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Optimization of Toolpath Planning and CNC Machine Performance in Time-Efficient Machining

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Abstract: This study explores the optimization of the machining time in CNC milling machines by varying the machine parameters and toolpath strategies. Using the ICAM3D simulation software version 3.1.0, this approach focuses on minimizing the machining time while adhering to operational constraints. In addition, a novel approach to the optimization of the G-code in time machining, focusing on reducing the machining time while maintaining the required precision and quality of the finished product, is presented. We propose a method that integrates advanced algorithms to identify and eliminate redundant movements, optimize the toolpaths, and improve the machining strategies. The experimental results demonstrate a significant reduction in the machining time without compromising the machining accuracy, offering substantial cost savings and efficiency improvements for industrial applications. The importance of this work lies in the correct choice of the toolpath strategy. In the P3 project, the optimization process reduced the machining time from 15 min and 23 s to 13 min and 33 s by utilizing the optimized G-code. The initial machining time of 20 min and 2 s corresponds to the completion of the P3 project when the CNC machine was operated at 75% speed. To further enhance efficiency, additional software tools such as ARTCAM and ASPIRE have been utilized to implement a new toolpath strategy.

Keywords: CNC; machine time; simulation; toolpath strategy; optimization

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1. Introduction

In machining, numerical control, also known as computer numerical control (CNC), refers to the automated control of tools using a computer. CNC is a manufacturing method that uses preprogrammed computer software to automate the operation, movement, and precision of machine tools. This software is integrated into machinery. It can automate the functions of various cutting tools, including mills, lathes, routers, drills, grinders, water jets, and lasers.

The optimization of the G-code for the machining time is a critical aspect in enhancing the efficiency and performance of computer numerical control (CNC) machining processes.

This paper presents the optimization of the machining time resulting from variations in the speed, feed rate, and toolpath strategy. Advanced computer-aided manufacturing (CAM) software can enhance the toolpath strategies to boost both efficiency and quality. Through optimization, the machining time can be shortened, the surface finish improved, and tool wear reduced. The machining time of each variation was obtained by simulation using ICAM3D software Version 3.1.0 and AutodeskArt-Version 2018.0.0 ECMAScript 6 (ES6)/ECMAScript 2015–2017 CNC simulation software. ICAM3D software

makes it possible to achieve and simulate manufacturing processes to check the correctness of a project before it is implemented [1]. The machining strategy affects the overall machining time [2]. The implementation and selection of cutting path strategies with appropriate cutting parameters have significant effects on the surface [3]. Nowadays, programmable automated CNC machine tools rely upon CAM software as opposed to manual programs. This has led to a decrease in program time requirements, coupled with a reduction in the potential for human error [4].

In the world of CNC machining, achieving optimal performance in terms of precision, efficiency, and cost-effectiveness is essential for modern manufacturing. One of the critical factors driving this optimization is the toolpath strategy, which refers to the preprogrammed route that the cutting tool follows to shape a workpiece. The toolpath strategy is a methodology developed to address the complexities of toolpath generation, with a focus on improving machining processes across different materials and machine configurations.

The toolpath strategy emphasizes the importance of efficient tool movement, minimized cycle times, reduced tool wear, and superior surface finishes. By leveraging advanced algorithms and optimization techniques, this strategy ensures that tools move in the most effective and economical way, without compromising the accuracy or quality [5]. With the rise of advanced CNC systems and the increasing demand for high-precision, low-waste manufacturing, the toolpath strategy has become a cornerstone of modern CNC programming [6].

The primary goal of the toolpath is to optimize the entire machining process, from minimizing the path distance to enhancing the material removal rates, thereby increasing the overall productivity and reducing costs. This strategy is particularly valuable for industries such as aerospace, automotives, and medical device manufacturing, where the precision of each part is paramount [7]. Furthermore, with the continuous advancement of CNC technology, the toolpath strategy is evolving to incorporate real-time machine feedback and adaptive learning algorithms, ensuring even greater levels of optimization and performance [8].

This study highlights significant advancements in CNC machining by addressing the limitations of standard ICAM3D software through the integration of ArtCAM and Aspire tools. These additional software platforms enabled advanced G-code generation and optimization, achieving a time-efficient machining process. While ICAM3D allowed only four toolpath strategies, our approach reduced the maximum optimized machining time from 15 min and 23 s to 13 min and 33 s, representing a 12% improvement. This methodology demonstrates how combining multiple software tools enhances efficiency, precision, and productivity, offering a competitive advantage in modern manufacturing.

The structure of this paper is as follows. Section 2 presents an overview of research on toolpath planning and CNC machine performance regarding time-efficient machining. Section 3 introduces the materials and methods used in different toolpath strategies and their effects on the machining time during processing. Section 4 reports the results obtained of three projects that have been considered in the analysis. Section 5 covers the discussion of data collected from both the simulation results of the CNC program and real-time CNC operations. Finally, Section 6 summarizes our conclusions.

2. Related Work

Nowadays, programmable automated CNC machine tools rely upon CAM software as opposed to manual programs. This has led to a decrease in program time requirements, coupled with a reduction in the potential for human error [9].

In general, toolpath generation methods must be selected from the set of ordinary toolpath options available—for example, zig zag, radial, zig, and spiral toolpaths [10]. The

significant benefits associated with CNC machining include the fact that it can ensure high machining accuracy through simple programming, as well as repeatability in complex part machining [11].

In the fast-paced world of CNC machining, the toolpath strategy is a critical approach to optimizing toolpath generation, enhancing the machining efficiency, and ensuring precision. Whether used in metalworking, plastic fabrication, or other materials, optimizing the toolpaths can yield significant improvements in production time, cost efficiency, and part quality. Below are the key benefits of employing a toolpath strategy in CNC machining.

An optimized toolpath strategy ensures that the CNC machine follows the most efficient and precise route to shape a part. By minimizing unnecessary movements and ensuring accurate tool engagement, the risk of dimensional errors is significantly reduced [12]. This is especially crucial for industries requiring high-precision components, such as aerospace and medical device manufacturing.

By reducing idle movements and avoiding unnecessary tool changes, an optimized toolpath can lead to much shorter cycle times. This means that more parts can be produced in less time, driving higher throughput in a factory setting [13]. The time saved from optimizing the path directly contributes to better resource utilization and increased production capacity.

A key benefit of the toolpath strategy is its ability to reduce tool wear. By selecting optimal cutting paths and strategies, such as controlling the cutting speeds, feed rates, and depths of cut, the tool is exposed to less stress and strain, which leads to a longer tool life [14]. This reduces the frequency of tool replacement, saving costs for consumables.

