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INTELLIGENT OPTIMIZATION OF TOOL PATHS TO ACCELERATE THE PRODUCTION OF 3D WOOD DECOR ON CNC MACHINES

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Abstract. *Guided by the "technology promotion platform," manufacturers often prioritize product identity over universal design. However, the transition to standardization does not promote user autonomy but reduces costs. This approach allows for the optimization of tool trajectories in CNC woodworking operations to accelerate the production of 3D decor. The thickness of the wood sheet cannot exceed 15 mm. Wood cubes were used as raw material to create a conceptual prototype that can be used in the future for built-in furniture.*

The main goal of the proposed study is to revolutionize and intelligently optimize tool trajectories, solving traditional problems of accelerating the production of 3D wood decor on CNC machines. The proposed method eliminates the need for adhesives, simplifying assembly and increasing structural integrity using CNC machines. Designers optimize bricks using CAD and FEA analysis, which facilitates rapid prototyping without glue. The focus on finite element analysis of mechanical properties, 3D cross-section, tool and material selection ensures the creation of functional prototypes. Key parameters, including finite element analysis of mechanical properties, slicing of a virtual 3D model into layers corresponding to brick thickness, and selection of appropriate tools and materials, are critical to achieving the desired results. By applying this approach, manufacturers can simplify production processes, reduce material waste, and increase product adaptability, which ultimately contributes to user autonomy and cost reduction.

Keywords: *3D decor, solid materials, manufacturing process, CNC machine, pins, finite element analysis.*

Introduction

The trend toward ready-to-assemble furniture is rapidly spreading in global manufacturing, significantly impacting both customers and manufacturers. Prototyping methods such as injection molding, metal casting, and additive manufacturing of 3D wood decorations play a crucial role in reducing production time and accommodating complex designs [1].

Reverse engineering methods create 3D CAD models from existing objects, facilitating the efficient production of complex shapes and surfaces. They are crucial for design modifications, re-engineering, or troubleshooting [2–3]. Finite element analysis (FEA) further supports the verification of the structural integrity of these models by simulating forces and ensuring compliance with safety criteria prior to prototyping [4]. Rapid prototyping (RP) technologies, such as fused deposition modeling (FDM) and laminated object manufacturing (LOM), enable rapid layer-by-layer prototyping from 3D CAD models [5]. Although these processes are efficient, they are often more expensive, making them suitable for unique applications with low production volumes. Solution analysis helps in selecting the most appropriate RP process based on cost, considering factors such as material and equipment costs [6–8].

