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# Application of ARAS Method for Finding Out the Best Possible Combination of Input Parameters for Least Hole Defects While Drilling CFRP Laminates

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## Abstract

The drilling of carbon fiber reinforced plastics (CFRP) composite laminates is quite different from those of traditional metal owing to the anisotropic nature of the composite laminates. The high stiff fibers were alternatively placed with a malleable matrix making things worse when the drill tool encounters these materials having different mechanical and thermal properties. Although having exceptional properties like a high strength-to-weight ratio, high stiffness ratio, corrosion resistance, etc., it has been kept in the hard-to-machine material category. Therefore, while drilling these materials an optimized parameter setting is essential for ensuring high standard damage-free holes for structural building purposes. A Multi-criteria decision-making (MCDM) method has been used to deal with the difficulty faced while selecting the process parameter settings from a large number of potentially viable alternatives. Therefore, in this particular research paper, a decision-making model using the Additive ratio assessment (ARAS) method was used for finding the best possible alternative for drilling CFRP laminates. It was confirmed that this method can be utilized in solving the real-time problem of selecting the best parameter setting while drilling CFRP composite materials. Based on this method alternative with a low drill point angle (110°), high spindle speed (3200 rpm), and low feed rate (0.025 mm/rev) was found to be the best setting for drilling holes.

## Keywords

Drilling, Carbon fiber reinforced plastic, Delamination, Multi-criteria decision-making, Additive ratio assessment

## Introduction

Carbon fiber reinforced composite laminates are the new steel in the structural-making industries like aircraft, automobile, and sports goods making industries. However, in the last two decades, its extensible use makes it the first choice for manufacturing engineers. In the aviation industry, it replaces traditional metals and its uses soar up to 60 - 70% of the total weight [1]. Unmatchable qualities like high strength-to-weight, corrosive resistance, and high stiffness, and can be molded into any intricate shape makes it different in comparison to its counterpart. In aircraft-making industries, the selected material undergoes various safety and quality checks to ensure the safety of the passengers boarding the aircraft [2, 3]. Complex structures have to be prepared with near-to-neat shapes to meet the stringent requirements which is much more difficult to prepare [4]. Therefore, parts were separately prepared with desired specifications and assembled in the final assembly line. Assembling the complex parts necessitates a joining process like riveting, bolting, and welding [5]. However, riveting and bolting are generally preferred above permanent joining like welding that allows the repair works.

Drilling is considered the most effective and widely used machining process for making holes. However, drilling holes in heterogeneous composite laminate is different from that of the homogeneous metal is and also rather difficult [6]. As the drill bit gets into the laminate it encounters layers of stiff carbon fibers and a pliable matrix simultaneously which makes the process even worse. The shearing action of the drill tool initially breaks the fibers and then detaches them from the parent matrix causing the material removal. However, this action also causes surface defects like delamination and fiber to pull out and it is severe, especially in those regions where the force of attraction between the constituting layers is weak. Similarly, the tool surface rapidly wears out due to the springing back action of the uncut fibers and eventually increases the surface roughness and roundness error [4, 7]. However, among the defects that occurred during the drilling of CFRPs, delamination damage has been considered the most critical one as it directly affects the bearing strength of the joint and service life. The delamination defects generally occur on the surface of the laminate where the drill tool enters and leave it while forming the through hole [8]. Though the delamination damage cannot be completely eradicated, controlling the machining parameters, and modifying the tool geometry can be controlled up to a certain extent.

Studying the drilling-induced thrust force and the corresponding torque is important as it directly regulates the damage that occurred on the hole surface. It is quite evident that the thrust force that occurred during the drilling process is the prime indicator of the occurrence of delamination damage. The thrust force is found to be increased with an increase in the feed rate and vice versa. The feed rate is the depth of cut as in the case of drilling, with an increase in it increases the internal resistance to the machining process and eventually increases the thrust force. However, the higher spindle speed (another controllable parameter in the drilling process) eventually reduces the hole damage [6]. Drilling is always considered the most complex process due to its geometry as the speed varies across the wedge. However, among the geometrical parameters, the drill diameter and the point angle play a crucial role. A low point angle tool with less contact area between the drilling surface and the material produces the least thrust force, eventually reducing the delamination factor. Therefore, an optimal parameter setting can result in a damage-free hole while drilling hard-to-machine material like CFRP.