Using an efficient toolpath strategy results in smoother, more accurate cuts, which directly contributes to better surface finishes. Fewer adjustments and corrections are needed post-machining, which minimizes the need for secondary operations such as polishing or deburring [15]. For industries producing high-quality components, this benefit is especially important.

The toolpath strategy can help to reduce material waste by ensuring that the toolpath is optimized for minimal cutting airtime and waste. Whether it is improving the nesting of parts on a sheet of metal or efficiently removing material from a block, the toolpath can maximize material usage while minimizing costs [16]. This leads to a more sustainable production process.

A well-designed toolpath strategy reduces the chances of machine crashes, tool collisions, or workpiece damage. By simulating the toolpath before physical machining begins, operators can identify and correct any potential problems [17]. This not only saves time and money but also improves safety in the workshop environment.

One of the significant advantages of an effective toolpath strategy is its adaptability to different materials. Whether working with metals, plastics, or composites, the toolpath can be adjusted to optimize the machining parameters based on the material's specific properties, ensuring optimal cutting conditions [18].

Regarding the theoretical frameworks for toolpath generation, several aspects from the literature on CAM software algorithms can be considered.

In complex geometries, freeform feature recognition algorithms play a crucial role in automatically generating toolpaths. These algorithms analyze the part geometry and suggest machining strategies that minimize tool wear and the machining time, a feature applicable to industrial CAM tools like ICAM3D. Discussing how ICAM3D incorporates such algorithms can provide deeper insights into its adaptability and automation capabilities [19].

Contemporary methods incorporate 3D point cloud data to design toolpaths dynamically, a practice that significantly enhances the precision and adaptability for intricate

components. Exploring whether ICAM3D employs similar data-driven methodologies can underline its technological robustness [20].

The paper by Giuseppe Venturini et al. [21] presents a non-uniform offset algorithm for the generation of milling toolpaths using Boolean operations, aiming to enhance the precision and efficiency in CNC machining.

The study presented in [22] compares various reinforcement learning algorithms for the optimization of CNC toolpaths, demonstrating improvements in machining efficiency and accuracy. In paper [23], the authors address CNC working time optimization through the strategic positioning and grouping of cutting tools, enhancing the operational efficiency. The author in paper [24] aimed to reduce the surface over-cutting or under-cutting of integral turbine blades by optimizing the machining path using non-uniform rational B-spline curves.

Two crucial areas of CNC machining are toolpath optimization and feedrate interpolation, both of which have shown notable improvements recently. In their thorough analysis of path planning and feedrate interpolation in CNC machining, Ma et al. [25] highlighted the advancements in technology and the variety of approaches used for toolpath optimization. The significance of the feedrate dynamics in improving the machining performance was also highlighted by Ward et al. [26], who presented a unique method for the precise forecasting of the machining feedrate and cycle time by simulating the trajectory-generating behavior of contemporary CNC machines.

Because of its capacity to manage intricate geometries, freeform surface machining has attracted interest. To increase the surface quality and machining efficiency, Lazoglu [27] investigated toolpath optimization techniques on freeform surfaces.

A useful technique for the modeling and improvement of CNC machining operations is virtual machining. The advantages of virtual machining in increasing the precision and decreasing trial-and-error efforts in toolpath design were covered in a study [28] that emphasized recent developments in this field. The use of multiaxis machining was also examined, showcasing its capacity to manage intricate geometries and its interaction with cutting-edge CAM software for increased efficiency.

Toolpath planning techniques for CNC pocket milling, a popular machining technique, have been continuously improved. A study examined developments in this field, emphasizing methods for effective material removal and reducing the machining time. In a similar vein, advancements in freeform surface machining, including customized toolpath-generating methods, were examined, with a focus on their contributions to accurate and timely operations [29–31].

Many CAM software algorithms now include adaptive techniques that modify toolpaths in real-time based on factors like the material properties and cutting dynamics. Highlighting ICAM3D's position regarding adaptive machining strategies could add value to this area of study.

Optimizing toolpath planning plays a vital role in enhancing the overall efficiency of CNC machines, especially when prioritizing time-efficient machining. This study explores the assessment of various toolpath strategies and their impact on the machining time when processing projects with differing levels of geometric complexity.

3. Materials and Methods

This study utilizes simulation and optimization methods to analyze machining processes. It involves using CAM and CNC simulation software to analyze the program efficiency and machining time. The ICAM3D software is utilized to create CNC programs by defining parameters such as the speed and toolpath strategy based on the workpiece's cross-sectional variations.

For the analysis of the projects, we used marble as the material. Marble is a type of metamorphic rock that forms from the recrystallization of limestone under conditions of heat and pressure. It is primarily composed of calcium carbonate ($CaCO_3$), and its characteristic veins or patterns are the result of impurities such as clay, silt, sand, or other minerals present during its formation.

In projects P1 and P2, we used cream line marble with a thickness of 20 mm, while, in project P3, cream line marble with a thickness of 15 mm was utilized. Marble has been widely employed in sculptures, buildings, countertops, flooring, and decorative elements due to its esthetic qualities and ease of workability.

3.1. Description of Toolpath Strategies

In this study, we used four toolpath strategies, which are described below.

In the Spiral In strategy, the tool starts at the outer edge of the pocket or shape and gradually moves inward in a spiral pattern toward the center. This toolpath is typically used for pocket milling, engraving, or contouring tasks, where the cutting tool needs to remove material in a smooth, continuous manner.

The equations for Spiral In for TP1 are described as follows:

$$\begin{aligned} x &= (D - k{\cdot}a){\cdot}\cos(a) \\ y &= (D - k{\cdot}a){\cdot}\sin(a) \end{aligned} \tag{1}$$

where:

- D: outer diameter;
- a: angle parameter;
- k: step reduction per revolution.

The Spiral Out strategy for TP2 is the reverse of Spiral In. The tool begins at the center of the pocket or shape and spirals outward toward the perimeter. This method is often used when the goal is to start from the center and work outward, such as in engraving or shallow pocketing operations.

The equations for the Spiral Out strategy for TP2 are described as follows:

$$\begin{aligned} x &= (k{\cdot}a){\cdot}\cos(a) \\ y &= (k{\cdot}a){\cdot}\sin(a) \end{aligned} \tag{2}$$

where:

- a: angle parameter;
- k: step reduction per revolution.

