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RESEARCH ARTICLE OPEN ACCESS

AN EFFECTIVE GTO ALGORITHM BASED COST-BENEFIT ANALYSIS OF DISCOS BY OPTIMAL ALLOCATION OF DG AND DSTATCOM IN A REDIAL DISTRIBUTION NETWORK

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ABSTRACT

Electric power Distribution Companies (DISCOs) is playing a major role for delivering active power from distribution substations to customers with lover cost, high reliability and voltage stability. In the DICOs, the transmission lines are redial in nature; all buses are containing the load and no generating buses. Therefore, voltage at each bus is minimized, loss of the network and voltage deviation is increased, and cost and benefit of the DISCOs and consumers are minimized. This paper maximizes the cost–benefit, and voltage stability of DISCOs is improved by optimally considering the Distributed Generation (DGs) and DSTATCOM. Here, applied a novel comprehensive Group Teaching Optimization (GTO) algorithm for planning DG units and DSTATCOM which considers both the Distribution Company's and the DG Owner's (DGO) profits simultaneously. The proposed GTO is applied to a 33-node test system and simulations are carried out using MATLAB platform and results show the applicability of the GTO in the DISCOs.

I. INTRODUCTION

Generally, the prime objective of the Distribution Companies (DISCOs) is to supply the reliable electric energy to the consumers and satisfy required load demand of the Radial Distribution Network (RDS). Due to the fact that the majority of loads connected to the distribution network is inductive in nature, there exists possibility of higher energy loss and lower reliability in the distribution feeder sections [1]. Any outages in the part of distribution system, will heavily affect the continuous and reliable supply of power to the end consumers. Therefore, it is essential for distribution system planners to design, operate, and maintain distribution system with higher reliability and lower energy loss. For this purpose, compensation devices are installed in the distribution network so as to achieve higher technical and economic benefits [2],[3].

The researchers developed various compensating devices and approaches to maximize the reliability, voltage stability and profit of DISCOs udder competitive environment. Artificial immune systems [4] approach has to enhance the voltage and reduce the network loss of the system. The author DSTATCOM is installed optimally using artificial immune system with less installation cost. Biogeography Based Optimization [5] method has been applied to solve the same problem. Here, DG units were optimally allocated to minimize the network loss. The Salp Swarm Algorithm [6] also applied to solve the same problem.

Renewable Distributed Generation and Capacitor Units [7] have been fudged with the RDS to reduce the network loss and improve the stability of the network. An analytical optimization method has been implemented in a in public medium voltage distribution networks. The DG and D-STATCOM [8] have been integrated with the RDS to reduce the network loss and improve the stability of the mitigated.. Here, VSI and Loss Sensitivity Factor has been applied to find optimal location and value of DG and D-STATCOM.

Under Competitive Environment, the PSO algorithm [9] has been applied to find the DISCOs cost and benefit of DG owners in RDS. The PSO was optimally allocated the value and size of DG and Capacitor units. Here, installation cost, operating cost and maintenance cost of both DG and capacitor was taken in account.

A hybrid Weight Improved Particle Swarm Optimization with Gravitational Search algorithm [10] has been proposed to analyse the cost-benefit of DISCOs. The multiple DG and capacitor units are optimally implemented using the projected method and results ware compared with other methods. Elephant herding optimization algorithm [11] has been applied to analyse cost and benefit by installing DG units. The benefits ware analysed with different power factors. The energy storage systems and DG units has been used to maximized the profit of DISCOs. The storage level and location and size of DG were optimized by PSO method [12]. A hybrid oppositional social engineering differential evolution with Lévy flights approach [13] was applied to solve the same problem.

Modified GA with decision-making analysis [14] has been implemented to find benefit between DISCOs and DG owners. Different types of DGs were interconnected to determine the benefits of both DISCOs and DG owners. Moth – Flame Optimization approach [15] has been applied to improve the profit of DISCOs by optimally considering the network reconfiguration, DGs and Capacitors. A classical Consumer Payment Index and Local Marginal Price [16] was used to maximize the DISCOs profit in a mesh network. The simulations have been analysed using DG units.

The optimal power flow [17] method has applied to enhance the profit of DISVOs. The authors considering the production and transmission cost of the electricity market. A fuzzy logic with e-constraint method [18] has been projected to maximize the DISCOs profit. Here, short-term scheduling, energy storage system and active network management was considered to obtain the nursery solutions. Single and Multiple DSTATCOM has been interconnected to analyse the cost and benefit of DISCOs Ant-Lion Optimization Algorithm [19]. When considering the two DSTATCOM connected optimally, the profit of DISCOs has been improved. When single and three DSTATCOM connected to the network, the profit was reduced due to more installation and maintenance cost of DSTATCOM.

In this paper, an intelligent soft computing technique of Group Teaching Optimization (GTO) algorithm is applied to maximise the reliability and analyse the Cos-benefit of DISCOs in a competitive energy market. The DSTATCOM and DG units are interconnected optimally to compensate the reliability of the proposed test system. The searching operators of GTO are having more ability to determine best location and size of DSTATCOM and DG units. It effectively maximizes the DISCOs profit and satisfying the standard operating constraints in electricity market. The IEEE33 node test system is taken to check the validity of GTO method.

II. PROBLEM FORMULATION

The costs and benefits of DISCOs are determined using GTO approach by properly connecting both DGs and DSTATCOM with optimal values.

II. 1 OBJECTIVE FUNCTION

The objective of the proposed work is maximize the profit of DISCOs

Max Profit = Benefits - Investments (1)

Profit = Benefits from DG and DSTATCOM - Cost of DG and DSTATCOM (2)

$$Profit = B_1 + B_2 - \{C_1 + C_2 + C_3\} \quad (3)$$

II.2 BENEFIT EVALUATION OF DISCOS

Benefits of Active power demand reduction from distribution line

Energy sold to the electricity market (Grid) during ΔT time segment,

$$B_1 = \sum_{i=1}^{NDG} K_{DGi} \times EP_G \times \Delta T \quad (4)$$

If IR is the interest rate and IF the inflation rate, then the present worth factor can be represented as:

$$Present\ Worth\ Factor, \beta^t = \sum_{t=1}^{n} \left(\frac{1+IF}{1+IR}\right)^t \quad (5)$$

The present worth value of electricity generated from DG by the distributed company can be calculated as:

$$PWV(B_1) = \sum_{i=1}^{NDG} K_{DGi} \times EP_G \times \Delta T \times \beta^t \quad (6)$$

Benefits of Loss reduction

$$B_2 \sum_{i=1}^{NDG} \sum_{j=1}^{NCap} \Delta LOSS_{ij} EP_G \Delta T \quad (7)$$

He present worth value of loss reduction revenue in a planning horizon can be calculated as:

$$PWV(B_2) = \sum_{i=1}^{NDG} \sum_{j=1}^{NCap} \Delta LOSS_{ij} \times EP_G \times \Delta T \times \beta^t \quad (8)$$

II.3 COST EVALUATION OF DISCOS

Investment cost of DG and DSTATCOM

$$C_1 = \sum_{i=1}^{NDG} K_{DGi} \times IC_i + \sum_{i=1}^{NCap} K_{DSTATCOM} \times IC_j \quad (9)$$

Operating Cost of DG and DSTATCOM

$$C_2 = \sum_{i=1}^{NDG} [K_{DGi} \times OC_i] \times \Delta T \quad (10)$$

The present worth value of operating cost in a given planning year can be calculated as:

$$PWV(C_2) = \sum_{i=1}^{NDG} [K_{DGi} \times OC_i] \times \Delta T \times \beta^t \quad (11)$$

Maintenance Cost of DG and DSTATCOM

$$C_3 = \left[\sum_{i=1}^{NDG} (K_{DGi} \times IC_i) \times MC_{DGi} + \sum_{i=1}^{NCap} \left(K_{DSTATCOM} \times IC_j\right) \times MC_{DSTATCOM}\right] \quad (12)$$

The present worth value of this annual cost in the planning period is calculated as:

$$PWV(C_3) = \left[\sum_{i=1}^{NDG} (K_{DGi} \times IC_i) \times MC_{DGi} + \sum_{i=1}^{NCap} \left(K_{DSTATCOM} \times IC_j\right) \times MC_{DSTATCOM}\right] \times \beta^t \quad (13)$$

II.4 SYSTEM CONSTRAINTS

a. Power balance constraints

$$P_i = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right] \forall i = 1,2,3,\ldots\ldots N \quad (14)$$

$$Q_i = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] \forall i = 1,2,3,N \quad (15)$$

b. *Voltage limits*

Voltage constraint at each bus (±5% of rated voltage) must be satisfied

$$|V_i|^{min|V_i||V_i|^{max}} \qquad \forall i \in N \quad (16)$$

c. *Current limit*

The current in distribution lines should not exceed from their ratings:

$$I_i \leq I_i^{Rated} \qquad \forall i \in N_{Br} \quad (17)$$

d. Size of the DG and DSTATCOM

The sizes of DSTATCOM units must be within the permitted size limit, which is listed below:

$$P_{min}^{DSTATCOM} \leq P^{DSTATCOM} \leq P_{max}^{DSTATCOM} \quad (18)$$

$$Q_{min}^{DSTATCOM} \leq Q^{DSTATCOM} \leq Q_{max}^{DSTATCOM} \quad (19)$$

III. SOLUTION METHODOLOGY

III.1 PROPOSED GTO ALGORITHM

The proposed GTOA is considered as an idea of excellence targeting to improve the learning skills and knowledge of the entire class by simulating the group teaching process. As there are various differences among students, considering those differences is an important factor in implementing the group teaching mechanism and also it is rather complicated in practice. Hence considering the above is an essential criterion in students learning process. The four rules of GTO are properly reported in the reference [20, 21] and structure of the GTO is shown in Figure 1.

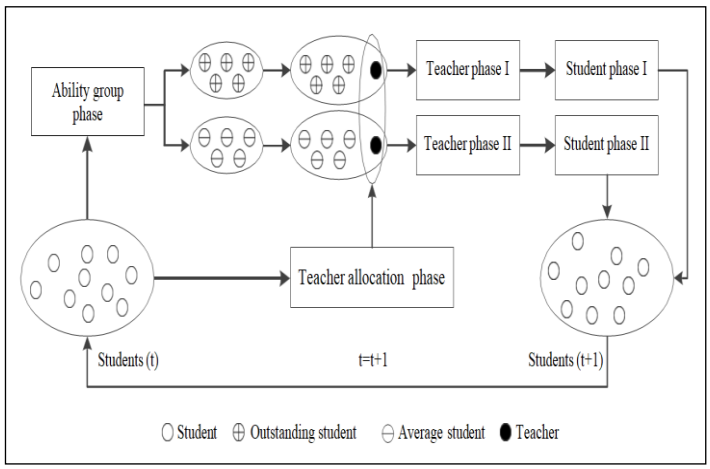

Figure 1: Framework structure of the GTO algorithm
Source: Authors, (2025).

This GTO has four phases and are mathematically represented as follows [17].