Over the last two decades, various traditional and non-traditional optimization techniques have been used by manufacturers for selecting the optimal parameters setting while drilling high abrasive materials like CFRP [9-13]. In this case, a MCDM is proved to be a reliable decision-making technique while dealing with problems where the selection of the parameters directly influences the acceptability of the job [14-17]. In this method, the optimal solutions are calculated based on the 'closeness' to the 'ideal solution' by comparing the evaluated ranks of each alternative. This method also proved to be beneficial where a large number of probable alternatives of various criteria are associated with it. Various MCDM methods are available for decision making like MOORA, GRA, CODAS, ERAS, TOPSIS, ELECTRE, VIKOR, etc. [16-18]. However, none of the proposed works of literature provides a generalized method for selecting the input drilling parameters for drilling heterogeneous CFRP laminates which can address all the issues. Therefore, in this research paper, a decision-making model has been developed to select the best possible process parametric combination which eventually reduces the defects and enhances the production. The ARAS method has been used in this study to evaluate the possible alternatives and rank them accordingly to the user requirements. This has been explained in the following section. The criteria weights used in the proposed optimization technique have been evaluated by adopting the compromised criteria weighting method that includes the Analytic hierarchy process method and entropy method and the values are presented in table 1. The graphical overview of the present investigational study has been presented in figure 1.

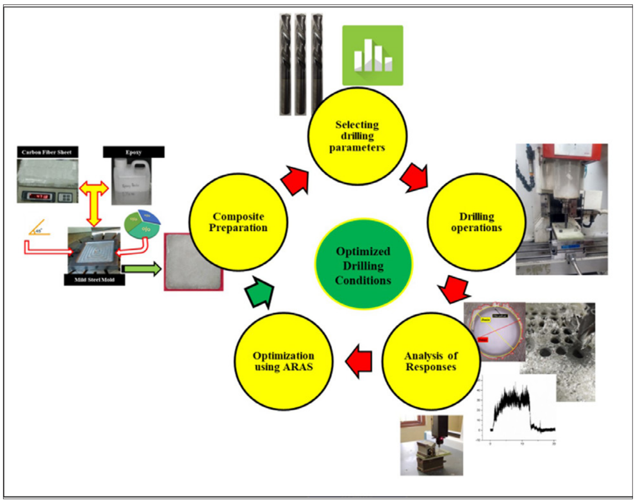

Figure 1: Graphical illustration of the present study.

## Experiment

The ARAS decision-making method is assigned the task of ranking a finite number of alternatives [19]. Those alternatives were described in terms of different decision criteria and analyzed at the same time. However, as per this method, the efficiency of an alternative is represented by a utility functional value which is directly proportionate to the numerical values and weight assigned to the main criteria. This decision-making method starts with forming a decision-making matrix by exhibiting the performance value of different alternatives concerning various criteria.

A matrix ($D$) with 'n' number of criteria and 'm' number of alternatives is represented as [19]:

$$D = \begin{array}{c} D_1 \\ D_2 \\ \dots \\ \dots \\ D_m \end{array} \begin{pmatrix} x_{11} & \dots & x_{12} \\ x_{21} & \dots & x_{2n} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ x_{m1} & \dots & x_{mn} \end{pmatrix} \quad (1)$$

Where, '$x_{ij}$' is the performance value, i = 1, 2, 3, … m and j = 1, 2, 3, … n for i$^{th}$ alternative and j$^{th}$ criteria.