In the One Way strategy for TP3, the cutting tool moves in a single direction along the workpiece, typically following a linear path. This toolpath is most used for simple pocketing or contouring tasks and is characterized by tool movement in one direction (either left to right or right to left) for each pass, followed by retraction and a new pass in the same direction.

With 20 flutes, the tool engages with the material at multiple points simultaneously. The cutting path for one pass is determined by the flute spacing with the equations

$$\begin{aligned} x &= x_0 + n{\cdot}w, \\ y &= y_0 + i{\cdot}S_{effective} \end{aligned} \tag{3}$$

where:

- $S_{effective} = s/20$—reduced stepover due to 20 flutes;
- x_0, y_0—start position;

- n—number of passes in X;
- i—number of steps in Y.

The Zig Zag toolpath for TP4, also known as back-and-forth milling, alternates between two directions (left to right and right to left), creating a zig zag pattern. This strategy is often used for pocket milling, profile cuts, and other operations where the material removal needs to be uniform and fast.

In the Zig Zag strategy for TP4, the tool alternates directions, and the 20 flutes reduce the effective cutting stepover distance. The equations become

$$\begin{aligned} x &= x_0 + (-1)^i \cdot (n \cdot w) \\ y &= y_0 + i \cdot S_{effective} \end{aligned} \tag{4}$$

where:

- $S_{effective} = s/20$—reduced stepover distance for 20 flutes;
- x_0, y_0—starting position;
- w—pocket width (adjusted for tool diameter);
- n—zig zag pass number;
- i—row index (alternating directions with $(-1)^i$.

With 20 flutes, the tool maximizes the material removal efficiency while maintaining high cutting accuracy.

Regarding the material removal rate (MRR) for each strategy, we need to consider the following formulas:

$$f_t = f/N = 700/20 = 35 \text{ [mm/tooth]} \tag{5}$$

and

$$MRR = f_t \cdot N \cdot D \cdot W \cdot DOC \text{ [mm}^3\text{/min]} = 3 \cdot 20 \cdot 85 \cdot 70 \cdot 2 = 8330 \text{ [mm}^3\text{/min]} \tag{6}$$

where:

- f—total feed rate (mm/min);
- f_t—feed per tooth (mm/tooth);
- N—number of teeth (flutes) on the tool;
- D—diameter of the tool (mm);
- W—width of cut or stepover (mm);
- DOC—depth of cut (mm).

3.2. Description of Projects

The first project, titled P1, was a square geometry with dimensions of 1200×900 mm^2. The material used was natural stone. The stone was processed using the T0050 tool, with the pocketing procedure performed at a depth of 3 mm in a single step. Project P1 was completed using four toolpath strategies, labeled TP1 (Toolpath Strategy 1) through TP4 (Toolpath Strategy 4). The results are presented in a table, and the time required to complete the project is provided in minutes.

In the second project, titled P2, the geometry was a square with dimensions of 1600×750 mm^2. The material used was natural stone, and the pocketing procedure was carried out with the T0050 tool at a depth of 2 mm. The work process was the same as in the P1 project, and the same tool was used. The simulation of the project was performed using the ICAM3D software.

In the third project, titled P3, a $100 \cdot 50$ square geometry trench was studied. The trench was finished in natural stone material using the side of the T503 tool at a depth of 2 mm in a single pass. The plowing was performed with four different toolpath strategies, labeled TP1 to TP4. The simulation was conducted using the ICAM3D software, and the

final product was created with the Intermac Master 33.3 CNC. The results are presented in a table, showing the time required to complete the work with each of the four strategies, given in minutes. The tools used for the study are described in the following figures.

In Figures 1 and 2, the tools used to complete the work with the four toolpath strategies are presented. The tool shown in the first picture, T503, was used in the third project to complete the trench. The tool shown in the second picture, T0050, was used for the first two projects, titled P1 and P2.

V	Y	D	L	MATERIAL	DIRECTION OF ROTATION	RPM	FEED mm/min	REMOVAL mm	CODE
30	10	10	55	M	DX	7000-8000	300-500	2-3	DFFR00776



Figure 1. Tool T503.

POS	ITEM TYPE	D	H	GRIT	CODE
1-2	Rough segmented	85	35	D427	DRI70162



Figure 2. Tool T0050.

The tool T0050 is designed for material drilling, with a diameter of D = 85 mm and a height of H = 35 mm. It is equipped with 20 teeth and operates within an RPM range of 3800–4200. The permissible feed rate for the T0050 tool is between 600 and 1000 mm/min, with a working depth of 3.84 mm. The primary function of this tool is material removal, specifically through an emptying process.

The T0050 is mounted on a cone that complies with the ISO standards, ensuring ease of installation and replacement upon wear. The tool is equipped with a dual water-cooling system, consisting of external (external) and internal cooling mechanisms. The components of the tool are illustrated in the image below.

For the analysis of the work, an Intermac Master 33.3 CNC machine (Biesse Group company, Pesaro, Italy) was used. Three projects were considered in the analysis. For the first two projects, the simulation was performed using the T0050 tool. In the third project (P3), the simulation was performed with the T503 tool.

Table 1 presents the geometries of the projects, as well as the tools used for each geometry.

Table 1. Analyzed projects and their corresponding codes.

Project Code	Size	Tool
P1	1200 × 900	0050
P2	1600 × 750	0050
P3	100 × 50	503

A toolpath describes the specific route that a cutting tool takes during a machining process, such as milling or turning. Created by using the ICAM3D software, it outlines the movement of the tool over the workpiece to achieve the desired shape. The proper management of toolpaths is crucial in achieving high-quality machining results, including precise dimensions and a smooth surface finish.

In addition, toolpaths consider factors like the properties of the cutting tool, the machining parameters, and constraints related to the process, such as the limitations of the tool holder, ensuring efficient material removal.

There are four variations of toolpath strategies in the ICAM3D software: Spiral In, Spiral Out, One Way, and Zig Zag. These strategies are labeled TP1 to TP4. The toolpath strategy parameter has been used in pocketing operations.

Figure 3 shows the toolpath strategies used in the projects. As seen in Figure 3, all four toolpath strategies were applied: Spiral In, Spiral Out, Zig Zag, and One Way. Based on these strategies, we analyze their efficiency in completing the work in the shortest time possible.

