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Design Optimization of CNC Router 2413 for the Interior Design Industry Using Reverse Engineering and DFMA

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ABSTRACT

The wood industry faces prolonged production times due to the use of conventional tools and the declining number of artisans. This study aims to design the CNC 2413 machine to meet the production needs of the interior design industry by improving efficiency, precision, and adaptability. The design process applies the Reverse Engineering approach combined with Design for Manufacturing and Assembly (DFMA). The key technical aspects include torque calculation, Center of Gravity (CoG) analysis, and assembly mapping. The results indicate that a 3-axis CNC router is sufficient for cutting and engraving tasks, requiring a minimum torque of 0.4116 N·m (Y-axis), 0.3528 N·m (X-axis), and 0.0156 N·m (Z-axis), with a spindle torque of 0.159 N·m. The Nema 24 stepper motor and Bosch GKF router were selected as they meet the specified requirements. The CoG analysis produced X = 56.9–63.0 cm, Y = 100.9–127.3 cm, and Z = 3.884 cm, demonstrating structural stability and resistance to vibration. This design is considered feasible and reliable for long-term use. In addition, the study offers practical significance in terms of potential production cost savings through lower power consumption compared to conventional machines and the opportunity to enhance the production capacity of small and medium enterprises (SMEs) in the interior design sector. This research provides a practical reference for developing CNC routers using locally sourced components, aligned with the technical and economic needs of the interior design industry.

Keywords: *CNC Router 2413, Reverse Engineering, Design for Manufacturing and Assembly (DFMA), Interior Design Industry, Design Optimization.*

Introduction

The increasingly intense competition in products, marketing systems, and the manufacturing sector demands continuous innovation, including in the wood industry [1]. The development of manufacturing technology today is marked by the increasing adoption of automation and digitalization systems in the production process, including in the wood industry sector. The wood processing industry is considered old because its raw materials are always available and widely used in sectors such as furniture, construction, musical instruments, and cutlery [2]. Wood is often chosen for interior and exterior decoration because it is easy to process [3]. There are several challenges in the conventional wood industry, namely design limitations and inefficiencies in relatively long production times during manufacturing. Currently, the woodworking industry is experiencing a decline in the number of woodworking craftsmen, and manual processes still constrain the development of MSMEs for carving craftsmen in various regions. However, market demand continues to increase[1]. Using conventional processes in design limits production quality and capacity, and causes significant fatigue for operators [4]. The wood carving craft industry in Badung Regency faces constraints on capital, infrastructure, marketing, and a lack of [5]. Jepara carving production is constrained by the decreasing number of craftsmen, most aged 50 years and over [6]. The regeneration of carving craftsmen is decreasing, and carving craftsmen are now dominated by the senior generation [7]. Companies must adapt to technological developments to support their performance [8]. Small businesses face obstacles such as the quality of human resources, low productivity and quality of products and services, lack of technology and information, and limited facilities [9]. Conventional wood cutting is also less efficient, causing long production times and less than optimal results [10]. Long production times will increase costs and reduce profits for business actors [11]. Surveys show that conventional production processes are only effective on a small scale. Large orders often cause problems with inconsistent results and long production times. CNC machines connected to computers or gadgets can be a solution to increase production. CNC machines are a technology that plays a strategic role in improving production efficiency and precision. This CNC allows automatic cutting and forming of materials based on digital designs and is widely used for pattern making, milling, drilling, and groove making. Integration with other automation systems increases the processed materials' flexibility, productivity, and surface quality [12]. This CNC can cut materials with high precision, producing products that are exactly according to design, all controlled by computer commands [13]. The availability of affordable CNC machines that meet the needs of small and medium industries, especially for the production of complex patterned doors, is still a challenge. CNC is automatically used in the wood industry to cut, mill, drill, and shape materials [14].

CNC stands for Computer Numerical Control or computer-based numerical control [15]. A CNC machine is controlled by a computer with special software, producing high-precision shapes that are difficult to achieve manually. [16]. CNC is a machine controlled by a computer using commands in numeric codes, letters, and symbols in a numeric language according to ISO standards, and has been widely used [17]. CNC is a tool automation system based on programmed and stored commands according to ISO standards [18]. CNC routers can carve and cut wood with high precision, allowing the processing of areas with complex and difficult profiles [19]. Innovations in CNC machine tools can increase operations' productivity, efficiency, and accuracy. [20]. Optimal CNC machine operation helps save costs and time, and increases profits per production period. [21]The CNC process can reduce cycle time, increase the efficiency of the furniture and woodworking industries, and encourage the advancement of the woodcraft industry. [22].