III.1.1 Ability grouping phase

Without loss of generality, the knowledge of the whole class is assumed to be in normal distribution. The normal distribution can be defined as 6.

$$f(x) = \frac{1}{\sqrt{2\pi\delta}} e^{\frac{-(x-u)^2}{2\delta^2}} \quad (20)$$

III.1.2 Teacher phase

The knowledge of the students are obtained using teacher phase -1 and Teacher phase -2 are mathematically defined as

Teacher phase I

$$x_{teacher,i}^{t+1} = x_i^t + a \times \left(T^t - F \times (b \times M^t + c \times x_i^t) \right) \quad (21)$$

$$M^t = \frac{1}{N} \sum_{i=1}^{N} x_i^t \quad (22)$$

$$b + c = 1 \quad (23)$$

Teacher phase II

$$x_{teacher,i}^{t+1} = x_i^t + 2 \times d \times (T^t - x_i^t) \quad (24)$$

Where *d* is a random number in the range [0,1].

Additionally, a student's knowledge acquisition through the teacher phase may be Limited or lesser.

$$x_{teacher,i}^{t+1} = \begin{cases} x_{teacher,i}^{t+1}, f\left(x_{teacher,i}^{t+1}\right) < f(x_i^t) \\ x_i^t, \quad f\left(x_{teacher,i}^{t+1}\right) \geq f(x_i^t) \end{cases} \quad (25)$$

III.1.3 Student phase

*T*he student phase of the GTO is represented as

$$x_{teacher,i}^{t+1} = \begin{cases} x_{teacher,i}^{t+1} + e \times \left(x_{teacher,i}^{t+1} - x_{teacher,j}^{t+1}\right) + g \times \left(x_{teacher,i}^{t+1} - x_i^t\right), f\left(x_{teacher,i}^{t+1}\right) < f\left(x_{teacher,j}^{t+1}\right) \\ x_{teacher,i}^{t+1} - e \times \left(x_{teacher,i}^{t+1} - x_{teacher,j}^{t+1}\right) + g \times \left(x_{teacher,i}^{t+1} - x_i^t\right), f\left(x_{teacher,i}^{t+1}\right) \geq f\left(x_{teacher,j}^{t+1}\right) \end{cases} \quad (26)$$

In addition, a student can use it effectively and may not acquire knowledge at the student phase. an example can be taking the minimal problem

$$.x_i^{t+1} = \begin{cases} x_{teacher,i}^{t+1}, f\left(x_{teacher,i}^{t+1}\right) < f\left(x_{student,i}^{t+1}\right) \\ x_{student,i}^{t}, f\left(x_{teacher,i}^{t+1}\right) \geq f\left(x_{student,i}^{t+1}\right) \end{cases} \quad (27)$$

III.1.4 Teacher allocation phase

Based on the defined fourth rule of teacher allocation phase can be expressed as.

$$T^t = \begin{cases} x_{first}^t, & f\left(x_{first}^t\right) \leq f\left(\frac{x_{first}^t + x_{second}^t + x_{third}^t}{3}\right) \\ \frac{x_{first}^t + x_{second}^t + x_{third}^t}{3}, & f\left(x_{first}^t\right) > f\left(\frac{x_{first}^t + x_{second}^t + x_{third}^t}{3}\right) \end{cases} \quad (28)$$

III.2 IMPLEMENTATION OF GTO ALGORITHM TO MAXIMIZE THE DISCOS PROFIT

The following steps are used for optimal allocation and sizing of combined DG and DSTATCOM to evaluate the profit of DISCOs in a competitive electricity market using GTO algorithm. The proposed approach also does the various processes such as installation cost, operating cost and maintenance cost of the DG and DSTATCOM, Revenue, Power loss minimization, node voltage enhancement, optimal location and sizing of DG and DSTATCOM in radial distribution system:

1. Read the line, bus and load data of RDS, Installation cost, operating cost and maintenance cost of DG and DSTATCOM, Interest rate, Inflation rate, Market price and Planning period.
2. Run the distribution power flow and calculate the real and reactive power loss using exact loss formula for base case.
3. Fix number of DG and DSTATCOM are to be used to in Radial Distribution System.
4. Initialize the parameters of GTO algorithm such as Population, dimension, maximum no of iteration number, lower bound and upper bound (node and size of DG and DSTATCOM respectively).
5. Set iteration=1
6. Calculate fitness (i.e. loss and profit of DISCOs in network) for each moth by placing DG and DSTATCOM at their respective buses.
7. Evaluate the objective functions of each moth and determine the profit of DISCOs.
8. Update the position of Teacher phase and save the best fitness values in an array
9. Update the record of student phase and the flames are arranged based on their fitness values
10. Compute the present position of teacher phase.
11. Check the all constrains are satisfied, if yes move to next step, else go to step 6.
12. Check If the number of iteration process is equal to maximum number of iterations, go to step 13. Otherwise go to step 5.
13. Display the global best solution of various cost and DISCOs profit and STOP the program.

IV. RESULTS AND DISCUSSION

The ability of the proposed GTO algorithm is tested on IEEE-33 node test system. The projected algorithm efficiently optimizes the system parameters to achieve the optimal solutions which is obtain the maximum profit with less network losses. The optimization process has been approved out in MATLAB version R2021a environment on an Intel core i3 PC with 2.10 GHz speed and 4GB RAM. Generally, first bus is taken as reference bus and as connected to the substation (S/S) for 33 node test system. The control parameters of GTO are given in Table 1. The one-line diagram of 33 node RD network is displayed in fig.1. the line data, bus data and system demand are taken from reference [12]. The distribution load flow analysis has been used for network solution in each of the cases.

Table 1: Control parameters of GTO

Parameters	Value
Population Size	50
Number of Variables	10
Random Number	0 to 1
Maximum Number of iteration	500

Source: Authors, (2025).

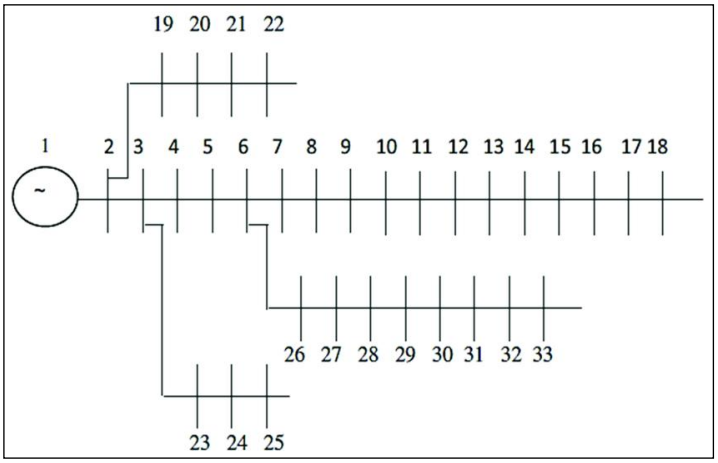

Figure 2: Single Line Diagram of IEEE-33 node radial distribution test system.
Source: Authors, (2025).

The DSTATCOM and DG placement are progressed for a planning period of 10 years. Optimal allocation is made to improve the voltage stability and profit of DISCOs. The projected GTO is properly optimized the location and size of the DG and DSTATCOM. The proposed GTO methodology has been applied to maximize the DISCOs profit considering three different test cases such as

Case 1: Profit of DISCOs considering Single DSTATCOM
Case 2: Profit of DISCOs considering two DSTATCOMs
Case 3: Profit of DISCOs considering both DG and DSTATCOM

In test case 1, single DSTATCON is considering with operating limits of 0 to 2MVAr capacity. The GTO operators (Teacher phase 1 & 2, Student phase and Teacher allocation phase) are efficiently turning the best location and required value of DSTATCOM to injector observe the reactive power to the network to enhance the voltage profile, system losses and maximized profit of DISCOs. The Simulation results of DISCOs considering single DSTATCOM is numerically reported in Table 2.

Table 2: Simulation results of DISCOs considering single DSTATCOM.

Parameters	Optimized variables, Various costs, Benefits and Profit of DISCOs		
	Base Case	ALO	GTO (Proposed)
Optimal location and size of DSTATCOM in MVAr	--	30 1.258	26 1.1256
P_{loss} (kW)	210.99	151.36	145.67
Q_{loss} (kVAr)	143.13	103.98	101.85
Investment cost of DSTATCOM ($) $\times 10^5$	--	0.6290	0.57404
Maintenance cost of DSTATCOM ($) $\times 10^5$	--	0.5284	0.49000
Total cost of DSTATCOM ($) $\times 10^6$	--	0.1157	0.106404
c_{PP}($) $\times 10^6$	14.16	13.94	13.91
c_{PW}($) $\times 10^6$	--	0.2163	0.2256
Profit of DISCOs ($) $\times 10^6$	--	0.1006	0.11919
V_{min} (p.u)	0.9038	0.9165	0.92051

Source: Authors, (2025).

The best location and tuned value of single DSTATCOM is 26 and 1.1256 MVAr respectively the minimum voltage and network real power loss is 0.92051 (p.u) and 145.67 KW respectively. The total profit of DISCOs is \$ 0.11919×10^6. The voltage profile, power loss and DISCO profit are effectively improved then the base case and ALO method. The power loss minimization is 30.95% is then base case and profit is 12.51\$ is improved then the ALO algorithm.

Similarly in case 2, two DSTATCOMs are consider to improve the profit of DISCOs. The upper and lower bounds of DSTATCOM are 0 to 5 MVAr respectively. The searching operators of GTO are effectively optimized the locations and sizing of DSTATCOMs. The simulation results of case 2 is displayed in Table 3. The optimized allocation and size of DSTATCOMs are 8, 30 and 3.657 MVAr, 1.054 MVAr respectively. The minimum voltage and network real power loss is 0.9589 (p.u) and 136.75 KW respectively. The total profit of DISCOs is \$ 0.12709×10^6 respectively.

Table 3: Simulation results of DISCOs considering Two DSTATCOMs.

Parameters	**Optimized variables, Various costs, Benefits and Profit of DISCOs**		
	Base Case	**ALO**	**GTO (Proposed)**
Optimal location and size of DSTATCOM in MVAr	--	(12) 4.659, (30) 1.063	(8) 3.657, (30) 1.054
P_{loss} (kW)	210.99	141.83	136.75
Q_{loss} (kVAr)	143.13	96.50	90.21
Investment cost of DSTATCOM (\$) $\times 10^5$	--	0.7640	0.7458
Maintenance cost of DSTATCOM (\$) $\times 10^5$	--	0.6418	0.6123
Total cost of DSTATCOM (\$) $\times 10^6$	--	0.1406	0.13581
$c_{PP}(\$) \times 10^6$	14.16	13.91	13.89
$c_{PW}(\$) \times 10^6$	--	0.2488	0.2629
Profit of DISCOs (\$) $\times 10^6$	--	0.1082	0.12709
V_{min} (p.u)	0.9038	0.9303	0.9589

Source: Authors, (2025).