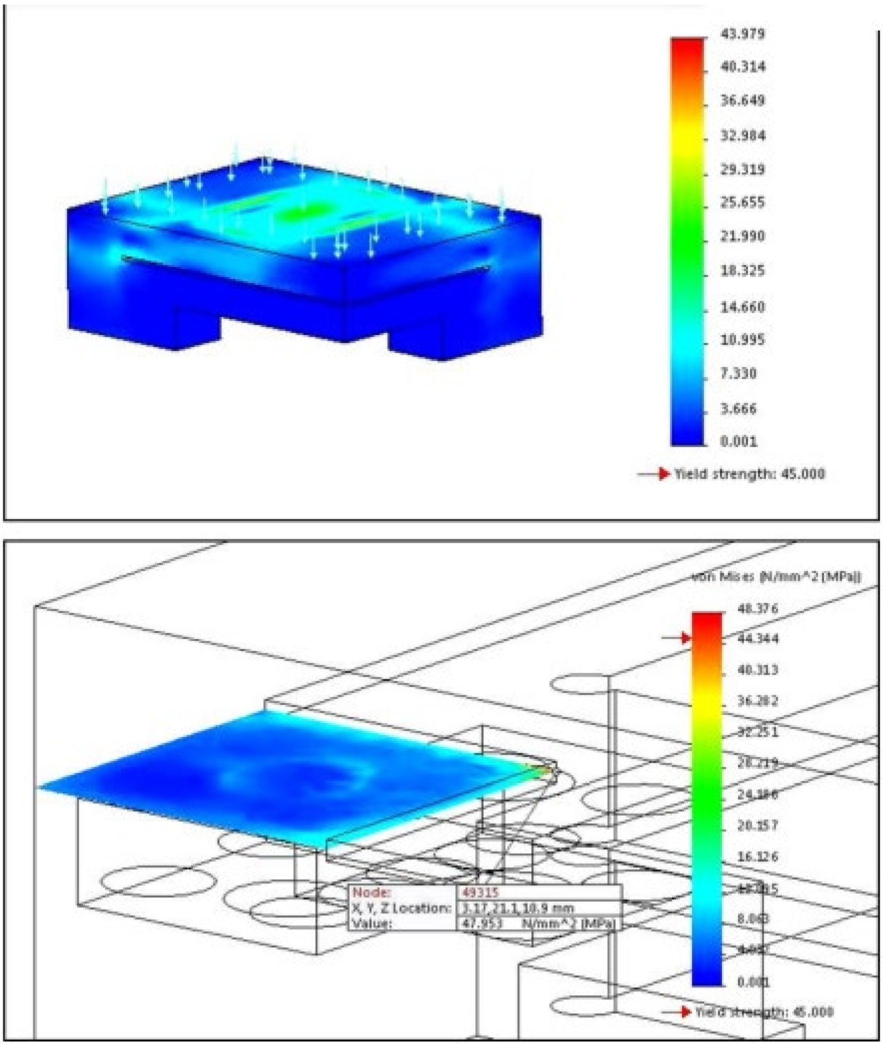

Figure 1 - Modeling of the force applied by a CNC machine to a wooden surface

Source: developed by the author based on [11]

In this study, CNC machines are used to make prototypes, which are commonly used in woodworking and decorative applications. By converting 3D virtual models into tool paths, the CNC milling machine precisely cuts materials, ensuring high-quality surface finishing. Incorporating user-friendly concepts into product design stimulates innovation and reduces design barriers [9]. Excessive investment in prototypes through trial and error can lead to reduced customer satisfaction due to a “technology push” approach [10]. Conversely, standardizing parts using a universal design platform promotes independent manufacturing of solutions, reducing costs and time while increasing product development efficiency. Thanks to CAD and CAM integration, machine operators can preview tool paths, fine-tune cutting parameters, and avoid costly mistakes before running the actual machine.

Research Results

Once an accurate 3D model has been created, CNC machines can be used to cut complex shapes out of wood, stone, or other materials, often used to create exact replicas of original components. The figure above shows that the von Mises stress around the fracture site was approximately 47.953 MPa, which exceeds the yield strength of the material (45,000 MPa). 3D trajectories include the movement of the Z-axis during the cutting process. The tool moves along a trajectory that bends and changes depth as needed. These trajectories are necessary for machining complex geometries. CAM software creates a triangular mesh of the workpiece to generate the 3D tool trajectory. To demonstrate the proposed approach, a sheet of wood was selected as the raw material, which was machined using a CNC machine based on the developed cutting conditions. Table 3 shows cutting heads made of different materials, and high-speed steel was selected for the study [12–13].

Table 1 – Permissible cutting speeds for various tool materials

Tool material	Year of first use	Permissible cutting speed for wood	
		m/min	ft/min
Ordinary carbon tool steel	1800	Below 10	Below 30
High-speed steel	1900	25-65	75-200
Cast cobalt alloys	1915	50-200	150-600
Ceramics (Al_2O_3)	1955		
Coated carbides	1970		

Source: developed by the author based on [14]

Due to the height of the cutting head groove (as shown in Fig. 2), the thickness of the wood sheet cannot exceed 15 mm. Wood cubes were used as raw material to create a conceptual prototype that can be used in the future for built-in furniture (Fig. 3).

