

The Evaluation of Machining Time in Drilling Process using Modified Ant Colony Optimization and Conventional Method

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Abstract

Machining time is one of the aspects of drilling process which affects productivity and cost efficiency. To minimize the machining time, optimization approaches which are based on Artificial Intelligence (AI) methods have been implemented to determine the optimum rapid tool path length in the drilling process. Ant Colony Optimization (ACO) was used in this study to optimize the tool path in the drilling process. However, ACO had to be modified due to facing convergence issues, leading to suboptimal solutions or enhancing the length of tool path. The best tool path length was achieved by implementing Modified ACO in Matlab R2024A software, which was then evaluated and simulated in Mastercam. There were two workpieces designed in SolidWorks software which contain 36 holes and 135 holes respectively in order to analyze the effectiveness of the Modified ACO. By using a ranking-based pheromone update mechanism, the Modified ACO has enhanced convergence and minimized rapid tool movement. The Modified ACO has reduced the machining time for Sample 1 by 0.17% when compared to the conventional ACO and by 0.55% when compared to the Mastercam technique. Improvements for Sample 2 were 0.12% and 0.84%, respectively. These results have demonstrated that the Modified ACO effectively reduces rapid tool movement, machining time and increases machining efficiency, fulfilling the main goals of this study.

1. Introduction

In modern manufacturing, efficient machining processes are crucial for enhancing productivity, reducing costs, and improving product quality. Among these processes, drilling remains a fundamental and widely used technique in various manufacturing applications. It entails creating circular holes in a workpiece with a spinning cutting tool known as a drill [1]. Hole making processes such as drilling, reaming and tapping account for a significant portion of the total machining time in production of manufactured parts [2]. The point-to-point movement in the hole making operations, along with the specific requirements of each process, varies based on factors such as tool changes and the machine table's movement from one location to another.

With continuous advancements in exploration and development technologies, drilling operations have evolved to become increasingly complex and dynamic [3]. Ren et al. [4] confirmed that traditional empirical rules and guidelines are no longer adequate to meet the efficiency and quality demands of modern drilling operations. To

identify the most efficient routes that minimize travel distance and ensure smooth transitions between machining operations, AI-based approaches such as Ant Colony Optimization (ACO), Genetic Algorithms (GA), Bee Colony, Cuckoo Search, and Particle Swarm Optimization (PSO) are increasingly being utilized. According to Ullrich et al. [5], the integration of AI in machining presented a valuable opportunity to enhance both operational efficiency and component quality.

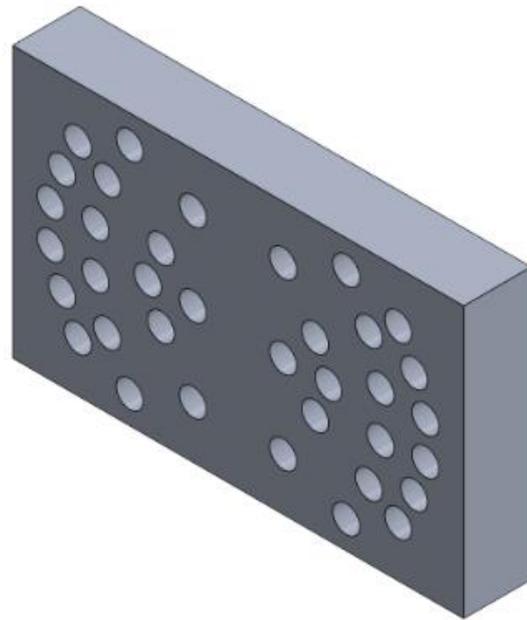
Taking into account the limitations of drilling tools and the geological environment, it is essential to optimize the trajectory parameters by defining an appropriate objective function, in order to increase the success rate and reduce costs[6]. According to previous research, various optimization models have been successfully applied to determine the optimal tool paths [7][8]. For example, according to Sha & Pan [9], the study achieved the highest convergence rate for drilling trajectory length by utilizing a quantum Genetic Algorithm based on the Fibonacci sequence. Halafawi & Avram [10] optimized the horizontal well trajectory by determining the drilling path length using the minimum Curvature method. The drilling trajectory length was optimized by Atashnezhad et al. [11] utilizing a unique Particle Swarm Optimization technique, and the algorithm's efficiency was enhanced by meta optimization. Xu et al. [12] optimized the drilling trajectory length with fast convergence using the Ant Colony algorithm. According to Darwis Asri & Abdullah [13], by reducing the length of the tool path taken during the drilling process, a non-traditional technique known as Ant Colony Optimization (ACO) was used to reduce the amount of time needed for the machining process. Ning et al. [14] stated that the ACO algorithm is one of the well-known incomplete algorithms, recognized for its high speed and accuracy in efficiently finding quasi-optimal solutions. In this study, the efficiency of drilling operations was evaluated by comparing the tool paths generated using the Modified ACO with those produced by conventional methods. The 3D machining model, used to simulate the precise drilling of holes in a workpiece was created using SolidWorks. The Modified ACO algorithm, designed to optimize the drilling sequence, was then developed in Matlab. By analyzing the resulting tool paths in Mastercam, this study evaluated the effectiveness of the Modified ACO in reducing machining time, providing valuable insights into its applicability for real world operations.