From the Table 3, the power loss minimization is 35.19 % improved then the base case value and DISCOs profit 18.01 % is improved then the ALO approach. When considering the two DSTATCOMs, voltage at each bus, VSI, power loss minimization and profit of DISCOs are improved the single DSTATCOM is installed in the proposed distribution network. Proper location and optimal value of DSTATCOMs are effectively improves the system stability and benefits of distribution companies.

In case 3, a single DSTATCOM with DG unit is consider to further improve the profit of DISC Os. The DG unit play a very important roll for maximize the DISCOs profit and minimize the real power loss of the projected test system. When DG unit and DSTATCOM implemented in the RDS, the real and reactive power are injected in the network. So voltage profile and power loss minimization are efficiently minimized. The installation cost, operating cost and maintenance cost of DISCOs are increased due to considering DG unit.

The projected GTO approach properly optimizes the location and size of DG and DSTATCOM to simultaneity maximize the profit and minimize the total cost of DISCOs. The optimized location and sizing of DG and DSTATCOM is 8, 26 and 1.4704 MW, 0.9481 MVAr respectively.

Therefore, voltage at each bus, voltage deviation and VSI are efficiently improved. The improved voltage and VSI are compared with base case and ALO algorithm and also displayed in Table 4 and 5. The graphical comparison of voltage profile and VSI with base case and ALO algorithm is given in fig 3 and fig. 4. From the Figure 3 and 4, the voltage level stability of majority busses are improved.

Table 4: Comparison of Voltage profile of 33-node test system.

Bus No.	**Base case**	**GTO (Proposed)**	**ALO**
1	1.0000	1.0000	1
2	0.9970	0.99828	0.99825
3	0.9829	0.99173	0.99064
4	0.9754	0.98935	0.98795
5	0.9680	0.98726	0.98553
6	0.9495	0.98263	0.97968
7	0.9460	0.98136	0.97807
8	0.9323	0.98031	0.98108
9	0.9260	0.9795	0.97507
10	0.9201	0.98183	0.9695
11	0.9192	0.98191	0.96868
12	0.9177	0.9822	0.96724
13	0.9115	0.98138	0.96139
14	0.9092	0.9798	0.95922
15	0.9078	0.98054	0.95787
16	0.9064	0.98197	0.95656
17	0.9043	0.98585	0.95462
18	0.9037	0.98808	0.95404
19	0.9965	0.99739	0.99772
20	0.9929	0.99061	0.99415
21	0.9922	0.98896	0.99344
22	0.9916	0.98658	0.99281
23	0.9793	0.98867	0.98708
24	0.9726	0.98293	0.98046
25	0.9693	0.9805	0.97717
26	0.9475	0.98235	0.97844
27	0.9450	0.98209	0.97596
28	0.9335	0.98157	0.9649
29	0.9253	0.98086	0.95696
30	0.9217	0.98202	0.95352
31	0.9176	0.98332	0.9495
32	0.9167	0.98406	0.94861
33	0.9164	0.98539	0.94834

Source: Authors, (2025).

Table 5: Comparison of VSI of 33-node test system.

Bus No.	**Base case**	**GTO (Proposed)**	**ALO**
1	1	1	1
2	0.98811	0.9931	0.99299
3	0.93213	0.96693	0.96273
4	0.90479	0.9896	0.95261
5	0.87755	0.96259	0.94334
6	0.81082	0.95646	0.92098
7	0.80059	0.94726	0.91507
8	0.75445	0.9303	0.92589
9	0.73494	0.92956	0.90374

10	0.7165	0.92752	0.8833
11	0.71397	0.92926	0.88048
12	0.70927	0.95797	0.87526
13	0.69018	0.95528	0.85408
14	0.68344	0.93296	0.84657
15	0.67918	0.92403	0.84183
16	0.67506	0.92559	0.83723
17	0.66896	0.93002	0.83044
18	0.66717	0.93462	0.82845
19	0.98607	0.99091	0.99091
20	0.9719	0.97671	0.97671
21	0.96922	0.97402	0.97402
22	0.96674	0.97153	0.97153
23	0.9197	0.92966	0.94924
24	0.8947	0.92395	0.92385
25	0.88273	0.92163	0.91168
26	0.80612	0.92051	0.91651
27	0.79742	0.9499	0.90723
28	0.75882	0.93192	0.86613
29	0.73277	0.92741	0.83828
30	0.72184	0.93122	0.82657
31	0.70887	0.93024	0.81269
32	0.70614	0.92824	0.80976
33	0.70527	0.92343	0.80883

Source: Authors, (2025).

Table 6: Simulation results of DISCOs considering both DG and DSTATCOM.

Parameters	**Optimized variables, Various costs, Benefits and Profit of DISCOs**	
	PSO [11]	**GTO (Proposed)**
Optimal Location of DG and DSTATCOM	8 30	8 26
Optimal Size of the DG and DSTATCOM	1.5 MW 0.9 MVAr	1.4704 MW 0.9481 MVAr
Real Power loss (KW)	99.924	84.646
Reactive Power loss (KVAr)	62.56	60.173
Planning period	10 year	10 year
Installation cost of DG ($)	375×10^5	367.605×10^5
Installation cost of DSTATCOM($)	9×10^4	4.7404×10^4
Benefits of loss reduction ($)	4.35×10^7	4.20×10^7
Benefits of reduction in purchased($)	4.99×10^8	4.89×10^8
Operational costs of DG ($)	2.49×10^8	2.45×10^8
Maintenance cost of DG ($)	6.34×10^7	6.22×10^7
Maintenance cost of DSTATCOM ($)	1.94×10^5	4.0004×10^5
Total profit of DISCOs ($)	**1937.94×10^5**	**2187.42×10^5**

Source: Authors, (2025).

The system variables are efficiently optimized and simulation results are projected in Table 6. This table clearly explains the optimal location and sizing of DG and DSTATCOM, minimum voltage and minimum VSI and power loss.

The power loss of base case and existing PSO method is 221 KW and 99.924 KW respectively. Therefore, proposed method provides minimum power loss compared with base case and PSO method.

Table 7: Comparison of Power Loss of 33 node test system with different cases.

Case	**Technique**	**Ploss (kW)**	**%Ploss**
Base Case	--	210.98	--
Single DSTATCOM/SC	Analytical	164.60	21.98
	IA	171.81	18.57
	CSO	175.01	17.05
	MVO	151.39	28.24
	CSA	151.52	28.18
	BA	151.52	28.18
	ALOA	151.36	28.86
	GTO (Proposed)	**145.67**	**30.85**
Two DSTATCOMs/SCs	Analytical	146.64	30.50
	WIPSO-GSA	141.84	32.77
	CSA	142.07	32.66
	ALOA	141.83	32.78
	GTO (Proposed)	136.75	35.18
DG with DSTATCOM	PSO	99.924	
	FA-SCAC-PSO	93.9877	
	GTO (Proposed)	84.646	

Source: Authors, (2025).

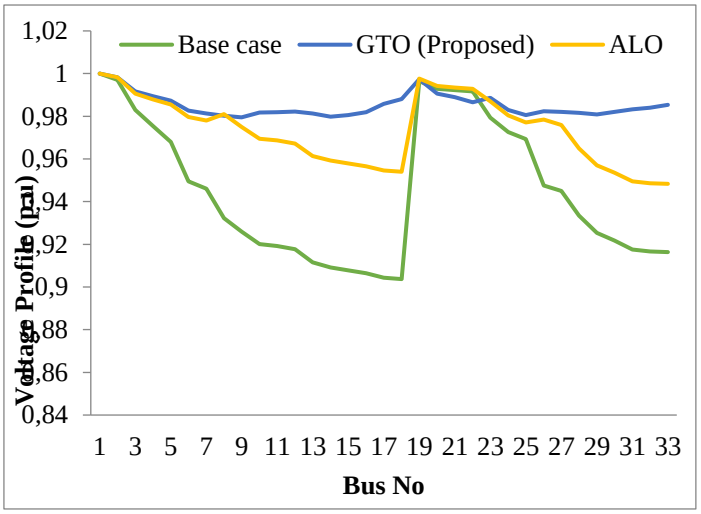

Figure 3: Comparison of Voltage profile of 33-node test system.
Source: Authors, (2025).

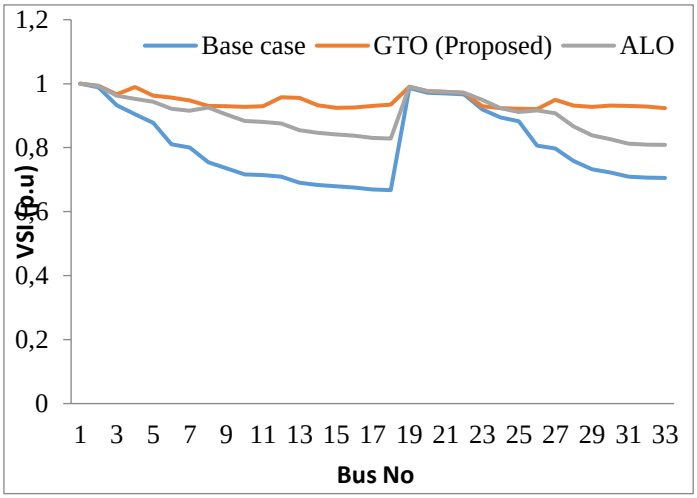

Figure 4: Comparison of VSI of 33-node test system.
Source: Authors, (2025).

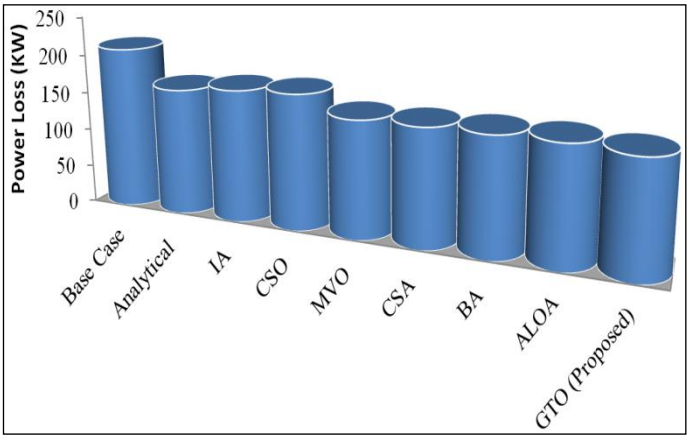

Figure 5: Comparison of Power loss Considering single DSTATCOM.
Source: Authors, (2025).

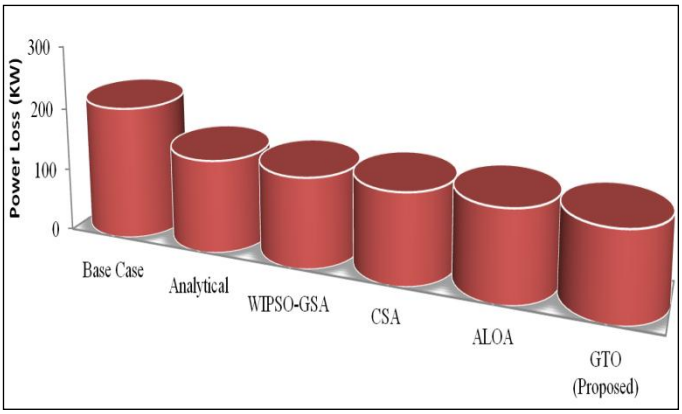

Figure 6: Comparison of Power loss Considering two DSTATCOMs.
Source: Authors, (2025).