**Table 1:** Performance characteristics with corresponding process variables.

| | **Input variables** | | | **Criteria** | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Point angle** | | | **Thrust force** | **Torque** | **Delamination factor** | **Roughness factor** | **Circularity error** |
| | ***θ*** | ***N*** | ***f*** | ***Fz*** | ***Mz*** | ***Fd*** | ***Ra*** | ***C*** |
| Measurement units | ° | *rpm* | *mm/rev* | *N* | *Nm* | - | *µm* | *µm* |
| Optimization Direction | - | - | - | min | min | min | min | min |
| Weight of criteria (*wj*) | - | - | - | 0.3617 | 0.4614 | 0.0064 | 0.1283 | 0.0421 |
| 0 - Optimum Value | - | - | - | 21.476 | 0.461 | 1.075 | 9.956 | 6.016 |
| Exp | *θ* | *N* | *f* | | | | | |
| 1 | 110 | 1225 | 0.025 | 27.018 | 0.469 | 1.094 | 11.046 | 6.265 |
| 2 | 110 | 1225 | 0.05 | 28.148 | 0.729 | 1.106 | 11.552 | 6.445 |
| 3 | 110 | 1225 | 0.075 | 35.67 | 0.986 | 1.125 | 11.737 | 6.78 |
| 4 | 110 | 2250 | 0.025 | 21.476 | 0.729 | 1.087 | 9.956 | 6.077 |
| 5 | 110 | 2250 | 0.05 | 29.242 | 0.745 | 1.108 | 10.994 | 6.129 |
| 6 | 110 | 2250 | 0.075 | 35.847 | 0.966 | 1.12 | 11.311 | 6.489 |
| 7 | 110 | 3200 | 0.025 | 22.101 | 0.461 | 1.075 | 9.959 | 6.016 |
| 8 | 110 | 3200 | 0.05 | 29.957 | 0.549 | 1.102 | 10.638 | 6.164 |
| 9 | 110 | 3200 | 0.075 | 38.461 | 0.966 | 1.12 | 11.118 | 6.295 |
| 10 | 128 | 1225 | 0.025 | 26.411 | 0.766 | 1.1 | 12.449 | 6.697 |
| 11 | 128 | 1225 | 0.05 | 33.442 | 0.665 | 1.111 | 13.469 | 6.999 |
| 12 | 128 | 1225 | 0.075 | 39.328 | 0.647 | 1.124 | 13.599 | 7.281 |
| 13 | 128 | 2250 | 0.025 | 25.179 | 0.664 | 1.102 | 11.717 | 6.714 |
| 14 | 128 | 2250 | 0.05 | 35.665 | 0.726 | 1.134 | 12.61 | 6.715 |
| 15 | 128 | 2250 | 0.075 | 44.34 | 0.833 | 1.142 | 12.748 | 7.017 |
| 16 | 128 | 3200 | 0.025 | 24.46 | 0.687 | 1.101 | 11.823 | 6.525 |
| 17 | 128 | 3200 | 0.05 | 39.542 | 0.55 | 1.136 | 12.207 | 6.636 |
| 18 | 128 | 3200 | 0.075 | 45.867 | 0.661 | 1.147 | 12.315 | 6.698 |

Thereafter, the decision-making matrix is normalized to make the process outcomes dimensionless. The normalization is done by a two-step procedure [19]:

$$X_{ij} = \frac{1}{X^{*}_{j}};\bar{X}_j = \frac{X_j}{\left[\sum_{i=0}^{m} X_j\right]} \tag{2}$$

Where, $X^{*}_{ij}$ normalized performance e value of $i^{th}$ alternative on $j^{th}$ criterion. However, one thing that can be noticed here is that the performance values are normalized irrespective of their type of attributes (beneficial or non-beneficial).

Weighted normalized values,

$$\hat{X}_{ij} = w_j \bar{X}_j \tag{3}$$

Optimality function,

$$O_i = \left[\sum_{j=1}^{m} \hat{X}_j\right] \tag{4}$$

Utility degree,

$$U_i = \frac{O_i}{O_0} \tag{5}$$

Finally, in this decision making the non-beneficial attributes (normalized performances) are subtracted from the beneficial normalized performances as per the following expression [19]:

$$P_i = \sum_{j=1}^{h} X^{*}_{j} - \sum_{j=h+1}^{m} X^{*}_{j} \tag{6}$$

Where, $P_i$ is the assessment value of $i^{th}$ alternative to all the criteria, h is the number of criteria to be maximized, and (n - h) is the number of criteria to be minimized. However, the alternative possessing the highest assessment value is considered the best one and the least assessment value is placed at the bottom of the ranking list and represents the worst one. It has been considered one of the robust non-subjective decision-making processes that work with cardinal and most recent data compared to the other available MCDM methods.