Figure 1. CNC G-WEIKE WK1212

Nevertheless, most research and applications of CNC technology remain concentrated on large-scale industries with high investment capacity, both in terms of advanced machinery and mass production systems. This creates a research gap, as the needs of the wood and interior MSME sector, requiring more affordable solutions that align with capital, resources, and production capacity limitations, are rarely addressed. [23]. In fact, MSMEs play a crucial role in sustaining the woodcraft industry, yet they often lag in adopting modern technology. [24]Therefore, this study aims to design a 3-axis CNC Router with dimensions of 130 cm x 240 cm that can be operated through computers or mobile devices. This machine is expected to improve production efficiency, design flexibility, and the competitiveness of MSMEs in the wood-based interior industry.

Research Methods

Research Flowchart

The research flow in designing the CNC Router 2413 machine is arranged systematically to ensure that each stage runs in a structured manner and per the stated objectives. The research flow can be seen in Figure 2.

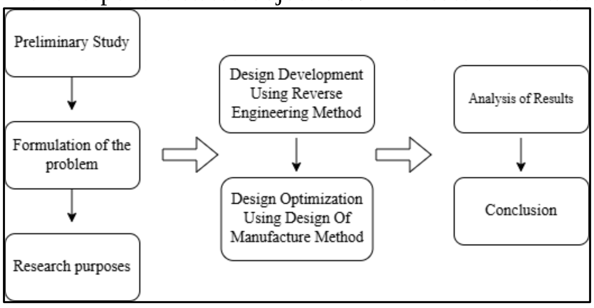


Figure 2. Research Flowchart

1. Preliminary Study. This is the initial stage of research, which involves conducting a field study to identify the needs of CNC machines and door leaves already on the market.
2. Problem Formulation. The second stage is to formulate research problems based on the background. The issue of this research is that the production of conventional door leaves still takes a long time because the work process is still manual. The lack of application of CNC machines, in addition to the high price, is also because CNC machines are available on the market.
3. Research Objectives. The third stage is the purpose of the research. This study aims to design a CNC machine for making door leaves using reverse engineering.
4. Design and Development. The fourth stage is to carry out the design and development process of the CNC machine using the Reverse Engineering method based on the needs of door leaf production. This stage has several stages: Disassembly, Assembly, Benchmarking, making 2D and 3D designs, and determining technical specifications. In addition, there is a design optimization of the machine using the DFMA method approach, which contains torque

requirements measurements, determining design specifications, measuring power requirements, measuring CoG, and designing the CNC machine assembly chart.

5. Prototyping. The fifth stage involves making a prototype of the CNC door leaf machine based on technical measurements derived from the design and development results.
6. Analysis of Results. The sixth stage involves testing the CNC door leaf machine prototype to determine the design optimization results.
7. Conclusion. The seventh stage is the final stage, which contains suggestions and conclusions from the design and development results, prototypes, and trial results.

Data and Instrument

This study requires several technical data for the reverse engineering process and optimization of CNC machine design. The data used includes:

- Geometric data and configuration of CNC machine components.
- Data on the characteristics of the drive motor and spindle, including torque, power, and rotational speed.
- Frame structure material data, including mass, strength, and response to vibration.
- Assembly and operational procedure data.

The instruments used in this study consist of measuring devices and analysis support software. Measuring instruments such as vernier calipers, micrometers, and angle gauges are used to obtain precise physical dimensions and component tolerances. The component remodeling process uses the Fusion360 application, as well as calculating the center of gravity.

Reverse Engineering

Reverse Engineering (RE) is a step in developing engineering data to support resource efficiency and increase productivity. [25]. RE is taking a new form from a manufactured object part by digitizing and changing the existing CAD model. RE is also a process of measuring, analyzing, and testing to reconstruct the image of an object or past event [26]. RE is developing engineering data through digitizing, measuring, analyzing, and testing existing objects to increase resource efficiency and productivity, and reconstructing old CAD models or objects.