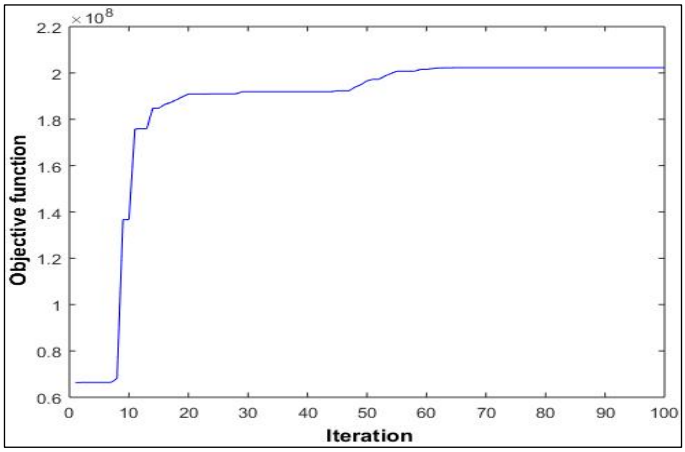

Figure 7: Convergence curve of 33-bus test system.
Source: Authors, (2025).

In the DISCOs, various cost, benefits and profit are calculated by using the GTO method. The Table 6 also explains the cost-benefit analysis of DOSCOs considering DSTATCOM with DG placement. The power loss and percentage of power loss reduction for three different cases are compared with other available methods and numerically and graphically represented in the Table 7 and Figure 5 and Figure 6. The Convergence curve of 33-bus test system is shown in Figure 7. From the Table 6, the proposed method having maximum profit, minimum power loss with less computational time compared with PSO method.

V .CONCLUSION

This paper analyzes the cost-benefit of DISCOs by optimal allocation of DG and DSTATCOM in radial distribution network. A simple and effective method of GTO algorithm has been proposed to obtain the best solution. Optimal placement of DG and DSTATCOM has been obtained using GTO to maximize the profit of DISCOs. The results of GTO are implemented for 33 node test systems. The algorithm is programmed in MATLAB software package. The outcomes such as voltage at each bus, VSI, real and reactive power loss, installation cost, operating and maintenance cost of both DG and DSTATOM, profit of DISCOs are compared with existing approaches. The results display efficacy of GTO approach for solving the voltage stability problem. The advantage of GTO is its simplicity, reliability and efficiency for practical applications.

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RESEARCH ARTICLE OPEN ACCESS

A FINGERPRINT-BASED ATTENDANCE SYSTEM FOR IMPROVED EFFICIENCY

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ABSTRACT

This paper presents the design and implementation of a fingerprint-based attendance system to address challenges in lecture attendance monitoring in developing countries. Leveraging a handheld fingerprint sensor, the proposed system streamlines attendance recording, eliminating manual collection inefficiencies and enhancing record reliability. The system enables lecturers to create and manage attendance sessions effortlessly, while students register and verify attendance conveniently. Key features include automated attendance tracking, reduced administrative burden, and improved accuracy. The system's successful deployment demonstrates its potential to improve operational efficiency and educational outcomes in resource-constrained environments. Results show significant reductions in attendance management time (by 75%) and errors (by 90%), alongside increased student accountability. User feedback indicates high satisfaction rates (95%). The system's effectiveness, usability, and scalability are discussed, highlighting its potential for widespread adoption. This research contributes to the development of efficient and reliable attendance monitoring solutions, providing valuable insights for educational institutions seeking to adopt biometric technology.

I. INTRODUCTION

Effective attendance tracking is vital for educators to monitor students' academic progress. Traditional attendance methods, however, can be cumbersome and time-consuming. Calling out each student's name in a large classroom can significantly slow down the process. Furthermore, managing attendance records for substantial student numbers can be overwhelming. Another issue arises when students sign on behalf of their absent peers on attendance sheets circulated in class, compromising the integrity of the attendance-tracking process.

To ensure students' academic success, prioritizing efficient attendance tracking is vital. It's encouraging to see numerous institutions adopting digital attendance systems. However, many institutions of higher learning worldwide still rely on outdated paper-based methods [1].

Therefore, it's important to encourage the adoption of modern technology and efficient attendance tracking systems to improve productivity and ensure the academic success of students. This study presents a biometric attendance system with a fingerprint feature which is portable and eliminates the weak point of using the existing method of marking attendance on paper or standing in long queues. Few of these other automated systems are attendance facial recognition systems, attendance RFID scanning systems, attendance iris scanning systems, and many others.

While facial recognition is a straightforward feature for automated attendance system, it is, however, often less effective as the standard facial recognition techniques embed inherent drawbacks that affect prima facie verification and enrollment features [2].

An example of such biometric recognition techniques is iris recognition whereby images of the iris patterns of either one or both of the eyes of a certain individual are taken and scanned employing some mathematical pattern recognition systems that are very stable and unique and can be obtained from a certain distance [3].

Corporate radio frequency identification (RFID) technologies include a system for noncontagious data transfer [4]. The system employs an RFID tag and RFID reader where the RFID TAG has a unique ID number for each tag. While this form of attendance system is efficient, it can also undermine the purpose of attendance by permitting proxy attendance. This research proposes

the design of an access control system which incorporates an ESP32 microcontroller with integrated Wi-Fi and an R305 fingerprint module. The R305 finger print scanner is equipped with a good performance image sensor which captures the finger image and analyzes it in milliseconds with an inbuilt memory of one thousand fingerprints. Each and every person will have to be given an ID number that will be captured during the enrolment of fingerprints. The ESP8266 Wi-Fi module is used for setting up an access point through which the client can link to the device. The client application is developed utilizing Node.js, an open-source JavaScript platform, and MongoDB is employed for database management.

MongoDB which is a Document-oriented database is used to store unstructured data contrary to Structured query language (SQL) which is relational database. It is a document oriented database, which is characterized by high speed and volume efficiency. This type of database works by grouping data into collections and keeping them in documents [5].

The document-oriented database is one of the non-relational databases, which are built in solutions that address the modern day's problems of large amounts of new categories of data being generated that have a possibility of being changing rapidly as well. These databases offer efficient query mechanisms, flexible querying capabilities, and seamless integration with modern programming languages through a natural document-data-model-to-object mapping [6].

Under the working conditions, the device is capable of authenticating a person by fingerprint and uploading the attendance with the time stamp to the client machine. Biometric attendance systems offer improved security, accuracy, and efficiency over traditional methods, reducing human error and enhancing data integrity. These systems use pattern recognition to capture biometric data, extract features, and compare them to a database for unique identification.

Recent advancements have expanded beyond fingerprint recognition to include facial recognition, iris scanning, GPS tracking, and voice recognition. Finger imaging remains widely accepted for identification [7]. GPS tracking requires users to install an APK and input office coordinates for automatic data transmission [8].

While facial recognition shows promise, it has accuracy issues due to factors like aging and posture [9],[10]. Automated systems continue to evolve, incorporating methods like fingerprint matching and data transmission via Zigbee [11].

II. MATERIALS AND METHODS

Fingerprint identification is one of the most well-known and common biometric identification systems. Because of their uniqueness and consistency over time, fingerprints have been used for identification for over a century, more recently becoming automated due to advancements in computing capabilities. The system will maintain a record of the fingerprints of various students in the database, and they will be matched and marked present when they place their finger on the fingerprint sensor. In designing the proposed system, both software and hardware implementations are required.

The design is divided into five sections: the power source section, control and LCD section, fingerprint section, indicator section, and IoT communication section. The block diagram in Figure 1 illustrates the methodology of the proposed system.

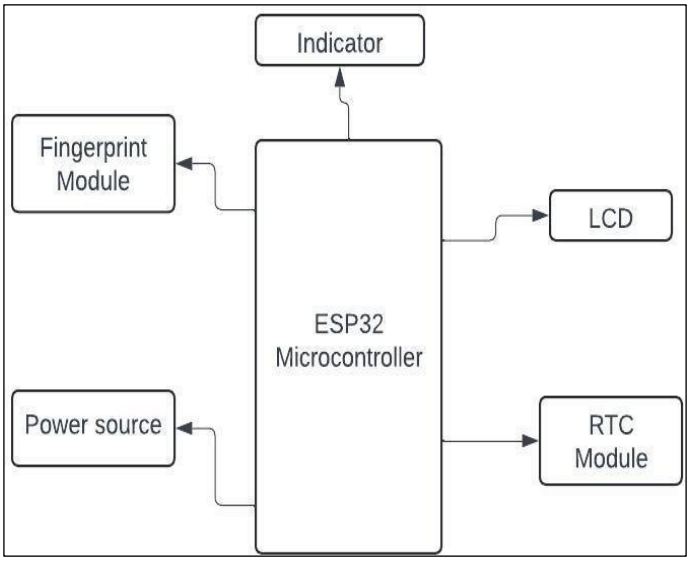

Figure 1: Block Diagram of the Proposed System.
Source: Authors, (2025).

The control and display section are formed by ESP32 System on Chip (SOCs) microcontroller and an alphanumeric LCD display. The biometric scanner section is an optical fingerprint scanning module R305, and DS3231 RTC Module is the IoT communication section, and buzzer 5v and LED 5mm for indicator section. Thepower source is a 3.7v 18650 lithium battery with 5 V power bank charger regulator.

II. 1. COMPONENTS UTILIZED

The following components were used for the overall setup of the hardware device. Here is a brief description of what each component does in the complete hardware.

a) ESP32-WROOM-32 Microcontroller

This specific module is quite interesting due to its flexibility and efficiency which is the reason as to why it fits perfectly into fingerprint biometric attendance system. To its high performance AS GTX8266, Espressif Systems, almost tops the chart among the WE MOVED Boards with superior dual-core, 32 bits, LX6 microprocessor at clock speeds of about 240 MHz: a very reasonable overclock for intricate processes. The module has built in wireless communication modules that includes Wi-Fi and Bluetooth which is essential for this device. Only the microcontroller has SRAM of 520 kb and 448 kb of ROM making it bulky in processing and storage memory. The consumption of low powers, thanks to TSMC's 40nm technology has been optimized making the chip useful in the case of portable devices and battery powered devices. The peripherals that ESP32-WROOM-32 can interface with includes, but are not limited to, capacitive touch interfaces, SD cards and Ethernet, which greatly expands the applications. Moreover, the module has several I/Os, ADCs, DACs, PWM outputs giving the ability to connect different types of sensors and actuators. Built in security features such as secure boot and flash encryption provide basic protection against data loss. In one word, the creation of smart and efficient attitude control system based on fingerprint biometric attendance system can be easily achieved in the framework of the ESP32-WROOM-32 (Figure 2).