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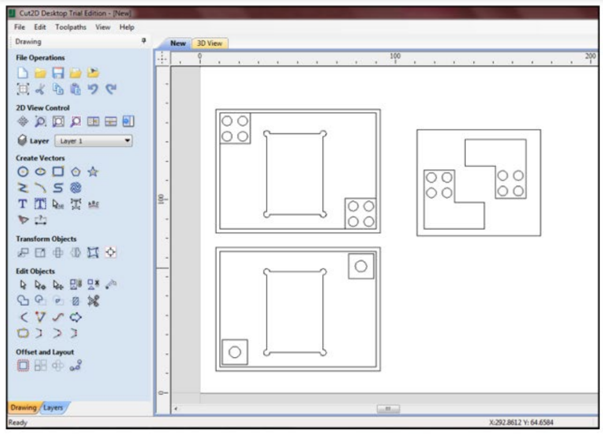

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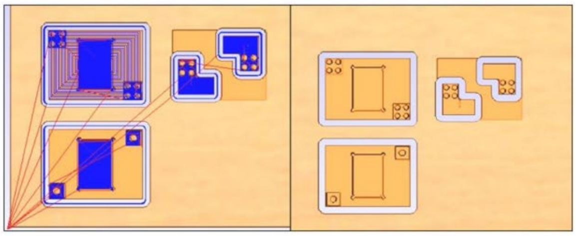

Figure 2 – A) Sketching the geometric shapes of the prototype, B) Cutting tool materials with their permissible cutting speeds, C) Previewing all tool trajectories before cutting the prototype

Source: developed by the author based on [15-17]

Modern CNC machines use additional axes to further refine tool movements. CNC operators use 4- and 5-axis tool paths when working with complex parts that require rotation around one or more axes. These tool paths allow for the machining of undercuts and complex curves that cannot be achieved with simpler 2D or 3D tool paths. Classic CAM systems (such as Fusion 360 and ArtCAM) use standard trajectory generation (Table 2). Path optimization can reduce processing time by 30–50% without compromising quality.

Unlike geometry reconstruction, texture reconstruction of 3D objects has received less attention. Previous work has explored this topic by studying color 3D reconstruction on voxels or point clouds [20-21] based on appearance synthesis and multi-view geometry. Recent approaches have alternatively studied 2D texture atlases

(UV mapping) for 3D meshes to map a point on a manifold to a pixel in a texture atlas.

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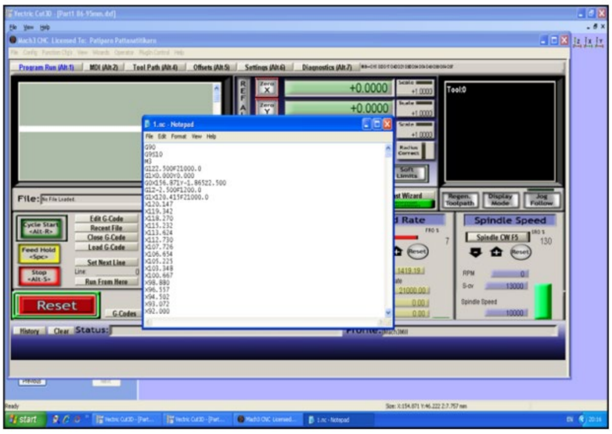

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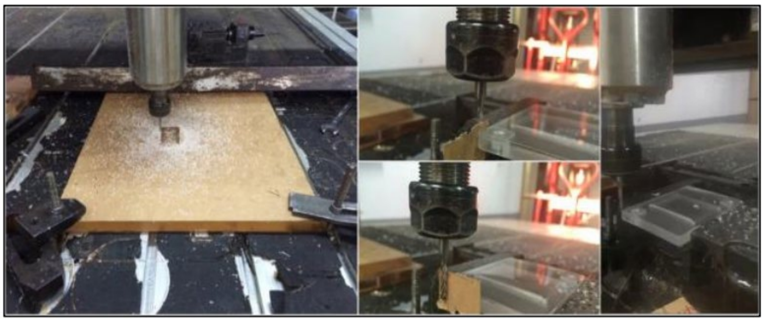

Figure 3 – A) Loading and editing G-code in CNC software, B) Setting the cutting head along the x and y axes to zero – the starting point

Source: developed by the author based on [18-19]