Design for Manufacturing and Assembly (DFMA)

Design For Manufacturing and Assembly (DFMA) is a systematic method used to evaluate product design by considering the ease of the manufacturing process, and functions to estimate production costs from the early stages of design [26]. Design for Manufacturing and Assembly (DFMA) is a design approach that simplifies product structures to facilitate assembly and manufacturing processes. This approach enhances manufacturing efficiency and significantly reduces production costs by minimizing component complexity, shortening assembly time, and enabling the use of standard tools and conventional manufacturing methods [27]. DFMA is essential in estimating manufacturing costs at the early design stages. Given the many variations in process technology and materials available, DFMA is an essential tool for designers to determine optimal process and material choices without requiring direct manufacturing practices. Thus, DFMA contributes to improving design efficiency and reducing potential production costs. In addition, there is the Center of Gravity (CoG) technique, a mathematical technique used to find the best load point for a machine that will affect the stability of the machine. Torque and power calculations are performed based on load parameters and transmission dimensions to obtain mechanical specifications that meet system needs. The formulas used in this calculation are presented as follows:

Torque Calculation

Theoretical calculations are performed to determine the engine's torque and power. The basic formulas used are:

Router Torque Calculation

$$T = \frac{P}{2\pi \mathrm{n}} \tag{1}$$

Description: T = Torque P = Power N = Rotational Speed

Rack Gear Torque Calculation

$$T = F.r \tag{2}$$

Description: T = Torque F = Axial Force r = Pulley Radius

Leadscrew Torque Calculation

$$T = \frac{F.P}{2\pi \mathrm{n}} \tag{3}$$

Description: T = Torque, F = Axial Force p = Thread Pitch n = Transmission efficiency

Power Calculation

$$P = V.I \tag{4}$$

Description: P = Power V = Voltage I = Current

Validation

Design validation is done in two stages:

- Theoretical validation involves calculating the motor's torque and power requirements and analyzing the frame's stability using a mathematical approach.
- Simulation validation involves virtual testing using Autodesk Fusion 360 software to simulate mass distribution and the Center of Gravity (CoG) position.

Results and Discussions

Reverse Engineering

This research is a type of applied research with a technology engineering approach, using the Reverse Engineering method to redesign the CNC Router machine that is already on the market into an efficient and affordable CNC Router 2413 machine. The object of this research is the CNC router machine, which includes mechanical components, drive systems, electronic controls, and software systems. The primary focus is redesigning so that small industry players can build it cheaply and with sufficient functionality. In this study, the Reverse Engineering approach was used. The product development process is carried out through several stages: disassembly, assembly, benchmarking, CNC Router system design for door production, and prototyping.

1. Disassembly

At this stage, the old machine, the G-Weike WK1212 CNC Router Machine, is dismantled to obtain a bill of materials and analyze the functions of each component. The focus is on the main components and component sizes. The results of the disassembly of the G-Weike WK1212 CNC Router Machine are obtained, which can be seen in Table 1.

Table 1. Specification Machine CNC Router G-Weike WK1212

Component	Specification	Quantity
Router Spindel	0-24.000 Rpm with water cooling	1
Motor	Stepper Motor 450B	4
Driver Motor	DMA860H	4
Control System	DSP A11	1
Main Board	Rich Auto	1
Railing	Square Linear Rail PMI Taiwan for X, Y, and Z axes, equipped with an oil pump-based lubrication system	6
Frame	Solid Steel	1
Limit Switch	Omron Proximity Sensor	5
Power Supply	RiHH JBK5-1200VA	1
X and Y Axis Transmission	Helical Rack Gear and Pinion	3
Z-axis Transmission	Ball Screw	1
Dimension	1200x1200mm	

2. Assembly

The next step is to carry out the assembly process on the product that has been assembled, namely the G-Weike WK1212 CNC Router machine. To find the assembly time. The assembly process time is needed to create an Operation Process Chart. Figure 3 below shows the Assembly diagram of the G-Weike WK1212 CNC Router Machine.

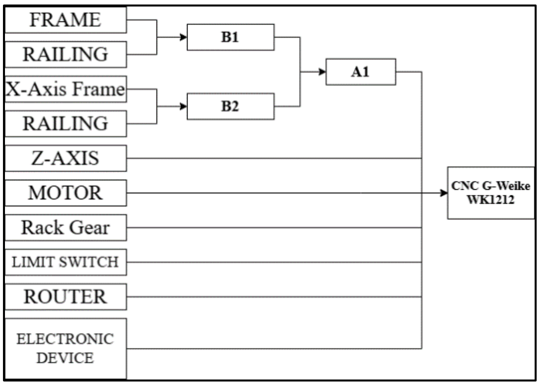


Figure 3. Assembly Chart CNC Router G-Weike WK1212

3. Benchmarking

At the benchmarking stage, direct observation was carried out on one of the CNC Router machines circulating in the market, the CNC Router G-Weike WK1212. This activity aims to thoroughly review the product's advantages and disadvantages and compare it with similar devices with similar characteristics.