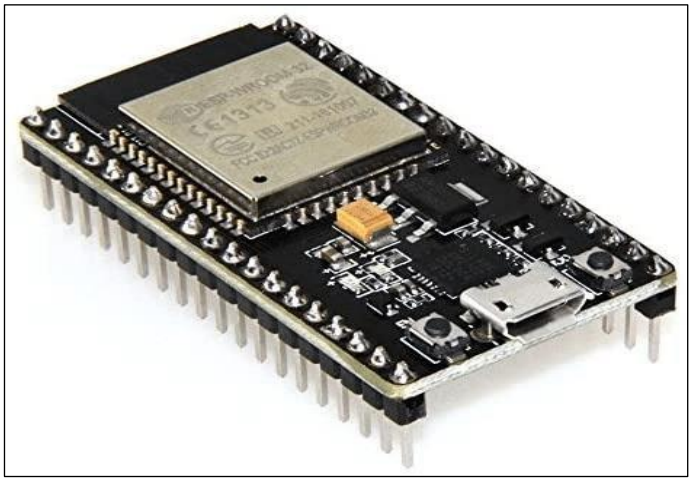

Figure 2: ESP32 Microcontroller.
Source: Authors, (2025).

b) 16x2 LCD Display with 12C

This display module shows real-time information such as attendance status, error messages, and prompts, enhancing user interaction and system feedback. The I2C interface simplifies wiring byreducing the number of pins required for connection, making it easier to integrate with microcontrollers like the ESP32. Additionally, the I2C interface allows for efficient communication between the LCD and the microcontroller (Figure 3).

In a fingerprint attendance system, this display can show messages like “Sending FP data,” “Access Denied,” or “Error in image,” providing immediate feedback to users. It can also display the current date and time, sourced from the RTC module, ensuring users are aware of the system’sstatus at all times. This enhances the overall user experience and makes the system more intuitiveand user-friendly.

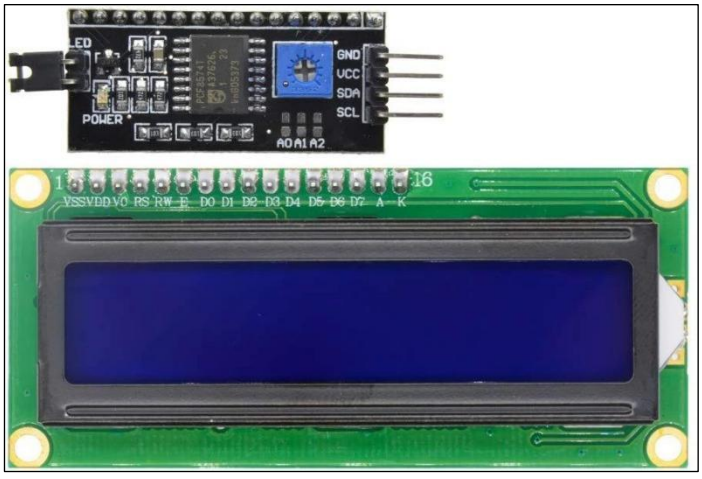

Figure 3: 12864 LCD 16x2 and I2C Adapter.
Source: Authors, (2025).

c) DS3231 RTC Module

The DS3231 RTC (Real-Time Clock) module is a highly accurate timekeeping device, ideal for use in a fingerprint attendance biometric system. Unlike the DS1307, the DS3231 has an integrated temperature-compensated crystal oscillator, which ensures precise timekeeping even in varying environmental conditions. This makes it particularly reliable for applications where accurate timeand date stamps are crucial. It relies on a backup battery to maintain accurate timekeeping even when the main power is off. If you remove this battery, the module will lose its timekeeping dataand reset. This means that when the power is restored, the DS3231 will no longer have the correcttime and date information. In a fingerprint attendance system, the DS3231 ensures that each fingerprint scan is accurately timestamped. This module communicates with microcontrollers like the ESP32 via the I2C protocol, using just two pins (SDA and SCL). When a user scans their fingerprint, the system logsthe exact time and date of the scan, which is then stored in a database (Figure 4).

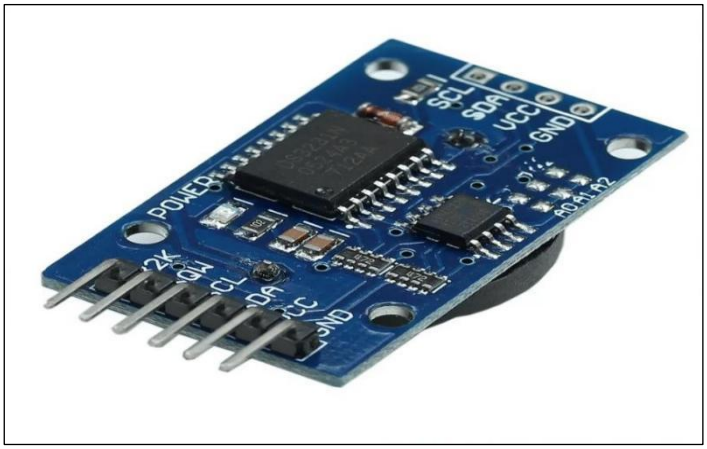

Figure 4: DS3231 RTC Module.
Source: Authors, (2025).

d) JM101B Fingerprint Module

The JM101B fingerprint module is an integrated optical fingerprint processing module, ideal for use in a fingerprint attendance biometric device. This module combines the optical path and fingerprint processing components into a compact unit, making it suitable for space-constrained applications. It features low power consumption, a simple interface, and high reliability, which are crucial for continuous operation in attendance systems. The JM101B module (Figure 5) communicates with microcontrollers like the ESP32 via UART, making it easy to integrate into your project. It has a high recognition speed and good adaptability to both wet and dry fingers, ensuring accurate and quick fingerprint identification. When a user scans their fingerprint, the module captures the fingerprint image, processes it, and compares it with stored templates to verify the identity of the user.

Figure 5: JM101B Fingerprint Module
Source: Authors, (2025).

e) 18650 Lithium Battery

The 18650-lithium battery is a popular rechargeable lithium-ion cell, named after its dimensions:18mm in diameter and 65mm in length. 18650 batteries can provide a reliable and portable powersource (Figure 6).

Figure 6: 18650 Lithium Battery.
Source: Authors, (2025).

f) Power Bank 18650 Charger

The power bank module can convert the 3.7V output to a stable 5V, suitable for powering components like the ESP32 microcontroller, fingerprint sensor, etc. (Figure 7).

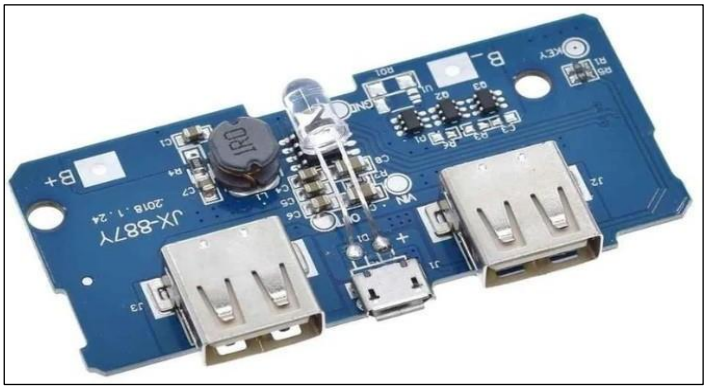

Figure 7: Power Bank 18650 Charger
Source: Authors, (2025).

II. 2. HARDWARE DESIGN

A modular design approach was used. Connectors were employed to interface different components wherever possible, facilitating better assembly and easier repair in the future. The microcontroller used in this design is the ESP32-Wroom-32. A fingerprint module is connected to the Universal Asynchronous Receiver-Transmitter (UART) interface, linking the transmitter and receiver pins of the module to those of the microcontroller. A bi-color LED indicates the status of fingerprint authentication. The graphic LCD's data connectors, control signal connectors, and power signal connectors are interfaced with the microcontroller circuit. The backlight of the graphic LCD is controlled through a microcontroller port, allowing it to be adjusted as needed. A USB type-A female connector is connected to the ESP32 using a USB module. The system uses an RTC DS1307 to keep track of time, interfaced with the ESP32-WROOM-32 via the I2C protocol. A 3V CR2032 CMOS battery serves as a backup. Figure 8 shows the circuit schematic of the device.

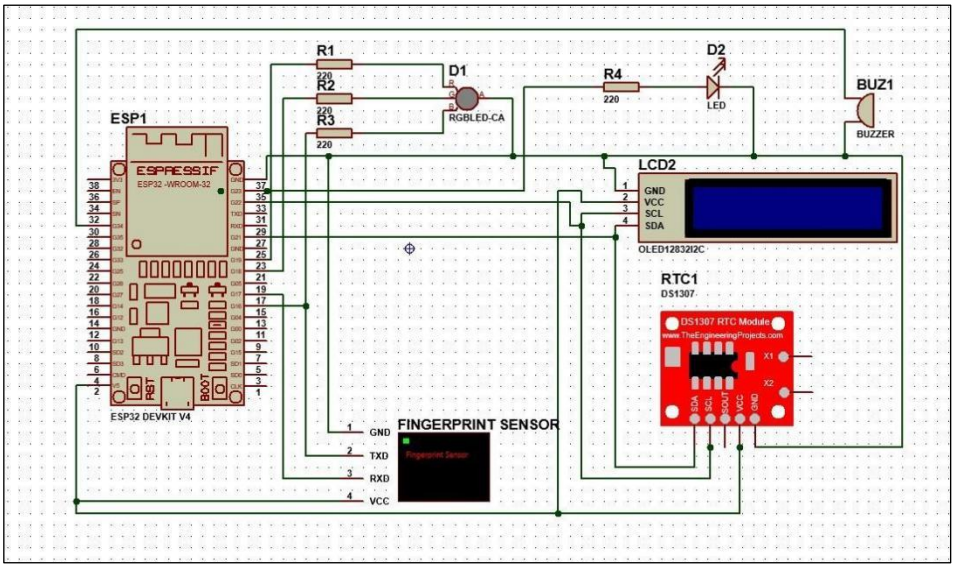

Figure 8: Circuit Schematic of the Device
Source: Authors, (2025).

The study employed the Bluetooth Low Energy (BLE) protocol for data transmission of fingerprints due to its advantages in low power consumption and efficient data transfer. BLE is widely used in applications requiring minimal energy usage, making it an ideal choice for devices that need to operate for extended periods on small batteries. This characteristic is crucial in environments such as wearable technology, IoT devices and health monitoring systems where battery life is a critical concern. One of the key advantages of BLE over other wireless communication protocols such as Wi-Fi, Zigbee or classic Bluetooth is its power efficiency. BLE operates by transmitting small data packets at intervals, sometimes as low as once per second, which significantly

reduces the power required for communication [12]. BLE also supports a large number of devices connected simultaneously, often referred to as a mesh network, which is particularly advantageous in IoT environments where multiple sensors and actuators need to communicate with a central hub or among themselves [13]. These characteristics make it an ideal choice for this research.