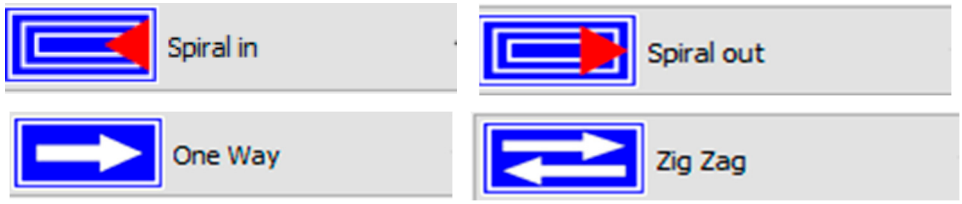


Figure 3. Pocketing toolpath strategy.

The experimental setup is given in Figure 4, which includes all parameters from the definition of the geometry and the materials of the workpiece to the finalization of the CNC program.



Figure 4. CNC toolpath optimization workflow.

In our work, we utilized the Intermac Master 33.3 CNC machine used in stone, glass, and ceramic processing. It is commonly employed in industries related to marble, granite, and other materials for tasks like cutting, shaping, and polishing. This machine is known for its precision and versatility in handling complex operations, such as cutting, drilling, shaping, and polishing. In the course of our work, two distinct tools were utilized for the respective projects. Tool T0050 was employed in projects P1 and P2, while tool T503 was utilized in project P3. The process was carried out on marble material with a thickness of 15 mm and a pocketing depth of 2 mm. Figure 5 demonstrates the CNC machine utilized for the execution of the projects.



Figure 5. CNC machine during the execution of the P3 project.

4. Results

Three projects were considered in the analysis (P1 to P3). A variety of toolpath strategies (TP1 to TP4) in sequence, namely Spiral In, Spiral Out, One Way, and Zig Zag, were used, and aspects such as the cutting speed, feed rate, and cut width were considered.

In projects P1 and P2, the tool used was T0050. Pocketing was performed to a depth of 2 mm, operating at 75% speed. The cooling system utilized water, with both internal and external cooling mechanisms applied for this operation.

Tool Specifications (T0050):

- Diameter (D) = 85 mm;
- Height (H) = 35 mm;
- RPM = 4000;
- Feed rate = 700 mm/min.

In project P3, the tool employed was T503. In the first phase of the operation, 75% speed was used, followed by 100% speed in the second phase. The cutting depth was 2 mm, and cooling was achieved using both internal and external water-cooling systems.

Tool Specifications (T503):

- Diameter (D) = 10 mm;
- Height (H) = 5.5 mm;
- RPM = 8000;
- Feed rate = 400 mm/min.

4.1. Machining Time of Workpiece P1

In the first project, a geometry with dimensions of 1200 × 900 was used. The pocketing of the geometry was performed with the T0050 tool. For the analysis, the total pocketing completion time was recorded for the required dimensions, using four different toolpath models.

Figure 6 shows the geometry used for the study. On the right side, the dimensions of the geometry are displayed, including the 1200 × 900 dimensions and the arc of the geometry. The geometry was created using the ICAM3D software.

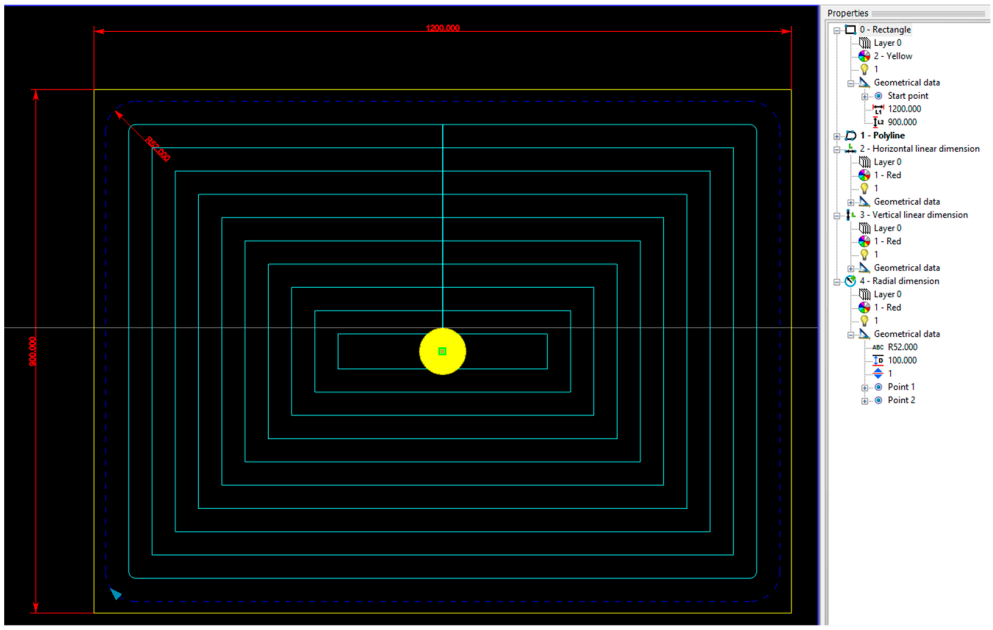


Figure 6. Geometry for pocketing.

In the following figures, one can see the types of toolpaths that were used.

Figures 7–10 show the toolpath views after the completion of the P1 project. The project was first simulated in the ICAM3D software and then processed on the CNC machine. The simulation helped to determine whether the geometry and tool choice were suitable and whether the project could be completed successfully.

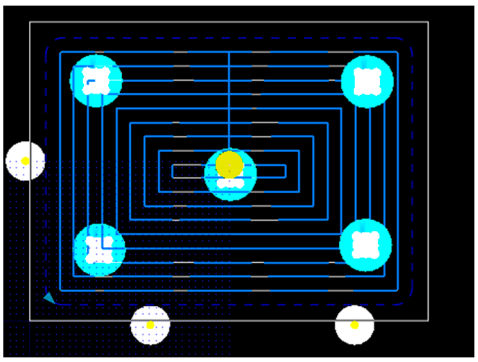


Figure 7. Spiral In.

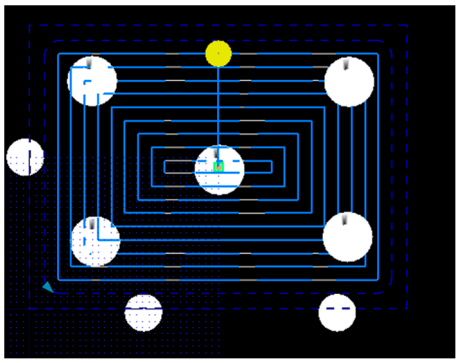


Figure 8. Spiral Out.