Table 2. Router Machine Features Comparison StyeleCNC 4x8 (STM1325-3TA), CK1325 T-slot, G-Weike WK1212, and CNC 2413

Category	StyeleCNC 4x8 (STM1325-3TA)	CK1325 T-slot	CNC G-Weike WK1212	CNC Research This
Router Types	Automatic spindle	HQD 9kW	Automatic spindle	Bosch GKF550
Spindle Speed Setting	Via CNC Control	Via CNC Control	Via CNC Control	Via CNC Control
Electronic Control	LNC	Taiwan Baoyuan Control System	Kontroler Industri	Arduino Mega
Linear Railing	SMG/Lapping	SMG/Lapping	SMG/Lapping	SBR16
Driver Motors	YAKO Drive	Leadshine	Leadshine	Driver DM556
Drive Motor	Yako Stepper Motor	Servo Motor	Stepper Motor 450B	Stepper Motor Nema 24
Limit Switch	Proximity Sensor	Proximity Sensor	Proximity Sensor	Mechanical Switch
Spindle Cooling System	Air Cooled	Air Cooled	Water Cooled	Air Cooled
User Interface	Control Panel	Control Panel	Control Panel	PC/Gadget operated via USB/Nircable
Modification Capability	Difficult – Closed System	Difficult – Closed System	Difficult – Closed System	Easy – Open Source System
Dimensions	1300x2500mm	1300x2500mm	1200x1200mm	1300x2400mm
Estimated Price	IDR 230 – 340M	IDR 155 – 168M	IDR 100 – 120M	IDR 15 – 18M
Advanced Features	Equipped with parameter backup and parameter restore functions	Equipped with parameter backup and parameter restore functions	Fitted with a router spindle speed regulator according to your needs	Equipped with a Bluetooth module, a lamp for lighting, a laser feature for guiding, and a Z-axis probe feature for precise zero-point centering