The system utilizes the R307 optical fingerprint verification module which features a high-powered DSP chip for image rendering, calculation, feature-finding and searching. This module offers high sensitivity and accuracy with a resolution of 500 DPI. The R307 module is interfaced with a microcontroller via TTL serial communication, enabling data packet transmission for image capture, print detection, hashing, and searching. The Adafruit Fingerprint Sensor Library is employed to interact with the fingerprint module, providing functions for fingerprint enrollment and verification. Further details on the pinout connection are provided in Table 1.

Table 1: Pinout Connection to Fingerprint Module.

FINGERPRINT SENSOR	ESP32
VCC	5V (RED WIRE)
TX	GPIO 17 (YELLOW WIRE)
RX	GPIO 16 (WHITE WIRE)
GND	GND

Source: Authors, (2025).

The R307 fingerprint module was connected to the ESP32 microcontroller by establishing the following connections: the VCC pin of the R307 was connected to the 5V pin on the ESP32, providing the necessary power for operation. The TX (transmit) pin of the R307 was connected to GPIO 17 on the ESP32, enabling data transmission from the fingerprint module to the microcontroller. The RX (receive) pin of the R307 was connected to GPIO 16 on the ESP32, allowing the microcontroller to receive data from the fingerprint module. Finally, the GND pin of the R307 was connected to the GND pin on the ESP32, completing the electrical circuit and ensuring a common ground between the two devices.

The system features a 16x2 LCD display module, which provides a user interface for feedback and information display, including prompts, status messages and attendance status. The LCD display utilizes an i2c interface, reducing the required pins to four and enabling easier integration. Additionally, the display includes a built-in potentiometer for adjusting contrast between the background and characters. The LiquidCrystal_I2C library (version 1.1.2) in Arduino IDE was employed to interface with the display, offering functions for initialization, cursor positioning and text printing. The pinout connection details are provided in Table 2.

Table 2: Pinout Connection to I2C LCD.

LCD WITH I2C	ESP32
VCC	5V
GND	GND
SDA	GPIO 21
SCL	GPIO 22

Source: Authors, (2025).

To establish communication between the i2c interface and the ESP32 microcontroller, the VCC pin of the i2c interface was connected to the 5V pin on the ESP32, providing the necessary power for the fingerprint module to operate. The SDA pin was connected to GPIO 21 on the ESP32, enabling data transmission from the fingerprint module to the microcontroller. The SCL pin was connected to GPIO 22 on the ESP32, allowing data reception from the microcontroller to the fingerprint module. Finally, the GND pin of the i2c interface was connected to the GND pin on the ESP32, completing the electrical circuit and ensuring a common ground between the two devices. These connections enable the ESP32 microcontroller to communicate with the fingerprint module via the i2c interface, allowing for data exchange and fingerprint recognition. The use of GPIO 21 and GPIO 22 on the ESP32 ensures reliable data transfer while the common ground connection prevents data corruption and ensures a stable power supply.

The DS3232 RTC module was employed to obtain current time, date and day for the fingerprint reader. This module maintains accurate time even during power outages, ensuring proper time stamping of attendance records. The RTClib library (version 2.1.4) in Arduino IDE was used to interface with the DS3232, providing functions to read and set the time and date. The pinout connection details are provided in Table 3.

Table 3: Pinout connection to RTC Module.

LED WITH 220 Ω RESISTOR	ESP32
RED	GPIO 19
BLUE	GPIO 23
GREEN	GPIO 18
BLUE	GPIO 16

Source: Authors, (2025).

To interface the DS3232 Real Time Clock (RTC) module with the ESP32 microcontroller, the VCC pin of the RTC module was connected to the 5V pin on the ESP32, providing the necessary power for the module to operate. The SDA pin was connected to GPIO 21 on the ESP32, enabling data transmission from the RTC module to the microcontroller. The SCL pin was connected to GPIO 22 on the ESP32, allowing data reception from the microcontroller to the RTC module. Finally, the GND pin of the RTC module was connected to the GND pin on the ESP32, completing the electrical circuit and ensuring a common ground between the two devices. These connections enable the ESP32 microcontroller to communicate with the DS3232 RTC module, allowing for accurate time and date retrieval. The use of GPIO 21 and GPIO 22 on the ESP32 ensures reliable data transfer while the common ground connection prevents data corruption and ensures a stable power supply. The device employs two LEDs for status indication: a power LED and a status LED. The power LED indicates the power status while the status LED displays the fingerprint status. A RGB LED and a blue LED with a 220Ω resistor are used to provide visual indicators. The pinout connection details are provided Table 4.

Table 4: Pinout Connection to LEDs.

D3231 RTC	ESP32
VCC	5V
GND	GND
SDA	GPIO 21
SCL	GPIO 22

Source: Authors, (2025).

The RGB LED and additional blue LED were connected to the ESP32 microcontroller. The red LED (RGB) was connected

to GPIO 19, enabling the microcontroller to control the red color. The green LED (RGB) was connected to GPIO 18, allowing the microcontroller to control the green color. The blue LED (RGB) was connected to GPIO 23, enabling the microcontroller to control the blue color. Additionally, a separate blue LED was connected to GPIO 16, providing an extra indicator. These connections enable the ESP32 microcontroller to control the RGB LED and additional blue LED, allowing for visual indicators of various statuses and notifications. The use of GPIO pins ensures reliable communication between the microcontroller and LEDs.

The device incorporates several user interface and feedback mechanisms to enhance user experience and provide effective communication. A push button is used for resetting the system, allowing for quick reinitialization in case of errors or malfunctions. This ensures that the system can be easily restored to its default state. A buzzer provides audible feedback when a student places their finger on the fingerprint sensor, indicating successful or failed scans and enhancing user interaction. Additionally, a power ON button enables easy switching of the system on and off, providing users with control over the system's operation. These mechanisms work together to create an intuitive and user-friendly experience, ensuring effective interaction and clear feedback on the system's status.

II. 3. SOFTWARE DESIGN

The Waterfall model was employed as the software development lifecycle to enhance the automated attendance system with a fingerprint-based approach in this study. The model's structured and sequential process ensured that each phase of development was completed before progressing to the next, thereby maintaining clarity and order throughout the study's duration. The linear approach of the Waterfall model facilitated a logical and methodical development process, which was particularly suited for this research's requirements. The features of the mobile application and programming languages implemented are discussed below:

a) Frontend Development

The frontend of the attendance system was developed using React Native, an open-source User Interface (UI) software framework created by Meta Platforms, Inc. [14]. React Native enables the development of native mobile applications for iOS and Android using JavaScript and React. Specifically, it was utilized to create the mobile application for this study. For biometric authentication, the react-native-biometrics package was employed, providing a simple bridge to native iOS and Android keystore management. This allows for the creation of public-private key pairs stored in native keystores and protected by biometric authentication. Furthermore, React Native's robust ecosystem offers various libraries and packages, such as react-native-ble-plx, which enables communication with devices and sends fingerprint data to the database. By leveraging React Native and its associated packages, the frontend development was streamlined and a seamless user experience was achieved.

b) Backend Development

Node.js was utilized as the backend technology to develop a server for handling authentication requests, interacting with MongoDB for data storage and retrieval, and managing application logic. Node.js is a cross-platform, open-source JavaScript runtime environment that leverages the V8 JavaScript engine, which powers Google Chrome, to achieve exceptional performance. The non-blocking, event-driven architecture of Node.js enabled the handling of thousands of concurrent connections without creating new threads for each request. This allowed for efficient use of system resources and improved responsiveness. The standard library's asynchronous I/O primitives prevented JavaScript code from being blocked, ensuring that I/O operations such as database access and network reads did not waste CPU cycles. By employing Node.js, this study effectively harnessed its benefits to develop a scalable and efficient backend system.

c) Database Selection and Design

MongoDB, a NoSQL database was selected for its flexibility in storing and retrieving large volumes of data, a critical requirement for managing attendance records in the system. Unlike traditional relational databases, MongoDB offers a document-oriented format for storing unstructured data, allowing for greater adaptability to the project's evolving needs. Each attendance record is stored as a document containing fields such as user ID, timestamp and metadata, facilitating easy querying and analysis. Moreover, MongoDB's scalability ensures that the system can efficiently handle an increasing number of records as the user base grows, without compromising performance.

III. SYSTEM MODELING DIAGRAMS

III. 1. FLOWCHART DIAGRAM

The flowchart depicted in Figure 9 illustrates the sequential steps involved in the fingerprint attendance system. The process initiates with *Enrollment*, where a new user registers their biometric fingerprint data. During enrollment, the user places their finger on the fingerprint sensor, capturing a fingerprint image. This image is then securely stored in the database. Once enrolled, the user marks their attendance by placing their finger on the sensor. The system compares the captured fingerprint with the stored template. If the fingerprints match, the user's identity is verified and their attendance is recorded in the database along with the time and date. In cases of non-matching fingerprints, the system displays an error message or prompts the user to try again.

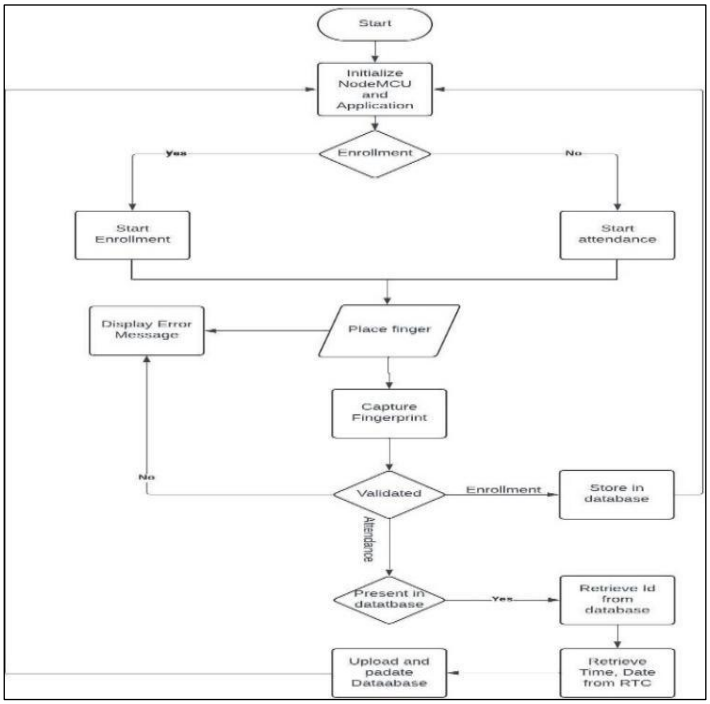

Figure 9: Flowchart of the entire system.
Source: Authors, (2025).

III. 2. DATAFLOW DIAGRAM

The Data Flow Diagram (DFD) provides a visual representation of the fingerprint attendance system's data flow, illustrating the interaction between various components. Figure 10 details this diagram. The DFD utilizes standardized symbols to represent four primary elements: inputs, which are external data sources including student information and attendance records; processes, which are actions performed on the data such as fingerprint capture, identity verification and attendance recording; data stores, which are locations where data is stored including databases and files; and outputs, which are the final results produced by the system including attendance reports and notifications. Arrows in the DFD indicate the direction of data flow between these components, facilitating a comprehensive understanding of data collection, processing, and distribution within the system (Figure 10).