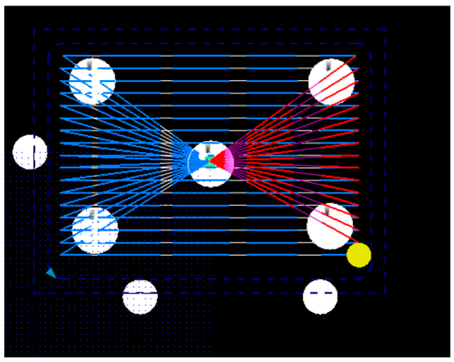


Figure 9. One Way.

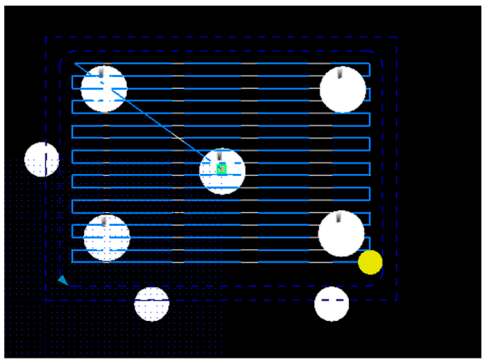


Figure 10. Zig Zag.

Table 2 shows the time taken for project implementation using the four strategies. The toolpath types are labeled TP1 to TP4. The results presented in the table are given in minutes for each strategy. Here, the minimum machining time was achieved with TP4 (Zig Zag) and was 26 min and 37 s.

Table 2. The duration of the project.

Code of Pocketing	Type of Pocketing	Time
TP1	Spiral In	00:28:13
TP2	Spiral Out	00:27:44
TP3	One Way	00:39:18
TP4	Zig Zag	00:26:37

4.2. Machining Time of Workpiece P2

In the second project (P2), the 160 × 750 geometry was used. The pocketing procedure was the same as in the first case and was carried out with the same T0050 tool. Pocketing was performed using four variants of toolpaths, and the results are presented at the side of the table.

In the P2 example, the geometry under analysis had dimensions of 1600 × 750. In contrast to the P1 project, the process of machining the internal surface in P2 was carried out with the surface inclination of A = 0.4. The pocketing process utilized the same toolpath strategies as those employed in the other projects. Figure 11 illustrates the design with the 3D surface tilt from the P2 project.

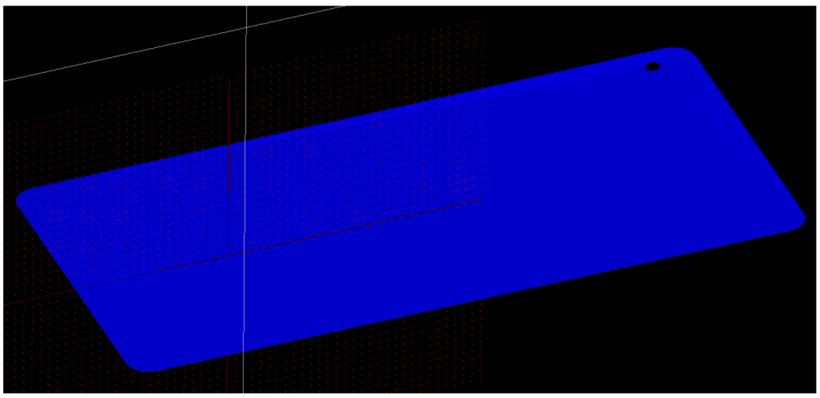


Figure 11. Three-dimensional surface machining with tilt.

In Figure 12, the second project, which we used as a case study for welding toolpaths, is presented. The geometry was analyzed using the ICAM3D software, and its dimensions were 1600 × 750. The geometry data are displayed on the right side of the figure. After the geometry procedure, pocketing was performed using the toolpath strategies from TP1 to TP4.

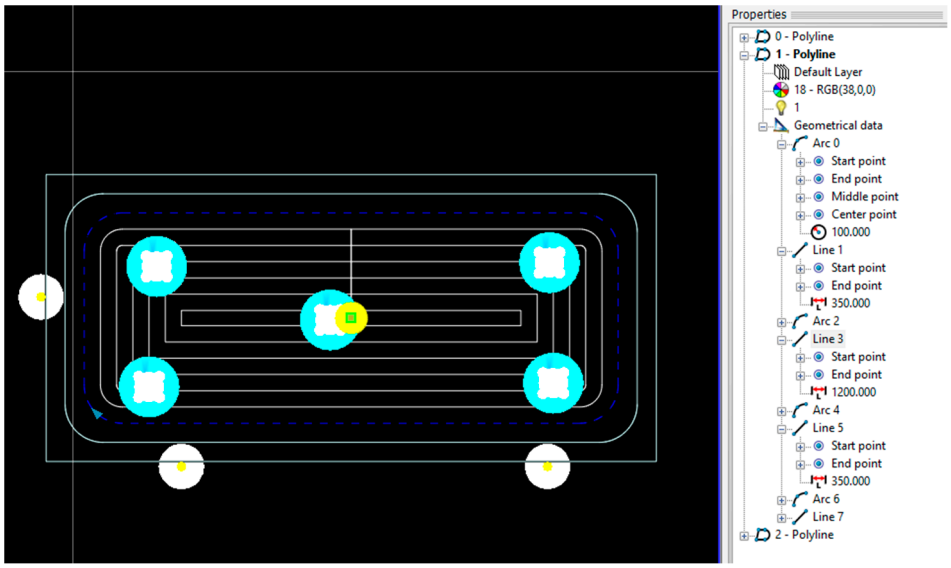


Figure 12. Geometry for pocketing.

In Table 3, the results obtained from the toolpath strategies TP1 to TP4 for the second project, along with the corresponding time results in minutes, are presented. Here, the minimum machining time was achieved with TP4 (Zig Zag) and was 22 min and 6 s.

Table 3. The duration of the project.

Code of Pocketing	Type of Pocketing	Time
TP1	Spiral In	00:23:44
TP2	Spiral Out	00:23:26
TP3	One Way	00:31:47
TP4	Zig Zag	00:22:06

The following figures show the types of toolpaths used for the analysis.

In Figures 13–16, the simulations for the second project (P2) are presented. The simulation process, along with the CNC operations and toolpaths of the project, was analyzed in four ways, as described previously.

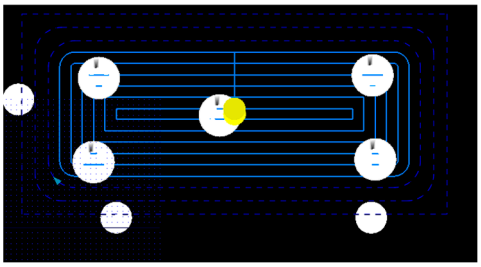


Figure 13. Spiral In.