4. 2D and 3D Render Design Models

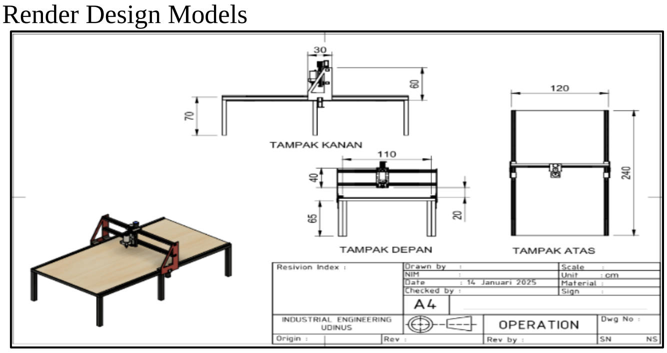


Figure 4. 2D Machine Design CNC 2313

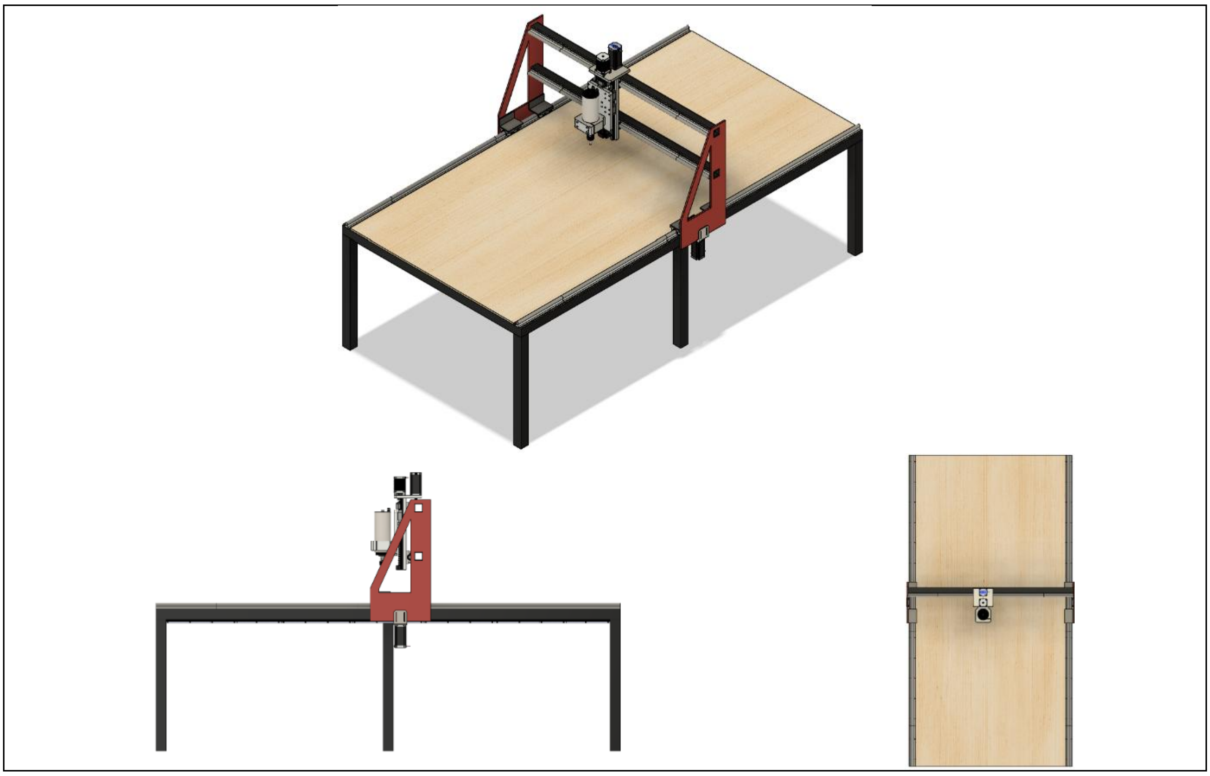


Figure 5. 3D Machine Design CNC 2413

5. Determination Technical Specification
   - The dimensions of the machine frame are determined according to the SNI door leaf SNI 03-0675-1989, which is 240 x 130 cm with a work table of 200 x 120 x 20 cm.
   - Selection of the router, namely using the BOSCH GKF550, which can produce a rotational speed of 10,000 to 30,000 RPM and process wood from low to high hardness levels according to the ISO 21876:2020 standard concerning tests and performance criteria for protective windows from saw chain splinters on forestry machines.
   - Selection of frame: The CNC machine uses a 5×5 cm hollow steel frame with a thickness of 2 mm because this material has lower production costs, and due to the abundant materials on the market, its weight is relatively light.
   - The drive system uses a linear rail SBR16 (dia. 16 mm), rack gear, and pinion transmission. The SBR16 delivers smooth, precise linear motion and is strong enough for medium workloads. With proper mounting, the system reduces vibration and maintains motion accuracy. Rack Gears are chosen because they support high speed, fast response, and minimal maintenance.
   - The control system uses Arduino Mega, which is flexible and easily integrated with various components. It supports connection to DM556 motor drivers (up to 5.6A), limit switches, and other interfaces. A power supply (AC 220 V to DC 12 V) with 30 A maintains system stability. Limit switches on each axis add safety and support homing features. This system is economical, modular, and easy to develop.
   - The use of NEMA 24 motors because they offer a balance between torque, precision, and compatibility with various motor drivers, including the DM556. In addition, NEMA 24 provides stability in axis movement and reduces the risk of losing steps, especially when combined with the right microstepping driver and a stable power supply.
   - MDF is used as a CNC workbench because it is economical, has a flat surface, is easy to shape, and is stable in controlled environmental conditions. This material also dampens vibrations, supporting light cutting, such as wood carving

Design for Manufacturing and Assembly

The design of the CNC 2413 machine, based on the Design for Manufacturing and Assembly (DFMA) approach, includes several main technical parameters, namely torque requirements, machine dimensions, Center of Gravity (CoG), and system assembly chart.