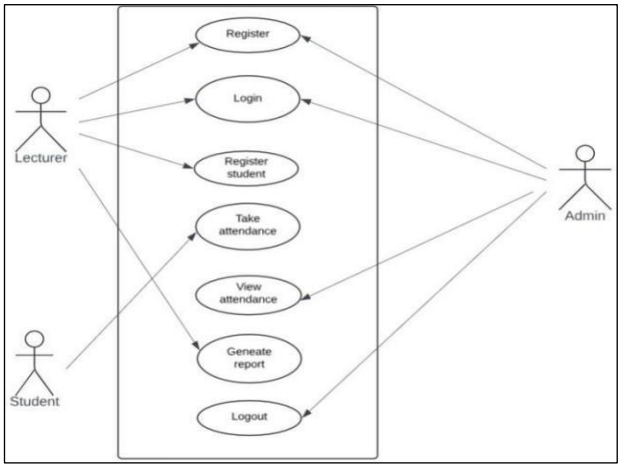

Figure 10: Dataflow for the Database.
Source: Authors, (2025).

III. 3. USE CASE DIAGRAM

The use case diagram provides a visual illustration of user interactions within the fingerprint biometric attendance system. Ovals represent distinct system actions, such as "Register Student," "Verify Attendance," and "Take Attendance," while lines link these actions to their corresponding system users, also known as actors (students, administrators and lecturers). This visualization clearly maps user roles and system interactions, offering an instant understanding of the system's functionality and user engagement (FIgure 11).

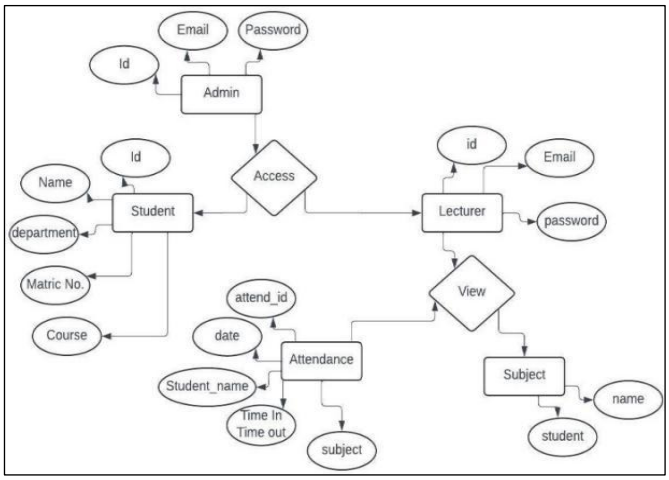

Figure 11: Use Case of the Mobile Application.
Source: Authors, (2025).

IV. RESULTS AND DISCUSSIONS

IV. 1. IMPLEMENTATION OF THE NEW SYSTEM

The deployment of the fingerprint-based attendance system encompasses multiple phases, integrating hardware components, software applications, and data flow to ensure seamless functionality. The system architecture consists of a fingerprint scanning device linked to an application responsible for recording and managing attendance data. This application features a user-friendly interface, enabling lecturers to effortlessly view and manage attendance records.

a) Hardware Setup

The experimental setup consisted of the installation and configuration of the JMI01B fingerprint sensor connected to the ESP32 microcontroller. Supporting components integrated into the system included an RTC module, 16x2 LCD display, and RGB LEDs. Power supply management was achieved using two 3.7V LiPo batteries connected in series with an 18650-power bank module. The experimental setup is as shown in Figure 12.

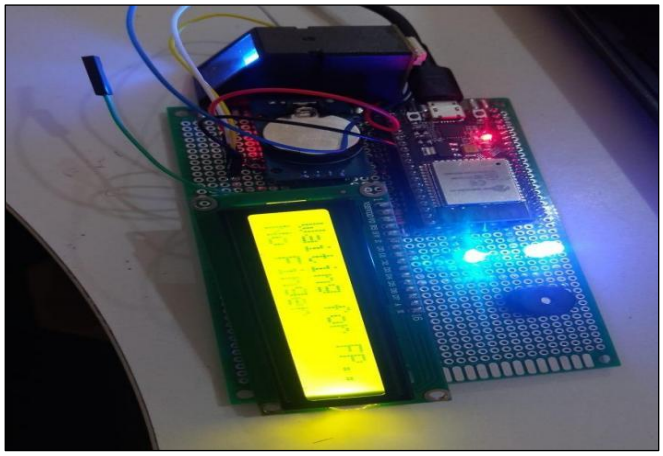

Figure 12: Device Setup.
Source: Authors, (2025).

b) System Architecture and Deployment

The proposed attendance management system's architecture comprises a backend server and a mobile application. The backend server leverages MongoDB for data storage and Node.js with Express.js for API endpoint configuration, handling fingerprint data registration, student attendance tracking and attendance retrieval. The backend server is deployed on Render's cloud server. The mobile application, built using React Native, facilitates student registration and attendance management through real-time data transmission with the fingerprint device via BLE communication, implemented using the React Native BLE PLX library. The application's user interface prioritizes intuitiveness, ensuring easy access to attendance lists for lecturers.

c) System Integration and Validation

The developed system underwent rigorous testing to validate hardware-software communication and backend-frontend synchronization. Hardware-software communication was verified by confirming the successful transmission of fingerprint data from the device (Figure 13) to the ESP32 microcontroller and subsequently to the mobile application via BLE. Data flow

validation ensured reliable transmission to the backend server. Backend-frontend synchronization was achieved through thorough testing of application-backend API interactions, ensuring data consistency. Student records and attendance logs were synchronized in real-time, enabling lecturers to access accurate and up-to-date information.

Figure 13: The Device.
Source: Authors, (2025).

IV. 2. USER INTERFACE ANALYSIS AND VISUALIZATION

This section presents a comprehensive examination of the developed attendance management system's software application screens, supplemented by visual representations (screenshots) to illustrate the interface. The objective of this analysis is to verify that each screen meets functional requirements while providing a seamless user experience.

a) Login Screen

As shown in Figure 14, the login screen presents a minimalistic design, requiring email and password input. Successful login redirects users to the homepage, while incorrect credentials trigger an error message. This design ensures secure authentication and intuitive navigation.

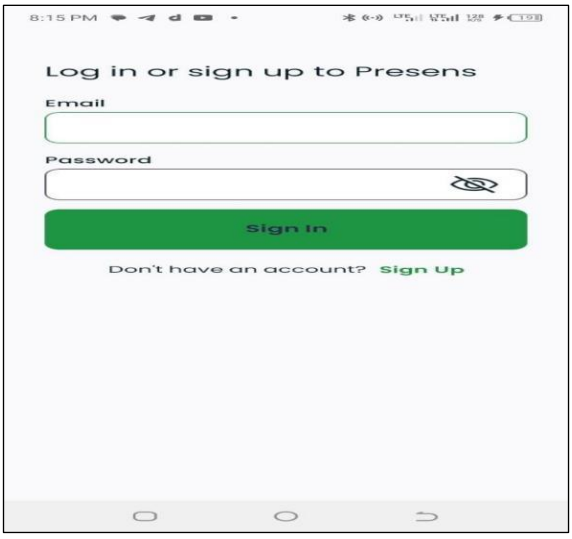

Figure 14: Login Screen
Source: Authors, (2025).

b) Signup Screen

The sign-up screen as shown in Figure 15 facilitates user registration, requiring email and password input. Upon successful registration, users are redirected to the homepage.

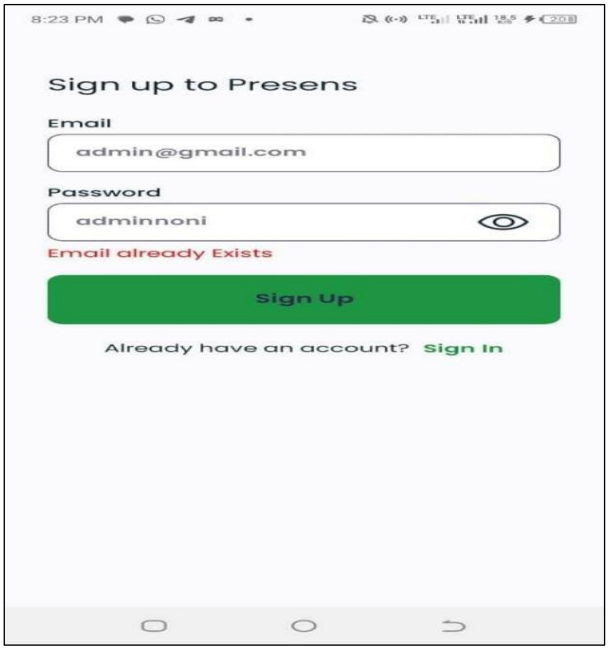

Figure 15: Signup Screen.
Source: Authors, (2025).

c) Homepage

The homepage displays the time, network connectivity status and a greeting message. The main features of the app are accessible through icons: "Create Attendance" for marking attendance, "Register Student" for adding new students to the database and "Connect Device" for pairing biometric fingerprint readers. Additionally, there are tabs for "Attendance List," "Student List," and "Settings" (Figure 16).

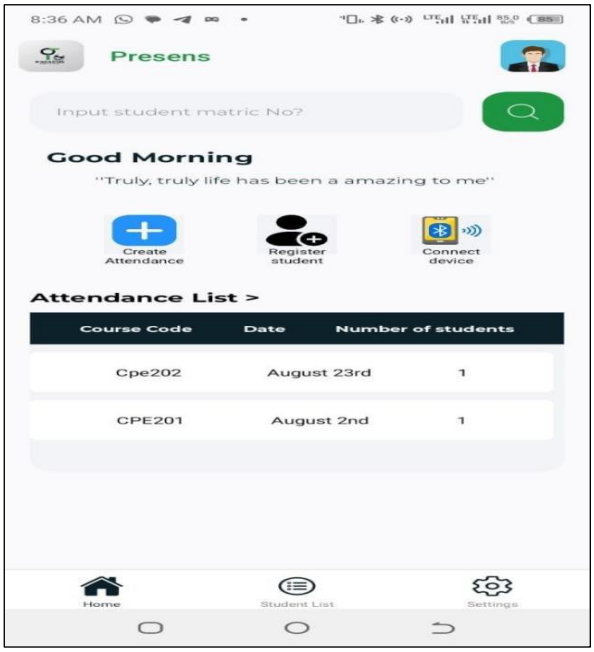

Figure 16: Homepage Screen
Source: Authors, (2025).

d) Student Registration Screen

The student registration page is where the registration of students is done. When the student registration menu is clicked on, on the homepage, it takes the user to the student registration page thatwill display the registration form (Figure 17a and Figure 17b).