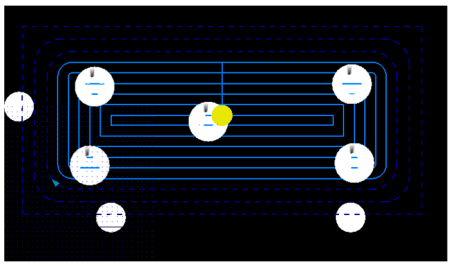


Figure 14. Spiral Out.

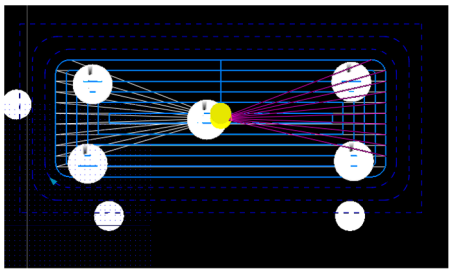


Figure 15. One Way.

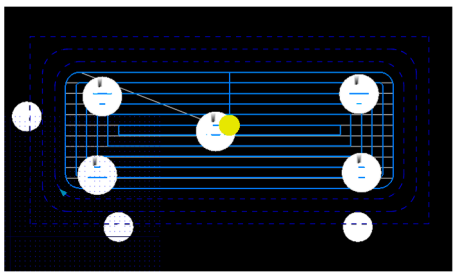


Figure 16. Zig Zag.

From the simulation, the direction of CNC movement during each strategy in the studied toolpaths could be observed.

4.3. Machining Time of Workpiece P3

In the third project, a 100 × 50 logo was used as the basis for the toolpath design. To achieve the pocketing of the geometry, the tool with the code T503 was used. The time taken for pocketing with each toolpath model is shown at the side of the table.

In project P3, the process for creating the logo is demonstrated. In the pocketing operation, the designed text can remain both on the surface of the material and beneath it. Specifically, in project P3, the area surrounding the text was machined to a depth of 2 mm, leaving the text (ALDEX) visible on the remaining surface. The tool employed for this operation was the T503. The machined surface was analyzed using four distinct toolpath strategies. The tool used in project P3 had a diameter of D = 10 mm and a

height of H = 5.5 mm, operated at an RPM range of 7000–8000, and had a feed rate of 300–500 mm/min. The machining was performed on marble with a thickness of 15 mm.

Figure 16 shows the logo used for the analysis in the third project, identified as P3. The P3 project was completed using four toolpath strategies, and the results in terms of time are presented in a table. From the image, one can see the paths of the toolpaths. Figure 17 illustrates all four strategies in one image. The trench pocketing procedure was performed with the T503 tool.

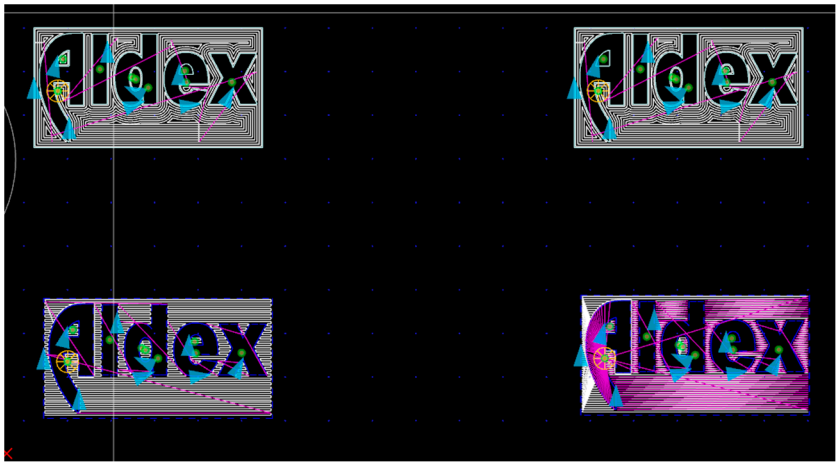


Figure 17. Geometry for pocketing.

Table 4 shows the time taken to complete the trench project using the T503 tool. Here, the minimum machining time was achieved with TP2 (Spiral Out) and was 20 min and 2 s.

Table 4. The duration of the project.

Code of Pocketing	Type of Pocketing	Time
TP1	Spiral In	00:20:10
TP2	Spiral Out	00:20:02
TP3	One Way	01:21:46
TP4	Zig Zag	00:22:19

In the figure below, the final products produced using the four toolpaths are presented.

In Figure 18, the final product of the trench created in marble using the T503 tool is presented. The work was carried out using the four toolpath strategies. The time results are presented in tabular form, and the entire study was analyzed through graphs generated by JavaScript ECMAScript 2015–2017.

Table 5 shows the results obtained from the ICAM3D software and its simulation. The software provided good times for each project (P1, P2, P3). The table presents the best times for the completion of the projects, as well as the most favorable strategy for each, from TP1 to TP4. According to the ICAM3D simulations, the best strategy for the first two projects (P1 and P2) was TP4, which corresponded to the Zig Zag strategy. For the third project (P3), the most favorable strategy was TP2, corresponding to the Spiral Out strategy.

Table 5. The duration of the project from ICAM3D.

Code of Project	Code of Pocketing	Time
P1	TP4—Zig Zag	00:26:37
P2	TP4—Zig Zag	00:22:06
P3	TP2—Spiral Out	00:20:02



Figure 18. The final product from the P3 project.

5. Discussion

Data analysis was performed using JavaScript. The data was collected from both the simulation results of the CNC program and real-time CNC operations. Based on this data collection and analysis, conclusions regarding the impact of the toolpaths on the machining time have been drawn. To create a graph with these values using JavaScript, one can use the Chart.js library, which is a popular and easy-to-use charting library. Below, we give a simple example that shows how to create a bar chart with the given data.

From the above figures, it is evident that the toolpath is most optimized in the fourth mode, i.e., TP2, which corresponds to the Spiral Out type.

For the first project (P1), the minimum machining time was achieved with TP4 (Zig Zag), taking 26:37, while the maximum time occurred with TP3 (One Way), taking 39:18.

For the second project (P2), the minimum machining time was achieved with TP4 (Zig Zag), taking 22:06, while the maximum time occurred with TP3 (One Way), taking 31:47.

For the third project (P3), the minimum machining time was achieved with TP2 (Spiral Out), taking 20:02, while the maximum time occurred with TP3 (One Way), taking 01:21:46. See Figure 19.