a) Calculation of Torque Requirements

Table 3. Calculation of Torque Requirements

Spindle Router	X Axis	Y Axis	Z Axis
$T = \frac{P}{2\pi n}$ $= \frac{60 \text{ x } 550}{2 \text{ x } 3.14 \text{ x } 33000}$ $= \frac{33{,}000}{207{,}345}$ = *0.159N.m*	*F = m.g* *= 5 kg x 9.8 m/s²* *= 49 N* *F* = Planned force on the X axis *T = F.r* *= 49 N x 0.014* *= 0.686 N.m*	*F = m.g* *= 11 kg x 9.8 m/s²* *= 107.8 N* *F* = Planned force on the Y axis *T = F.r* *= 107.8 N x 0.014* *= 1.509 N.m*	*F = m.g* *= 11 kg x 9.8 m/s²* *= 107.8 N* *F*= Planned force on the Z axis $T = \frac{P}{2\pi n}$ $= \frac{19.6 \ x \ 0.002}{2\pi \ x \ 0.4}$ *= 0.0156 N.m*

Based on the calculation of torque requirements, the spindle used in the system is a Bosch GKF550 with a power of 550 W and a maximum speed of 33,000 RPM. Based on the formula, the torque produced is around 0.159 N.m. This value is sufficient for the wood cutting and engraving process. Meanwhile, the results of the torque calculation on the motion system show that the NEMA 24 stepper motor, which has a maximum torque of 2.1 N m, can drive all axes of the CNC machine efficiently. The X and Y axes, with loads of 3 kg and 5 kg respectively using rack gear transmission, require torques of 0.686 N.m and 1.509 N.m. While the Z axis, using a leadscrew with a pitch of 2 mm and a load of 2 kg, only requires a torque of 0.0156 N.m.

b) CNC 2413 Technical Specifications Design Optimization

Table 4. CNC 2413 Technical Specifications

Component	Technical Specifications
Frame Dimensions	240 cm x 130 cm
Table Height	70 cm
Work Table Dimensions (Net)	210 cm x 100 cm x 20 cm
Work Table Material	MDF Board, Thickness 18 mm
X-Axis Range of Motion	210 cm
Y Axis Range of Motion	100 cm
Z Axis Motion Range	30 cm
Motor Stepper	Nema 24
Spindle Motor	Bosch GKF550 with 65 mm Bracket
Driver Microstepper	DM556
Main Board	Arduino Mega
Power Supply	12 V, 30 A
X and Y Axis Transmission	Straight Rack Gear and Pinion 15 mm, Modulus 1
Z-Axis Transmission	Set Ball Screw SFU1605
Linear Motion System	SBR 16
X and Y Axis Gantry Dimensions	20 x 40 cm
X and Z Axis Gantry Dimensions	18 x 40 cm
Number of Frame Feet	6
Frame Material	Hollow Steel 5x5cm, Thickness 2mm

c) Power Requirement Measurement

The measurement of power requirements on the CNC 2413 system aims to determine the amount of electrical energy consumption required during the operational process. Measurements are made on the system's main components, including stepper motors on the X, Y, and Z axes, and the router spindle. The measurement method uses a digital multimeter and power meter, which are applied under no-load conditions, during axis movement, and the cutting process.

$P = V x I$
$P = 12 x 5.6$
$P = 67.2 W$
Total Motor 4
$P = 4 x 67.2$
$P = 267.8 W$

Power calculations are performed to determine the energy requirements of the CNC. The Bosch GKF 550 router machine has a power of 550 W. In addition, the stepper motor system on this CNC machine requires about 67.2 W of power per motor, with a total power for 4 motors reaching 268.8 W. Therefore, the total power needed to operate the CNC machine, including the motor and the router spindle, ensures efficient system performance and can meet production needs, while maintaining relatively low power for small industrial applications.