The woven type CFRP laminates used in these experiments were made up of hand lay-up techniques and a total thickness of 10 mm with a stacking sequence of $[0°/-45°/90°/45°]_{2s}$. The drilling experiments were performed on a CNC milling center fitted with a dedicated dynamometer (type Kistler-9257b) for acquiring the force signals. Two 10 mm diameter uncoated tungsten carbide (*WC*) twist drills with a point angle of 110° and 128° were used in this work. Similarly, three spindle speeds including slow, moderated, and high likewise 1225 rpm, 2250 rpm, and 3200 rpm, respectively, and three feed rates 0.025 mm/rev, 0.050 mm/rev, and 0.075 mm/rev were used in performing the experiments. The performance characteristics like delamination factor (*Fd*), roughness factor (*Ra*), and circularity error (*C*) along with the acquired thrust force (*Fz*) and corresponding torque (*Mz*) have been processed.

## Results and Discussion

In this particular research paper, the interaction effect of sensory parameters like thrust force and torque acquired during the drilling process have been studied. Hereafter, the response characteristics like delamination factor, circularity error, and roughness factor were also studied in detail for finding out the relation among these defects with the sensors' acquired signals. The influence of controllable machining parameters on the acquired thrust force and the corresponding torque has been presented in figure 2 and figure 3, respectively. The thrust force is seen to increase with the increase in the feed rate keeping the other two parameters (tool rotational speed and drill point angle) constant. Similarly, the effect of the drill tool point angle on the acquired thrust force is the same as the feed rate, thrust force tends to rise with a higher point angle tool. However, there is a very mitigated influence of spindle speed on the thrust force as seen. Therefore, it can be concluded that the effect of feed rate and drill point angle was found to be significant in the generation of thrust force during drilling. The average thrust force (17%) increased with an increase in point angle which was at a high drill point angle (128°). The effect of three controllable input parameters on the torque generation during the drilling process has been represented in figure 3. As similar to the thrust force generation, the effect of increasing feed rate on the torque generation was found to be the same. However, with the high drill point angle tool (128°) the torque was found to be reduced very slightly in the initial stages then it goes on increasing with speed. Therefore, it can be concluded that the fluctuation in the thrust force is compensated for by the torque for maintaining the stability of the drilling operation.