2. Research Methodology

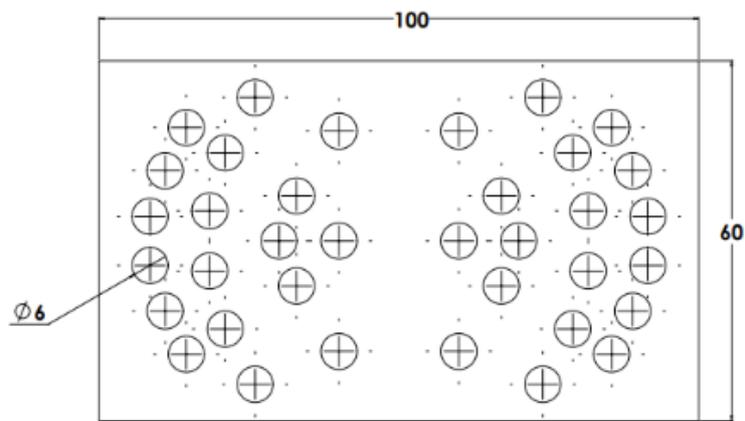
Fig. 1 and Fig. 2 show two workpieces that were used in this study. Both workpieces contain different dimensions and number of holes. Those workpieces are known as Sample 1, which has 36 holes and for complex design, Sample 2 has 135 holes. The two basic rectangles of different measurements with holes of the same radius but different coordinates were created using the SolidWorks2023 software. Sample 1 and Sample 2 were drilled with a diameter of 6 mm and a depth of 10 mm. Table 1 illustrates the specifications between Sample 1 and Sample 2. The type of workpieces that were used in this study is Aluminium 6061. These workpieces were chosen due to their widespread use in engineering applications [13].

Table 1 *The specifications of Sample 1 and Sample 2*

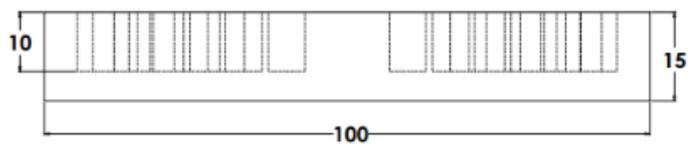
Specifications	Sample 1	Sample 2
Dimension (mm)	100 x 60 x 15	100 x 120 x 15
Diameter (mm)	6	6
Number of Hole	36	135
Depth of Hole (mm)	10	10
Material	Aluminium 6061	Aluminium 6061



(a)



(b)



(c)

