (8 \cdot R_S) \quad (3)$$

Where  $R_S$  is the detection resistance [35]. The nominal current for the motors used is 0.4A and the detection resistance of the driver is  $0.1 \Omega$ . With these values and based on Eq. 3, we obtain

$V_{REF} = 0.32V$ . This value is configured with the potentiometer included in the driver. The diagram

The general connection diagram is shown in Figure 4c). The Dremel is connected to the 110V power supply that feeds the 12V power supply, both of which have a switch to allow power to flow when required. The controllers are connected to the CNC shield board with their respective motors. In turn, the board is connected to the Arduino Uno, which has a female type B connector that communicates with the computer (PC) through a USB port.



**Figure 4.** a) CAD design of the complete CNC milling machine. b) Boards for assembling the structure. c) General diagram of electrical and electronic component connections for the CNC milling machine.

**Source:** Own work.

The assembly of the CNC milling machine and the electrical connection were completed successfully. The final version is shown in Figure 4. The machining process for a part is shown in the flowchart in Figure 4. The first step is to create the CAD design for the part. The second step is to export the CAD design with a DXF (Drawing Exchange Format) extension to a CAM program. The third step is to configure all the machining processes to produce the required part in the CAM program, for example, configuring the cut, roughing and drilling, depth, speed and tool for cutting, as well as the depth per pass, among others. Once the machining processes have been configured, the programming code (G code) is generated. Next, using the Universal G-Code Sender interface, the program is loaded and the parameters are set to zero so that that the Dremel has the location  $x_0, y_0, z_0$ , both in the software and physically. Figure 4 shows the process sheet for machining a hexagonal part. Columns one and two show the operations to be performed (roughing, drilling, cutting), as well as the operating parameters: cutting speed ( $V_c$ ), feed rate at which the milling cutter is inserted into the material to be machined ( $V_b$ ), and depth of cut in millimeters, respectively. The column shows information related to the type of cutting tool to be used, and column four shows the diagram for each process.

The CNC milling machine that has been developed meets the objective of cutting 2.5-12 mm MDF. During the machining process, the Dremel shaft and the milling cutter may heat up. In this situation, roughing is performed to a depth of no more than 1 mm to prevent the Dremel from overheating. In the tests that were carried out, the CNC milling machine was observed to work continuously for up to 2 hours on 5 mm MDF. A video on the commissioning of the developed CNC milling machine can be viewed at (Cortés-Maldonado, 2023). Finally, it is important to mention that commercial materials were used in the development of the project, bringing the approximate final cost of the project to USD 250.

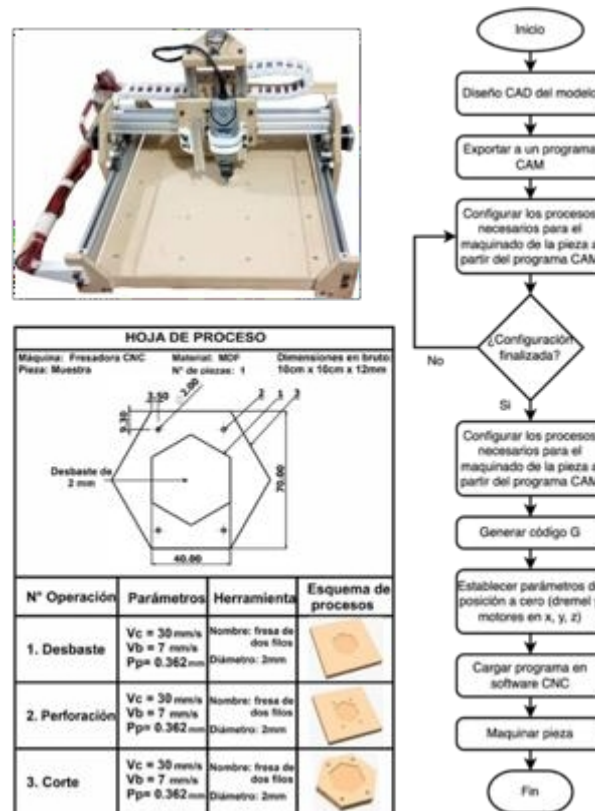


Figure 5. Developed CNC milling machine, flow chart, and process sheet for machining parts.

Source: Own work.

## CONCLUSIONS

In this work, the four-phase model was successfully applied to the design and implementation of a three-axis CNC milling machine for 2.5–12 mm MDF. The milling machine is focused on machining parts from 2D and 3D models. The final dimensions of the proposed machine are 580 mm wide, 320 mm high, and 510 mm deep. The working space on the x, y, and z axes is 270×270×50 mm, the cutting speed is 30 mm/s, and the spindle rotation speed is 9,600 rpm. Its ability to produce complex parts with high precision makes it a useful tool for micro and small businesses engaged in the manufacture of MDF crafts, as it allows them to optimize time, economic resources, and infrastructure, improving the quality of the products they offer. Likewise, the work presented contributes to demonstrating the methodological application established by Pahl & Beitz in a real example of engineering design that can be incorporated into training.

engineering students. Commercial materials and components were used in the implementation of the milling machine, resulting in an economically accessible machine.

## FUTURE WORK

The work carried out establishes a starting point for incorporating emerging technological tools into the machining process, such as the integration of monitoring systems using the Internet of Things (IoT) that allow for the dynamic adjustment of parameters such as spindle rotation speed, as well as the feed and depth of the cutting system.

Additionally, the four-phase model has proven to be a flexible and structured methodology that promotes good practices in modular design and scalability, facilitating the reproduction of projects in both industrial and academic contexts. As part of future work, it is proposed to apply the four-phase model to the design of other complex mechatronic systems, such as robotic arms, automation systems, 3D printers, and even oxidation furnaces.

## ACKNOWLEDGMENTS

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