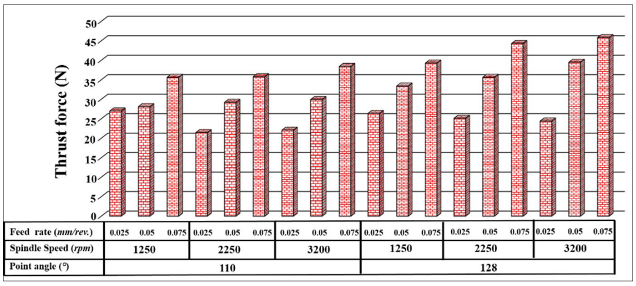

**Figure 2:** Variation of thrust force with process variables.

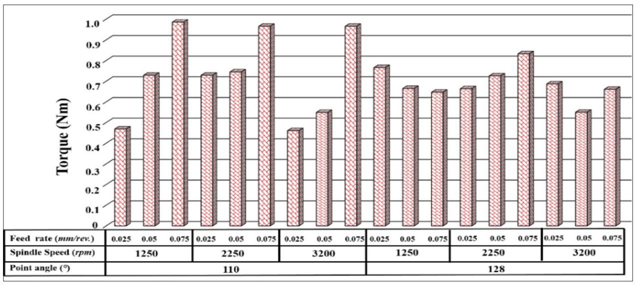

**Figure 3:** Variation of torque with process variables.

The drilling experiments were conducted on the CFRP laminates to demonstrate the applicability of the ASRS method in selecting the best possible parametric setting alternative. The different steps involved in the optimization process have been discussed in section 3. The weights were determined using the compromised weighing method for different criteria and then it has been used in the optimization method for solving the problem [15]. The output performance data has been given in table 1 along with the parametric settings and the criteria weights. The decision matrix (Eq 1) which has to be dimensional less was first normalized using equation (Eq 2) as per the algorithm and presented in table 2. Hereafter, using Eq 3 the weighted normalized values are calculated for all the pairs of alternatives. Then the optimality function (Eq 4) followed by the utility degree (Eq 5) has been calculated and is presented in table 3. Finally, the ranking of the alternatives was calculated as shown in table 3. In this decision-making problem, there are no beneficial attributes present. Therefore, the assessment value (Pi) which is resulted from the subtraction of non-beneficial from beneficial attributes is equal to the utility factor (Ui) as per Eq 6. The ranks obtained and a comparative analysis using the ARAS method shows that the alternative with a low point angle, high spindle speed, and a lower feed rate produces the least possible drill defects among all set of possible alternatives ranked as #1. Moreover, it also agrees with the data for the least delamination factor. Similarly, an alternative combination of high point angle, moderated spindle

**Table 2:** Normalized values of the performance characteristics.

| | $\overline{F_z}$ | $\overline{M_z}$ | $\overline{F_d}$ | $\overline{R_a}$ | $\overline{C}$ |
|---|---|---|---|---|---|
| 0 | 0.074 | 0.076 | 0.054 | 0.061 | 0.057 |
| 1 | 0.059 | 0.074 | 0.053 | 0.055 | 0.055 |
| 2 | 0.056 | 0.048 | 0.053 | 0.053 | 0.053 |
| 3 | 0.044 | 0.035 | 0.052 | 0.052 | 0.050 |
| 4 | 0.074 | 0.048 | 0.054 | 0.061 | 0.056 |
| 5 | 0.054 | 0.047 | 0.053 | 0.055 | 0.056 |
| 6 | 0.044 | 0.036 | 0.052 | 0.054 | 0.053 |
| 7 | 0.072 | 0.076 | 0.054 | 0.061 | 0.057 |
| 8 | 0.053 | 0.063 | 0.053 | 0.057 | 0.056 |
| 9 | 0.041 | 0.036 | 0.052 | 0.055 | 0.054 |
| 10 | 0.060 | 0.046 | 0.053 | 0.049 | 0.051 |
| 11 | 0.047 | 0.052 | 0.053 | 0.045 | 0.049 |
| 12 | 0.040 | 0.054 | 0.052 | 0.045 | 0.047 |
| 13 | 0.063 | 0.052 | 0.053 | 0.052 | 0.051 |
| 14 | 0.044 | 0.048 | 0.052 | 0.048 | 0.051 |
| 15 | 0.036 | 0.042 | 0.051 | 0.048 | 0.049 |
| 16 | 0.065 | 0.051 | 0.053 | 0.051 | 0.052 |
| 17 | 0.040 | 0.063 | 0.051 | 0.050 | 0.052 |
| 18 | 0.035 | 0.053 | 0.051 | 0.049 | 0.051 |

**Table 3:** Weighted normalized values of the performance characteristics and solution results.

| | $\hat{F}$ | $\hat{M}$ | $\hat{H}$ | $\hat{R}$ | $\hat{C}$ | Oi | Ui | Rank |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.027 | 0.035 | 0.000 | 0.008 | 0.002 | 0.072 | 1 | - |
| 1 | 0.021 | 0.034 | 0.000 | 0.007 | 0.002 | 0.065 | 0.904 | 2 |
| 2 | 0.020 | 0.022 | 0.000 | 0.007 | 0.002 | 0.052 | 0.717 | 8 |
| 3 | 0.016 | 0.016 | 0.000 | 0.007 | 0.002 | 0.041 | 0.575 | 16 |
| 4 | 0.027 | 0.022 | 0.000 | 0.008 | 0.002 | 0.059 | 0.822 | 3 |
| 5 | 0.020 | 0.022 | 0.000 | 0.007 | 0.002 | 0.051 | 0.706 | 10 |
| 6 | 0.016 | 0.017 | 0.000 | 0.007 | 0.002 | 0.042 | 0.583 | 15 |
| 7 | 0.026 | 0.035 | 0.000 | 0.008 | 0.002 | 0.071 | 0.990 | 1 |
| 8 | 0.019 | 0.029 | 0.000 | 0.007 | 0.002 | 0.058 | 0.810 | 4 |
| 9 | 0.015 | 0.017 | 0.000 | 0.007 | 0.002 | 0.041 | 0.571 | 17 |
| 10 | 0.022 | 0.021 | 0.000 | 0.006 | 0.002 | 0.051 | 0.713 | 9 |
| 11 | 0.017 | 0.024 | 0.000 | 0.006 | 0.002 | 0.049 | 0.686 | 11 |
| 12 | 0.015 | 0.025 | 0.000 | 0.006 | 0.002 | 0.047 | 0.658 | 12 |
| 13 | 0.023 | 0.024 | 0.000 | 0.007 | 0.002 | 0.056 | 0.778 | 5 |
| 14 | 0.016 | 0.022 | 0.000 | 0.006 | 0.002 | 0.047 | 0.650 | 13 |
| 15 | 0.013 | 0.019 | 0.000 | 0.006 | 0.002 | 0.041 | 0.565 | 18 |
| 16 | 0.023 | 0.023 | 0.000 | 0.007 | 0.002 | 0.056 | 0.776 | 6 |
| 17 | 0.014 | 0.029 | 0.000 | 0.006 | 0.002 | 0.053 | 0.729 | 7 |
| 18 | 0.012 | 0.024 | 0.000 | 0.006 | 0.002 | 0.046 | 0.633 | 14 |