Fig. 1 Workpiece of Sample 1 (a) isometric view (b) front view (c) bottom view

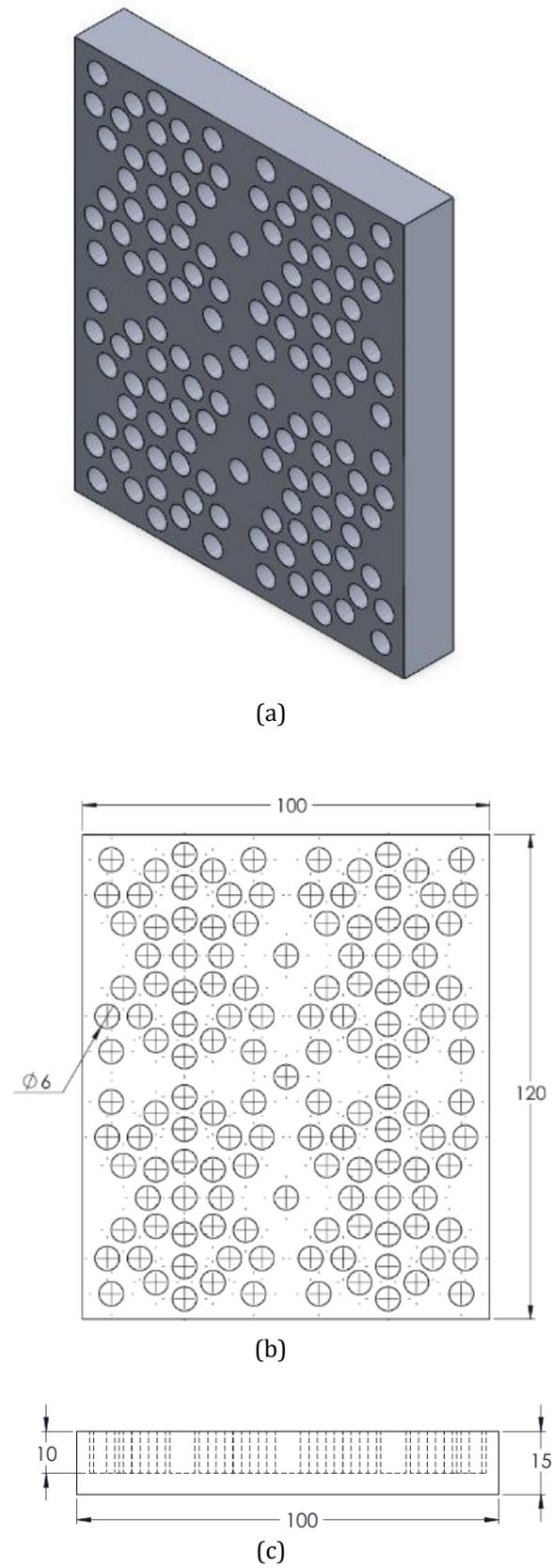


Fig.2 Workpiece of Sample 2 (a) isometric view (b) front view (c) bottom view

2.1 Modified Ant Colony Optimization

In this study, Matlab software was used to develop a Modified ACO algorithm aimed at minimizing the tool path length in the drilling process. The tool path length was defined as the total distance traveled by the drilling tool. The drilling sequence was determined based on the optimized route generated by the Modified ACO implemented in Matlab. As the virtual ant travels from the initial position to the final hole location, the algorithm constructed a complete and efficient drilling path. The movement of the ant from one point to another is guided by a probabilistic decision-making rule, commonly known as the arbitrary probability rule [15], as expressed in Equation 1. This rule determined the likelihood of the ant choosing a specific path, contributing to the formation of the optimal drilling route.

$$P_{i,j}^k(t) = \begin{cases} \frac{[\tau_{i,j}(t)]^\alpha [\eta_{i,j}(t)]^\beta}{\sum_{j \in N_i^k} [\tau_{i,j}(t)]^\alpha [\eta_{i,j}(t)]^\beta} & j \in N_i^k \\ 0 & \text{if } j \text{ has been passed} \end{cases} \quad (1)$$

Where;

- N_i^k = the list of nodes that weren't visited by ant
- $\tau_{i,j}(t)$ = intensity of trail on edge (i, j) at time (t)
- α = parameters affecting pheromone
- $\eta_{i,j}(t)$ = $1/d_{ij}$ (visibility)
- β = visibility weight

The ants were positioned at random on each hole, and the distance between each hole (β) or the pheromone trail value (α) affected their migration to another hole. The shortest distance would be ascertained once each ant had finished its own loop, and the pheromone had been changed on each vertex in accordance with the global updating algorithm. Until the maximum iteration set was reached, this operation was carried out repeatedly.

2.2 The Simulation of Drilling Process using Mastercam

Mastercam software has greatly improved the drilling process in computer-aided manufacturing (CAM) by offering advanced tools and features that enhance accuracy, efficiency and automation. In this study, Mastercam X5 software was used to simulate the drilling process on the workpieces. This section evaluated the effectiveness of the tool path generated by the Modified ACO by comparing its cycle time in Mastercam against both the conventional ACO and Modified ACO. The primary objective was to identify which method yields the shortest machining time and calculated the percentage difference in performance between them. Equation 2 was used to calculate the percentage difference. The goals of this study were achieved when the Modified ACO demonstrated improved machining time efficiency. To evaluate this, the tool path length generated by the Modified was compared with those obtained from Mastercam sort methods and the conventional ACO. Table 2 shows the type of methods of drilling process used in Mastercam.