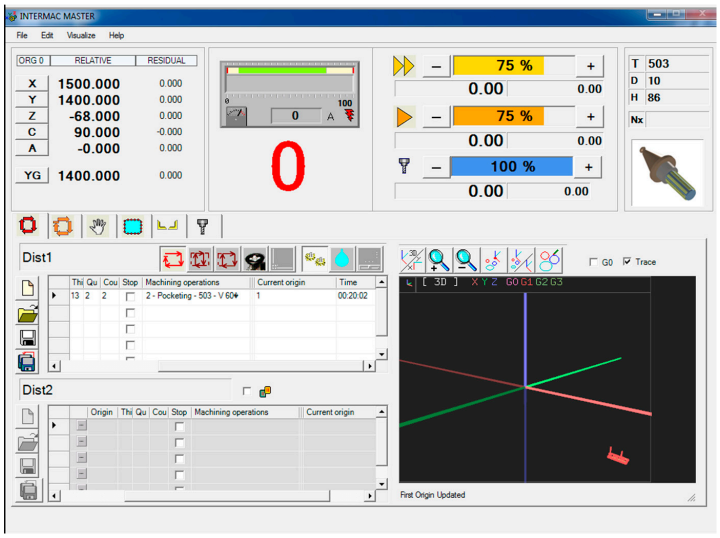


Figure 19. Machining time for the third project (P3).

A comparison of the machining processes for all toolpath strategies is shown in Figure 20.

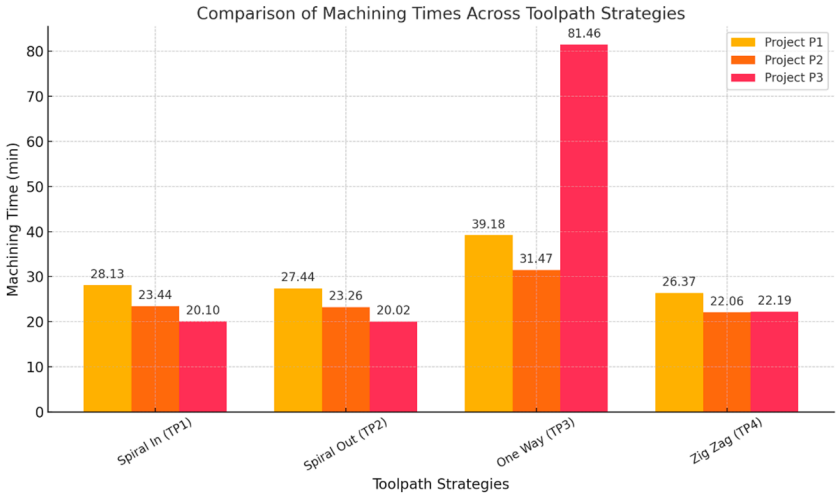


Figure 20. Graph of the work performed for all toolpath strategies.

Additional Optimization of the P3 Project's Time

To achieve the desired results, we utilized the capabilities offered by external software for the pocketing procedure, complementing the intended workflow. Specifically, this involved the use of tools not included in the software that controlled the Intermak Master 33.3 CNC machine. In this context, the ICAM3D software provides only four types of toolpath strategies. The strategies available within ICAM3D are illustrated in the figure below.

Additionally, other strategies were employed using the AutodeskArtCAM Version 2018.0.0 and Aspire software Version 2018.0.0. Toolpath optimization in ArtCAM enhances the efficiency and quality of CNC machining operations, especially for artistic and detailed tasks. By utilizing strategies such as tool selection, lead-in/lead-out optimization, depth control, and multi-tool management, ArtCAM users can significantly reduce the cycle times, improve the tool life, and ensure high-quality finishes. In Aspire, we have taken into consideration the entry and exit points. Optimizing these points ensures that the tool starts and finishes in areas that minimize rapid movements and reduce unnecessary travel time, thus improving overall efficiency. Optimization techniques such as lead-in/lead-out, step-over control, and toolpath linking have been examined for their roles in enhancing the material removal rates while minimizing tool wear.

The toolpath strategy that minimizes the machining time was selected and converted into G-code. This G-code was then optimized using the OptimizeCNC-G code optimizer 2015 software. OptimizeCNC is a specialized tool designed to enhance G-code for CNC machines, offering automatic optimization to reduce machining times by refining the toolpath strategy.

After receiving data from ICAM3D and the real data from the CNC for the P3 project, the final time for the completion of the project was reduced to 15 min and 23 s; see Figure 21. To further optimize this work time, additional software, including ArtCAM and Aspire, to implement a new toolpath strategy was used.

These software tools enabled us to generate an optimized G-code, which was then tested using G-code simulators. As a result, improved outcomes that significantly reduced the CNC machine's working time for the project were achieved. The optimization not only enhanced efficiency but also contributed to maximizing the overall performance of the CNC operation. The time as optimized by the software and G-code was 13 min and 33 s. In Figure 22, the simulation of the time optimization through the G-code is presented.

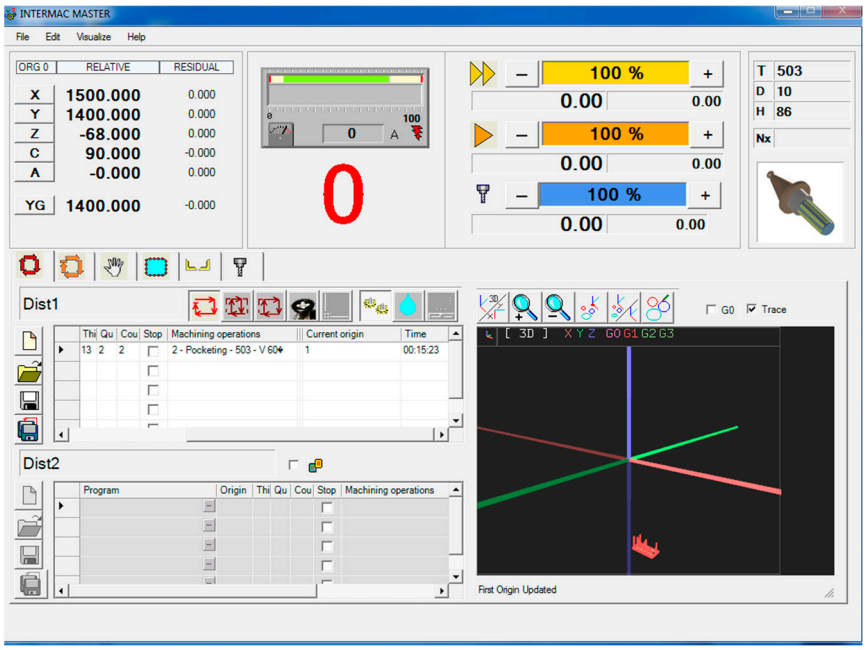


Figure 21. Real-time data from the CNC to complete the project.