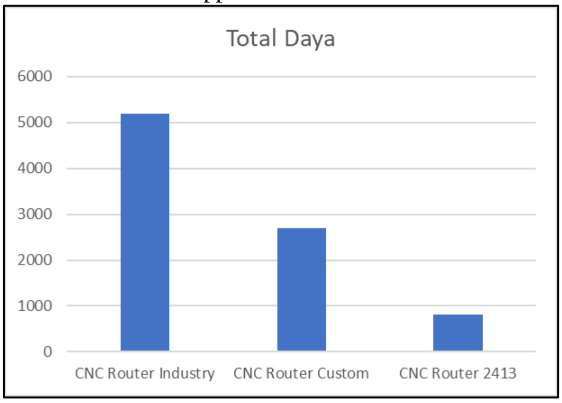


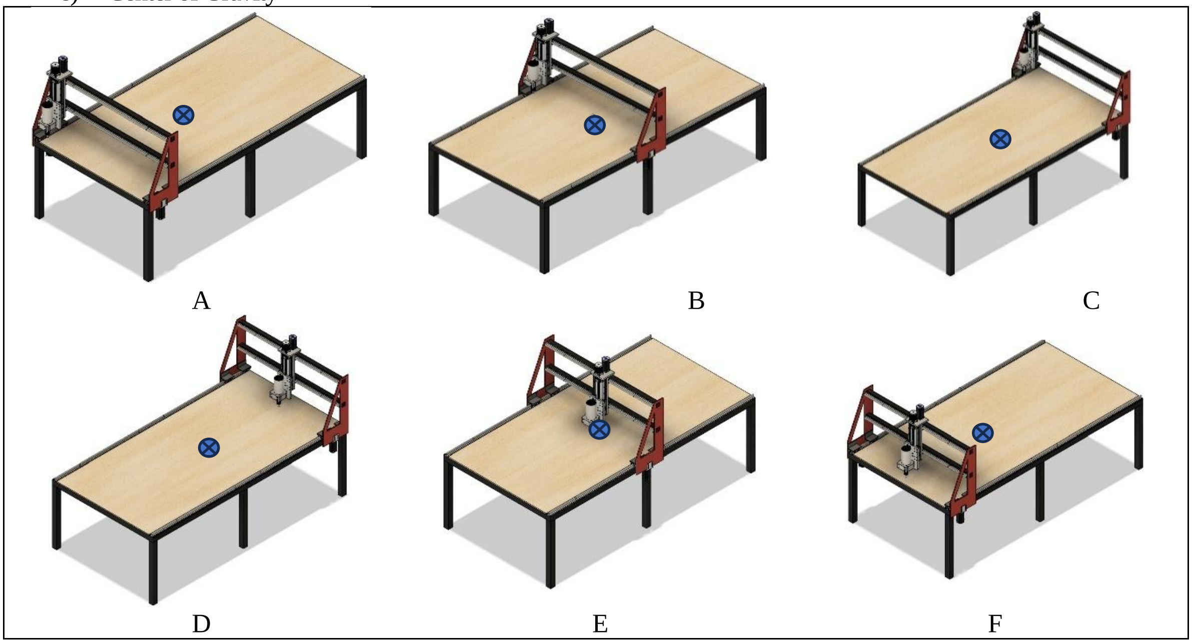
Figure 6. Power Consumption Comparison

The power consumption calculation shows that the CNC 2413 requires only around 818 W (550 W spindle + 268 W motor), significantly lower than conventional machines. This difference is illustrated in Figure 6.

d) Calculation of Total Weight

CoG calculation determines the center of gravity on the CNC machine. Determination of the Center of Gravity using the Fusion 360 application allows the calculation of total weight, the location of the load center, and interactive visualization of the CoG shift due to changes in the position of moving components. Determination of CoG is done to ensure that while the machine is working, the load center remains within the limits of the machine's base area, which is useful for preventing imbalance and excessive vibration. The following are the results of CoG using the Fusion 360 application from several different X, Y, and Z axis positions.

e) Center of Gravity



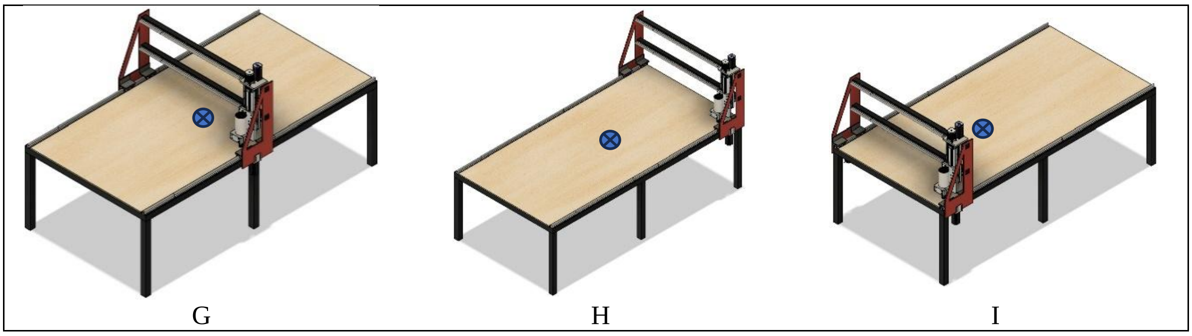


Figure 7. Positions Used for CoG

Table 5. CoG Result

Position	X (cm)	Y (cm)	Z (cm)
A	56.935	100.985	3.884
B	56.935	113.504	3.884
C	56.935	127.000	3.884
D	59.972	127.232	3.884
E	59.972	113.376	3.884
F	59.972	100.985	3.884
G	63.001	113.442	3.884
H	63.001	127.250	3.884
I	63.001	100.958	3.884