Table 2 The type of methods of drilling process used in Mastercam

No.	Methods
1	X+ Y+
2	X ZIG+ Y+
3	Y+ X+
4	Y ZIG+ X+
5	X- Y-
6	Conventional ACO by Matlab
7	Modified ACO by Matlab

Percentage differences % =

$$\frac{\text{Machining time of conventional method} - \text{Machining time of Modified ACO}}{\text{Machining time of conventional method}} \times 100 \quad (2)$$

3. Results and Discussion

The simulation has been performed to study the machining time in drilling process generated by the tool path length based on sort methods by Mastercam and both conventional and Modified ACO. To assess the effectiveness of the tool path generated by the Modified ACO in Matlab, the results were compared to determine which method produced the shortest machining time. Through this evaluation, the study aimed to highlight the efficiency and optimization capability of each technique.

3.1 Result of Simulation Based on Mastercam

As presented in Tables 3 and Table 4, five different sort methods were selected to simulate Sample 1 and Sample 2 using Mastercam X5 software for the purpose of obtaining results and analysis.

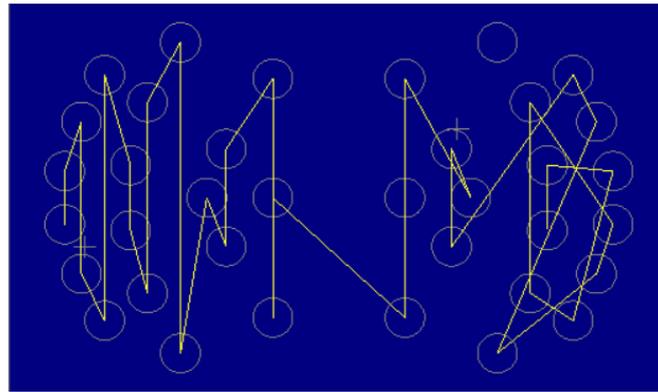
Table 3 The result of the total cycle time and tool path length in Mastercam for Sample 1

No.	Sort method	Feed path length, mm	Feed time, s	Rapid path length, mm	Rapid time, s	Total cycle time, s
1	X+ Y+	720	233.51	2574.98	12.35	245.87
2	X ZIG+ Y+	720	233.51	1944.2	9.3	242.82
3	Y+ X+	720	233.51	1554.971	7.41	240.92
4	Y ZIG+ X+	720	233.51	1359.544	6.35	239.86
5	X- Y-	720	233.51	2574.98	12.35	245.87

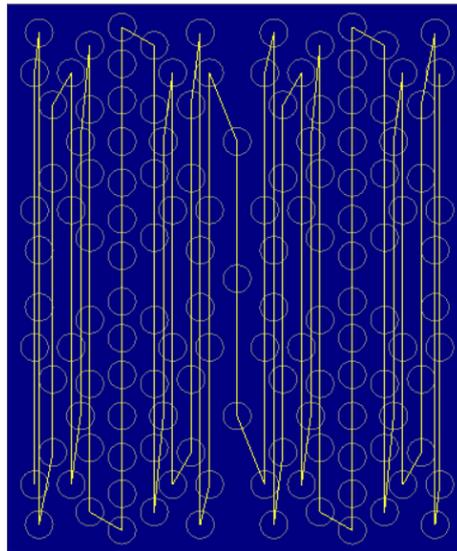
Table 4 The result of the total cycle time and tool path length in Mastercam for Sample 2

No.	Sort method	Feed path length, mm	Feed time, s	Rapid path length, mm	Rapid time, s	Total cycle time, s
1	X+ Y+	2700	875.68	7184.936	34.47	910.14
2	X ZIG+ Y+	2700	875.68	5442.778	26.07	901.74
3	Y+ X+	2700	875.68	7376.367	35.4	911.07
4	Y ZIG+ X+	2700	875.68	5423.315	25.97	901.64
5	X- Y-	2700	875.68	7182.878	34.46	910.13

Based on the results, the shortest machining time for Sample 1 was 239.86 seconds, achieved using the Y ZIG+ X+ sort method. For the more complex design, Sample 2 recorded the shortest machining time of 901.64 seconds, also generated using the Y ZIG+ X+ sort method. Figure 3 illustrates the tool path lengths produced by the selected methods in Mastercam for both Sample 1 and Sample 2.