speed, and high feed rate produce a high-defected hole ranked as #18. The priority order of alternatives for this particular investigation can be represented as 7 > 1 > 4 > 8 > 13 > 16 > 17 > 2 > 10 > 5 > 11 > 12 > 14 > 18 > 6 > 3 > 9 > 15. This model was developed for selecting the best possible alternative setting to reduce the drilling defects while drilling CFRP can be applied for different machining of various materials as well. The drilled hole images and corresponding axial thrust force and torque signals for the maximum and minimum delaminated holes have been presented in figure 4. It was observed that the maximum delamination was found for the Expt. no #15 with a parametric combination of high drill point angle, medium spindle speed, and higher feed rate as indicated in figure 4. It was also noticed at this parametric condition the other hole integrity features like fiber pullout, and matrix depletion are at maximum level. However, a combination of a low point angle along with a high spindle speed and low feed rate can yield better results as can be seen for the Expt. no #7 illustrated in figure 4. The steep increase in the thrust force and constantly fluctuating torque in the initial stages of the drilling as in the case of Expt. no #15 is the basic cause of the high delamination defects. However, the drill-induced delamination defects were comparatively less as in the case of Expt. no #7 hardly any abrupt alteration in the thrust and corresponding torque signals as indicated.

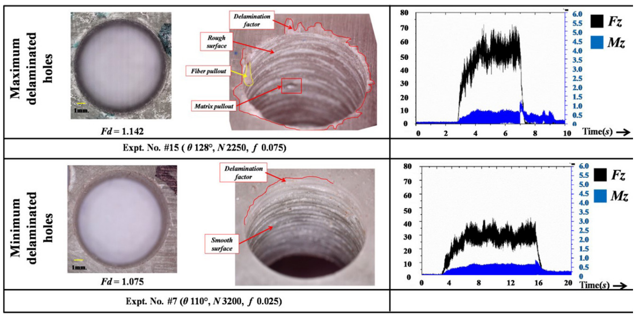

**Figure 4:** Maximum (Expt. no. 15) and minimum (Expt. no. 7) delaminated holes.

## Conclusion

In this particular paper, the problem regarding finding the best possible parameter setting while drilling the CFRP laminates has been solved by utilizing the ASRS model. This model ranks all feasible alternatives according to their determined criteria. The ranks were obtained utilizing the optimization process and the result of the method. The priority of the alternatives is determined according to the utility function value as the contribution of beneficial values are absent in this particular experiment. The alternative with a drill point angle of 110°, spindle speed of 3200 rpm, and feed rate of 0.025 mm/rev are the best feasible alternative that produces the least drill defects. This decision-making method provides a generalized technique applied to find out the best possible alternative in drilling hard-to-machine materials like CFRP and it can be extended to different machining operations.

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None.

## Conflict of Interest

The authors declare no conflict of interests that are relevant to the content of this article.

## Credit Author Statement

Tarakeswar Barik: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft preparation, Writing - review and editing; Suchismita Parida: Writing - original draft preparation, Writing - review and editing; Kamal Pal: Supervision. All the authors read and approved the manuscript.

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