Center of Gravity (CoG) shift analysis was conducted to assess the stability of the CNC machine during gantry and spindle movements. The results showed that the CoG on the Z axis remained constant (3.884 cm), while the X and Y axes experienced small but significant changes. The largest shift on the Y axis was 100.958 cm to 127.25 cm, while the X axis varied ±6 cm from the center point. These CoG changes remained within safe limits and did not affect the structure's stability or the machine movement's precision.

f) CNC 2413 Assembly Chart

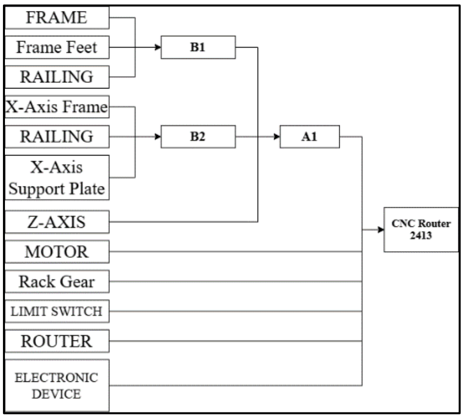


Figure 8. Assembly Chart CNC 2413

Discussion

This study applied the Reverse Engineering method to design a CNC router machine tailored to the needs of the door leaf industry, supported by the Design for Manufacture and Assembly (DFMA) approach to simplify the production process. Reverse Engineering enabled the analysis of existing machines to determine optimal specifications, while DFMA contributed to reducing the number of components and accelerating the assembly process. The design results demonstrate that the CNC 2413 machine meets the required technical criteria and supports production efficiency. The Center of Gravity (CoG) analysis also indicated a stable mass distribution, which has the potential to reduce vibration and improve cutting accuracy.

Compared to previous studies, the torque requirements of the CNC 2413 are significantly lower than those of industrial-scale CNC machines. This finding suggests that the proposed design is more energy efficient and cost-effective, aligning with studies that highlight the importance of modular, low-power CNC machines for small-scale industries. In addition, the CNC 2413's energy consumption is more efficient than that of conventional machines, reinforcing its contribution to the sustainability of small-scale manufacturing processes.

Nevertheless, several limitations must be acknowledged. First, the validation of torque and CoG calculations remains theoretical and simulation-based, without experimental or field testing. Second, the design's reliance on reference models may constrain flexibility, as the benchmark machine heavily influences the resulting specifications. Third, while DFMA promotes cost efficiency, the approach may compromise component quality if cost reduction is overly prioritized. Furthermore, this study has not considered variations in wood types or more complex workpiece geometries, which may affect machine performance under real production conditions.

Conclusion

This study produced the design of the CNC 2413 machine using the Reverse Engineering and Design for Manufacture and Assembly (DFMA) approaches. The resulting design is efficient, stable, and adaptive to production needs, particularly for door leaf manufacturing. Component selection was based on high market availability and cost efficiency, ensuring the design can be realized without reducing functionality or system reliability. The components are relatively easy to obtain and affordable, supporting design effectiveness without sacrificing performance.

The CNC 2413 machine was designed to provide structural stability, facilitate assembly, improve work accuracy, and reduce manufacturing costs. The torque and Center of Gravity (CoG) calculations confirmed the mechanical efficiency and supported precise machine movement. Compared to previous CNC studies that generally focused on large-scale industrial machines with high energy consumption and investment costs, this design offers a modular, open-source, energy-efficient, and low-cost alternative, making it more relevant for SMEs in the interior and woodcraft sector.

In practical terms, the CNC 2413 design provides an alternative solution for SMEs to adopt modern manufacturing technology with lower investment costs and improved energy efficiency. Its implementation is expected to enhance production capacity, product quality consistency, and market competitiveness. For further development, future research may focus on experimental validation in real production environments, the integration of Internet of Things and Artificial Intelligence for automation and performance monitoring, and Life Cycle Cost analysis to evaluate long-term economic efficiency.

Apprecisttion

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