(a)

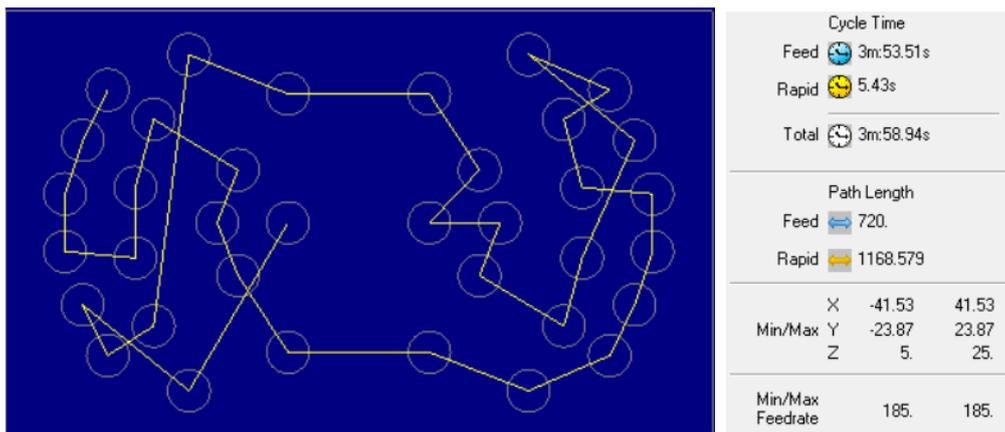


(b)

Fig.3 Sorting method Y ZIG+ X+ (a) Sample 1 (b) Sample 2

3.2 Result of Simulation Mastercam Based on Conventional ACO

The simulation in Mastercam based on conventional ACO was conducted after generating the tool path length using Matlab. The resulting shortest tour length was then applied in Mastercam to achieve the minimum machining time. Fig. 4 illustrates the tool path lengths for Sample 1 and Sample 2 created using the conventional ACO approach.



(a)

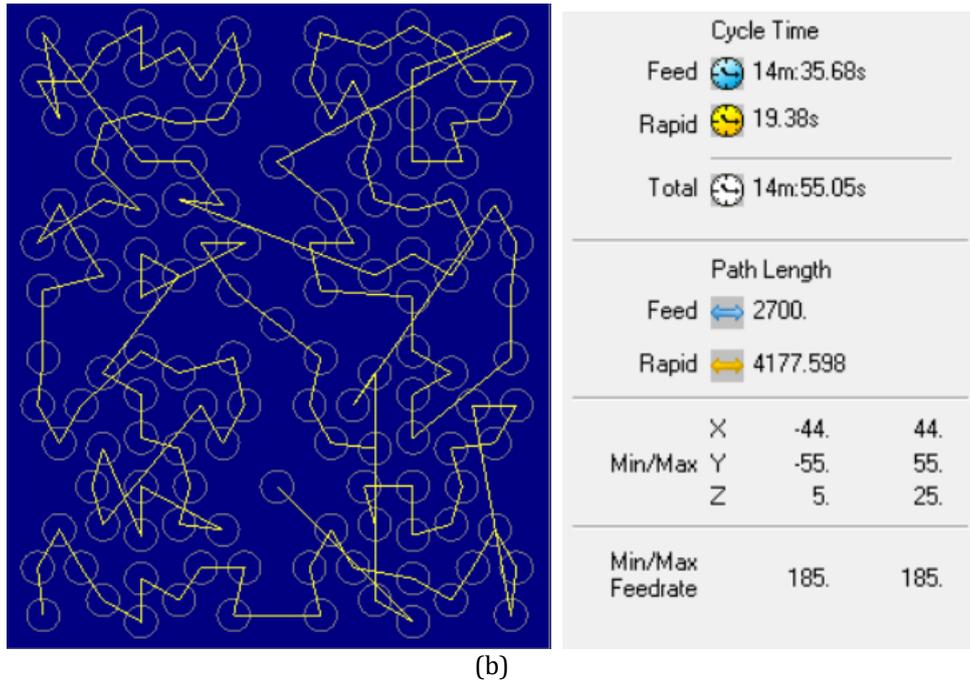
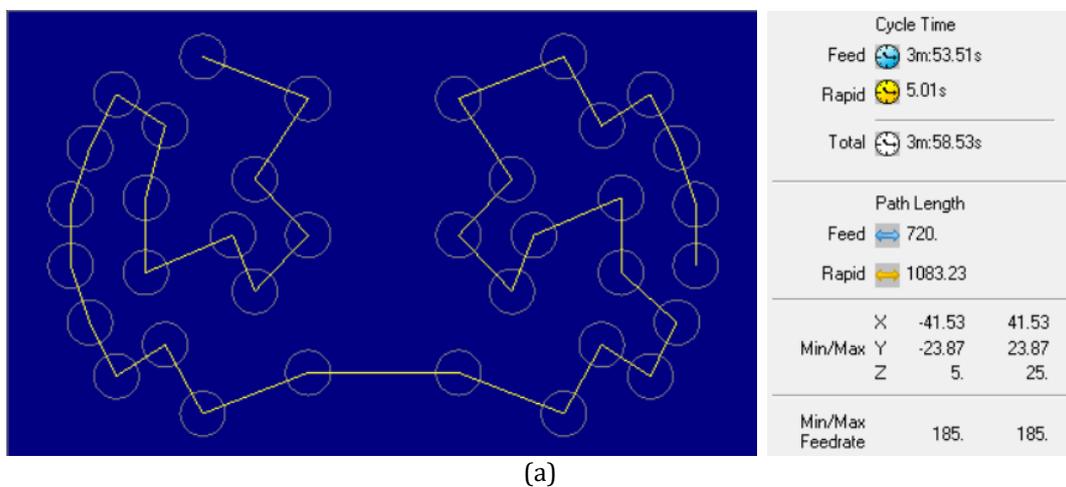