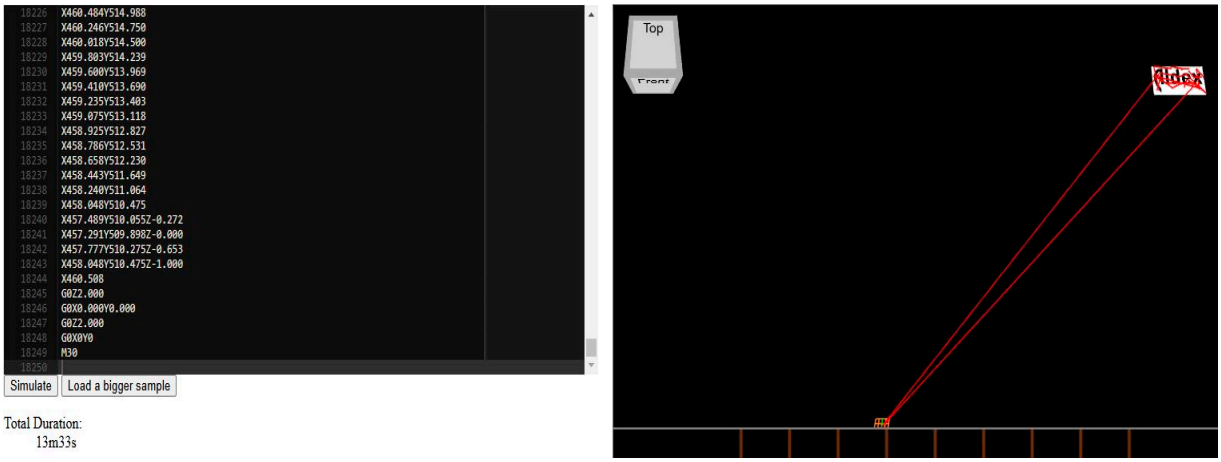


Figure 22. Time optimization of G-code.

In Figure 23, the completion time of the project using ICAM3D and the G-code is compared.

As is shown, the initial time to complete the project on the CNC machine was 15 min and 23 s. Meanwhile, after using the G-code and other software, the machining time was reduced to 13 min and 33 s.

The time required to complete project P3, using the analyzed model and the speed set at 75% during the analysis, was 20 min and 2 s. From this, we can conclude that, under the allowed conditions of the CNC machine, with a 100% speed setting (as shown in the figure and confirmed through the simulation), the required time to complete project P3 is 15 min and 23 s. The optimized time, achieved through the G-code generated by the ArtCAM and Aspire software, was reduced from 15 min and 23 s to 13 min and 33 s.

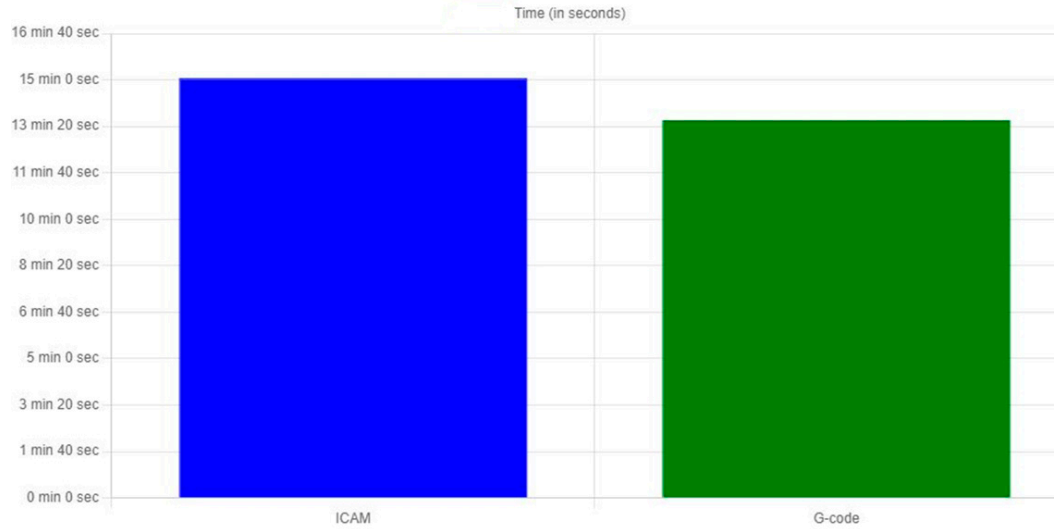


Figure 23. Time comparison: ICAM3D vs. G-code.

6. Conclusions

In this study, we evaluated four toolpath strategies: Spiral In, Spiral Out, Zig Zag, and One Way.

From the data analysis, one can conclude that the choice of toolpath is very important in the operation of CNC machines. The incorrect choice of tools will affect the machine's operating time, as seen in the P3 project, where the minimum work time was 00:20:02 and the maximum was 01:21:46.

However, the choice of toolpath also depends on the geometry of the workpiece. From the analysis, one can find that the minimum machining times for the projects and the corresponding toolpath types are as follows.

Overall, the minimum machining time was obtained using TP4, the Zig Zag pattern, while the maximum time was recorded with TP3, the One Way pattern. The completion time for project P3 was 20:02 min. Given the data from ICAM3D and the real data from the CNC for the P3 project, we reduced the final time for completion to 15 min and 23 s. The time as optimized by the software and G-code was further reduced to 13 min and 33 s.

Since only four strategy models were permitted by the software for the CNC type used in this case, we employed additional software such as ArtCAM and Aspire, which provide further optimization capabilities. From these software programs, a G-code was generated, which, after optimization, was used in the CNC machine.

In general, we took advantage of the limitations of the standard ICAM3D software in the pocketing process and the benefits offered by other software tools to create an optimized G-code in terms of time efficiency.

Starting from the maximum optimized time of 15 min and 23 s at the CNC's maximum speed, we were able to reduce this time to 13 min and 33 s by utilizing additional software and the G-code optimization process.

This study could help engineers to optimize their workflows, especially for complex geometries. By identifying optimal strategies, it aligns sustainable manufacturing practices by maximizing resource utilization.

Future studies should be focused on the usage of machine learning models to predict the optimal toolpath strategies based on the workpiece geometry, material, and machining parameters.

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