Table 2 - Key parameters of the CNC tool trajectory

Parameter	Meaning	Importance
Cutting speed	How fast the tool rotates (rpm or SFM)	Affects heating, wear, and processing
Feed rate	How fast the tool moves across the material	Balance between time and tool life
Entry/exit strategy	How the tool starts and ends cutting	Affects tool life and marks on the surface
Tool engagement angle	How much the edge of the tool touches the material	Helps maintain constant load on the tool

Source: developed by the author based on [20]

These methods mainly use differential rendering to transform the problem into an unobservable view synthesis problem. The created 3D repositories can support high-quality texture restoration studies. The applied 3D-FUTURE provides furniture shapes with informative textures. We applied two basic models for texture synthesis, Texture Fields and the BicycleGAN++ method.

To support the proposed concept of using CNC machines to reduce wood processing time, several prototypes were developed, manufactured on real models (ornaments, bas-reliefs) taking into account the direction of the wood fibers. These prototypes are scaled approximately 1:20 relative to the actual product. In CAM systems (such as Fusion 360, ArtCAM) using standard trajectory generation, the performance of CNC machines in cutting small-diameter figures and geometric shapes resembling a "Lego-like construction" that is both compact and complex was evaluated.

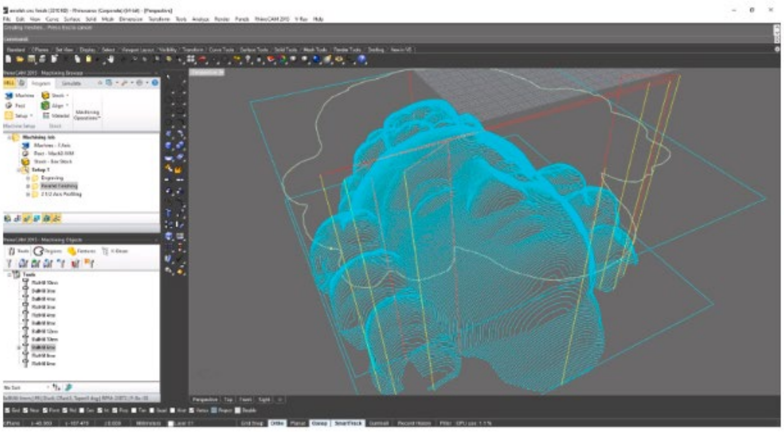

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Figure 4 – A) Tool paths for milling on a CNC machine, generated in CAM software, B) Railing element milled on a CNC machine

Source: developed by the author based on [21-23]

After refining the 3D model, the process moved on to physically reproducing the elements using CNC milling, which is provided by ArtCAM software. Fully integrated with the CAM system, tool paths were created based on the optimized digital model (Figure 4). These tool paths determined the movements of the CNC machine's milling tools, directing them to reproduce the complex details and shapes of the original Baroque patterns. Milling on a CNC machine was particularly effective in reproducing repetitive decorative motifs with high precision, which is an important feature for elements such as balusters or floral patterns that must fit together perfectly. Figure 4 shows examples of ornamentation and bas-relief applied to wooden railings. Using CNC machines with this innovative method, a deeper interpretation was achieved. In particular, the prototypes demonstrate innovative designs, providing a deeper understanding of the capabilities of CNC machines in processing complex details and smaller components. An analysis of the CNC machine's performance in generating trajectories is shown in Table 3.

Table 3 – Comparison of processing time and material consumption with and without adaptive modeling strategies in CAM systems and on CNC machines

Parameters	Method	
	CAM systems	Without prior modeling
Setup time	40 minutes	20 minutes
Processing time (all components)	76 minutes	254 minutes
Use of material	116 minutes	280 minutes
Use of supplementary material		6 minutes

Source: developed by the author based on [24]

Digital tools offer significant advantages for large-scale projects, but manual craftsmanship remains indispensable for unique, complex elements.

Conclusions

Well-designed tool paths are the basis for efficient and accurate CNC machining. The types of tool paths, key parameters, and optimization strategies that will reduce cycle time, extend tool life, and achieve better surface finish were discussed. Complex 3D decorative shapes on wood were obtained and designed by optimizing the tool path and adjusting the cutting head along the x and y axes to zero.

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