Fig.4 Tool path length based on conventional ACO (a) Sample 1 (b) Sample 2

According to the simulation results, the total machining times for Sample 1 and Sample 2 using conventional ACO were 238.94 seconds and 895.05 seconds, respectively. These findings indicated that the conventional ACO was capable of optimizing the tool path length more effectively than the sort methods available in Mastercam.

3.3 Result of Simulation Mastercam Based on Modified ACO

The Mastercam simulation based on Modified ACO was carried out after generating the optimized tool path length using Matlab. The resulting shortest tour length was applied in Mastercam to achieve minimal machining time. Fig. 5 illustrates the tool path lengths for Sample 1 and Sample 2 created using the Modified ACO approach.



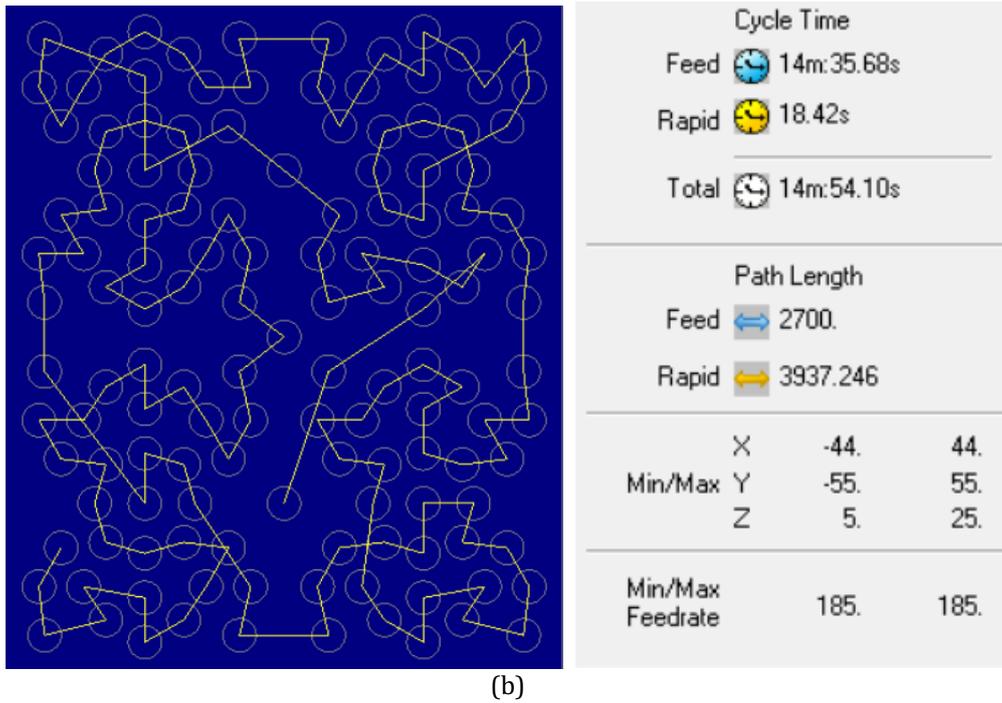


Fig.5 Tool path length based on Modified ACO (a) Sample 1 (b) Sample 2

Based on the simulation results, the total machining times for Sample 1 and Sample 2 using the Modified ACO were 238.53 seconds and 894.10 seconds, respectively. For Sample 1, the Modified ACO successfully reduced the rapid tool path length to 1083.23 mm, achieving a cycle time of 238.53 seconds. This outperformed the conventional ACO by 0.41 seconds and Y ZIG+ X+ sort method by 1.33 seconds. The performance advantage was even more significant in Sample 2, where the Modified ACO reduced the rapid tool path length to 3937.25 mm, resulting in a cycle time of 894.10 seconds. This reflected a 0.95-second improvement over the conventional ACO and a 7.54-second improvement compared to the Y ZIG+ X+ method. Overall, the Modified ACO demonstrated superior efficiency by minimizing both rapid movement length and machining time across both samples.

3.4 Comparison of Total Cycle Time and Tool Path Length Based on Default Mastercam, Conventional ACO and Modified ACO

When the Modified ACO was compared with both the conventional ACO and the Mastercam sorting method (Y ZIG+ X+), the results in Tables 5 and 6 clearly demonstrated the effectiveness of the Modified ACO in reducing overall cycle time and tool path length. These improvements were further supported by the calculated percentage differences between the Modified ACO and both default Mastercam method and conventional ACO.

Table 5 The result of the total cycle time and tool path length in Mastercam based on three techniques for Sample 1

No.	Sort method	Feed path length, mm	Feed time, s	Rapid path length, mm	Rapid time, s	Total cycle time, s
1	Y ZIG+ X+	720	233.51	1359.544	6.35	239.86
2	Conventional ACO	720	233.51	1168.579	5.43	238.94
3	Modified ACO	720	233.51	1083.23	5.01	238.53

Table 6 The result of the total cycle time and tool path length in Mastercam based on three techniques for Sample 2

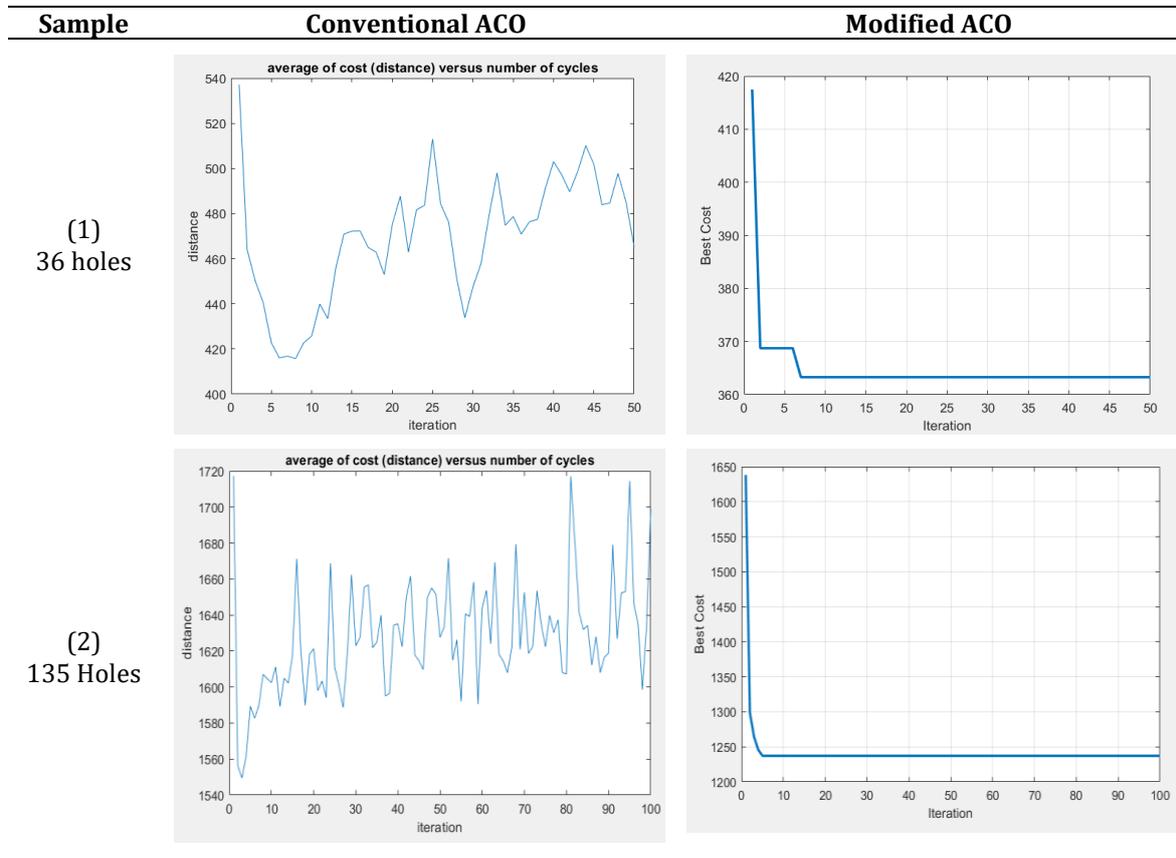
No.	Sort method	Feed path length, mm	Feed time, s	Rapid path length, mm	Rapid time, s	Total cycle time, s
1	Y ZIG+ X+	2700	875.68	5423.315	25.97	901.64
2	Conventional ACO	2700	875.68	4177.598	19.38	895.05
3	Modified ACO	2700	875.68	3937.246	18.42	894.10

Although the difference in total cycle time between the Modified ACO and conventional ACO in Mastercam was relatively small, it did not fully reflect the overall efficiency and effectiveness of the tool path planning. The Modified ACO achieved a notably shorter total tool path length compared to the conventional ACO, indicating a more optimized and efficient routing between drilling points. While the reduction in path length may have only a minor impact on machining time in small scale applications, its benefits became increasingly significant in larger scale production environments.

3.5 The Graphical Comparison of Conventional ACO and Modified ACO Using Matlab Implementation

The comparison of the two samples revealed a considerable difference in convergence behaviour. Table 7 illustrates the graphs of Sample 1 and Sample 2 implemented by Matlab using conventional ACO and Modified ACO algorithms.

Table 7 The graphical comparison of conventional ACO and Modified ACO



The graph for the conventional ACO displayed significant variability across iterations, with the cost (distance) fluctuating considerably and lacking a clear downward trend. This suggested that the algorithm has been struggled to reach an optimal or near optimal solution, frequently exploring less efficient paths. The inconsistency indicated that promising solutions were not effectively exploited, and excessive exploration led to instability in tool path optimization.

In contrast, the Modified ACO showed rapid and stable convergence. The cost decreased sharply during the initial iterations and then gradually levelled off, displaying minimal fluctuations in the remaining cycles. This behaviour suggested that the improved algorithm was more effective at identifying promising solutions early in the search process, leading to a shorter and more optimized tool path. The smooth and early convergence reflected a well-balanced approach between exploration and exploitation.

4. Conclusion

According to this study, it can be concluded that the goal of this study which is to study the machining time in drilling process using Modified ACO implementation has been successfully achieved. The Modified ACO was recommended to be an effective method for optimizing tool path length, thereby reducing machining time during drilling operations. Furthermore, analysis of various tool path strategies demonstrated that Modified ACO offered the best balance between machining time and tool path efficiency. By minimizing unnecessary travel and non-cutting movement, the Modified ACO not only enhanced productivity but also improved machine utilization and contributed to long-term cost savings. In summary, the Modified ACO proved to be reliable for improving machining efficiency in both simple and complex drilling tasks.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Nur Aisah, Haslina; **data collection:** Nur Aisah; **analysis and interpretation of results:** Nur Aisah, Haslina; **draft manuscript preparation:** Nur Aisah. All authors reviewed the results and approved the final version of the manuscript.*

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