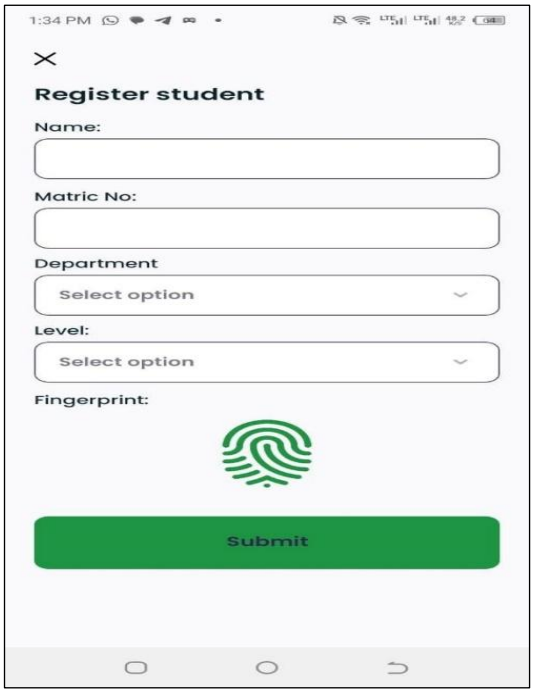

Figure 17a: Student Registration Screen.
Source: Authors, (2025).

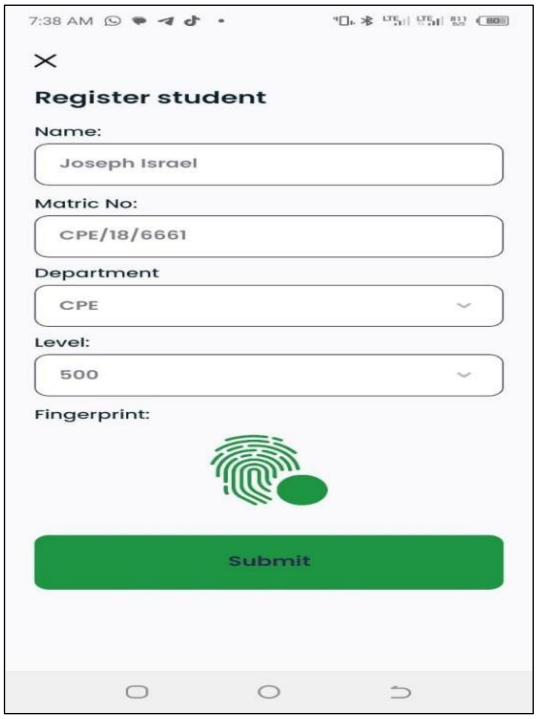

Figure 17b: Student Input Screen.
Source: Authors, (2025).

e) Attendance Creation Screen

This is the screen where the creation of new attendance is done. It displays the creation form of the attendance in Figure 18.

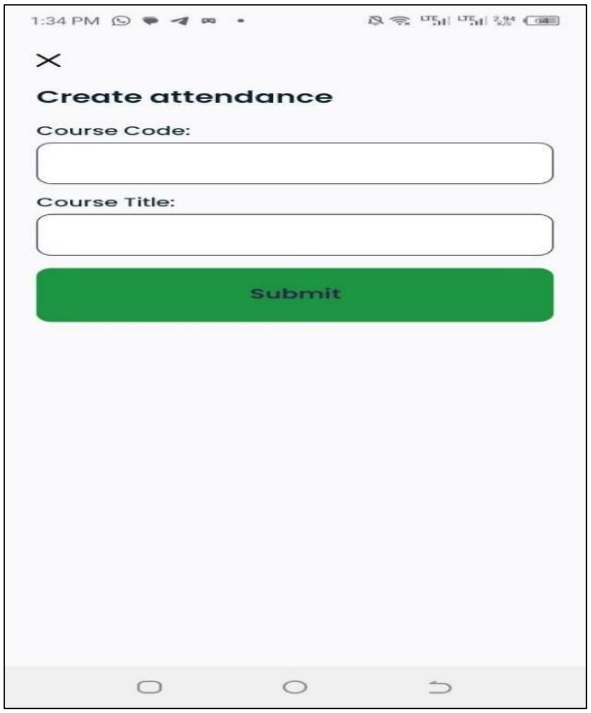

Figure 18: Attendance Creation Screen
Source: Authors, (2025).

f) Attendance List Screen

This displays the attendance list; it also has an icon that leads to a modal for taking fingerprint of student on each particular attendance created in Figure 19.

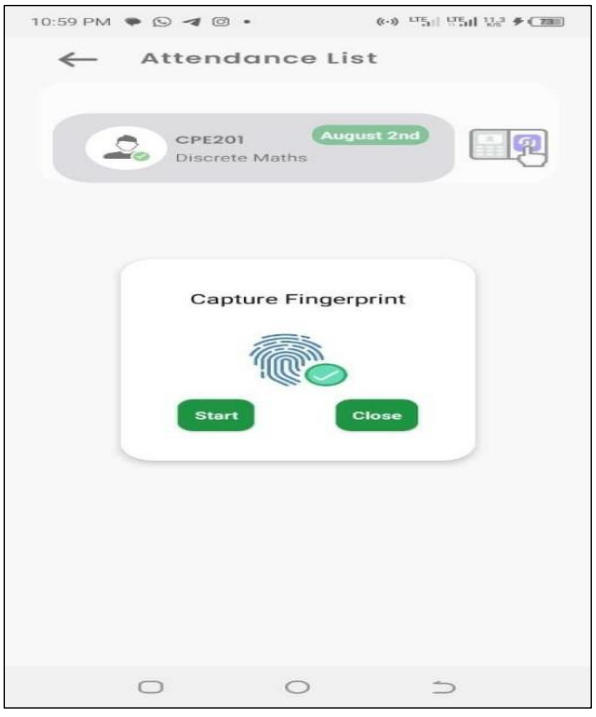

Figure 19: Attendance List Screen.
Source: Authors, (2025).

g) Connect Device Screen

The Connect Device screen serves as an onboarding interface for pairing Bluetooth devices, displaying a modal with available devices for connection in Figure 20.

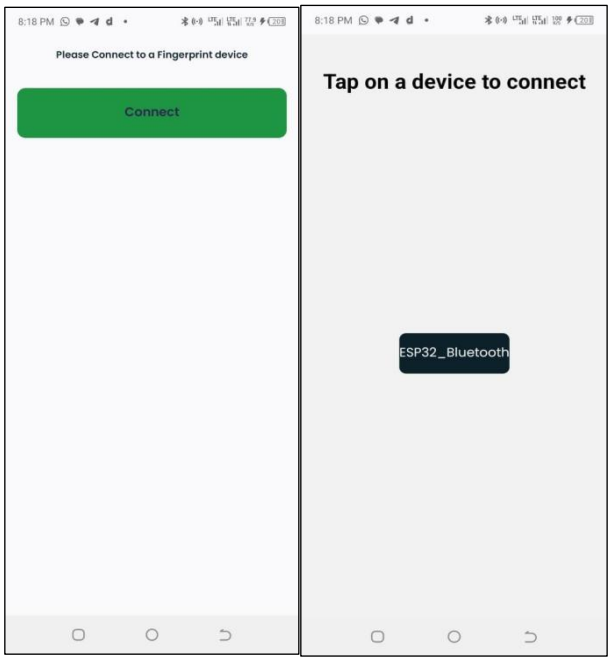

Figure 20: Onboarding to Connect.
Source: Authors, (2025).

IV. 3. SYSTEM OVERVIEW AND DOCUMENTATION

This section provides an in-depth description of the developed attendance management system, outlining its functionality, user access levels, and navigation guidelines.

a) System Description

The proposed system facilitates automated attendance tracking for educational institutions. Lecturers create attendance records for classes, while students register their presence using the biometric fingerprint device. Post-lecture, lecturers can access their portal to view attendance records for the day, enabling accurate attendance scoring.

b) User Access Levels

The system accommodates two primary user categories: students and lecturers. Students are restricted to registering their attendance via fingerprint verification and mandatory system registration. Lecturers have elevated access, enabling them to manage attendance records, register students, and access their profile.

c) System Navigation

Upon launching the application, lecturers can log in or sign up, directing them to their home page. From this central hub, they can manage their profile, register students, create attendance records and access attendance reports. Students, on the other hand, utilize the biometric device to sign in during classes.

d) Student Enrollment and Attendance Tracking

At the semester's commencement, students must register on the system. Thereafter, they utilize their registered fingerprint to sign in on the biometric device during classes. This streamlined process ensures accurate attendance tracking and minimizes disruptions.

e) System Operation

The system operates seamlessly, allowing lecturers to create attendance records, monitor student attendance and generate reports. The biometric device ensures secure and efficient student registration, while the application's intuitive interface facilitates navigation and management.

V. CONCLUSIONS

Traditional attendance tracking methods, using pen and paper registers are time-consuming, prone to errors and vulnerable to manipulation. Electronic biometric-based attendance management systems, specifically fingerprint recognition, offer a reliable and secure alternative. These systems utilize unique fingerprints to accurately identify and authenticate users, ensuring precise and secure attendance records. The fingerprint biometric attendance system consists of a scanner, database and software which captures and converts fingerprint images into digital templates, comparing them to stored templates to record attendance automatically. The implementation of fingerprint biometric attendance systems provides numerous benefits, including enhanced reliability, efficiency and security. It eliminates proxy attendance, reduces administrative burdens, saves time, prevents forged or duplicated records and minimizes human errors, thereby improving accuracy. Overall, fingerprint biometric attendance systems streamline attendance management, reducing errors and fraud. This modern solution addresses traditional method challenges, making it invaluable for organizations and institutions.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Author One
Methodology: Author One and Author Two.
Investigation: Author One and Author Two.
Discussion of results: Author One and Author Two
Writing – Original Draft: Author One and Author Two.
Writing – Review and Editing: Author One and Author Two.
Resources: Author One and Author Two.
Supervision: Author One.
Approval of the final text: Author One and Author Two

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RESEARCH ARTICLE OPEN ACCESS

COMPARATIVE EVALUATION BETWEEN JAVA APPLICATION USING JNI AND NATIVE C/C++ APPLICATION RUNNING ON AN ANDROID PLATFORM

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ABSTRACT

Android is a popular operating system based on the Linux kernel and has a Java-based framework. As it is built on Linux, it supports the development of applications written in C/C++, known as native applications. The Native Development Kit (NDK), along with the Java Native Interface (JNI), provides a solution for communication between Java applications and native C/C++ applications, resulting in a significant performance boost. This article evaluated the performance difference between Java applications using JNI with the NDK and native C/C++ applications, focusing on algorithms widely used in various areas such as automation, networking, telecom, cybersecurity, etc. We conducted sequence of executions initiated either through a graphical interface or via the Android Debug Bridge (ADB) command line, with timing performed by external hardware with its own firmware for this evaluation. Based on the results, we observed that in all test cases, the native application performs faster, except when there are variations related to process scheduling, which may rarely lead to a reversal of this pattern.

I. INTRODUCTION

Android [1] is an operating system initially developed with a focus on mobile devices, but nowadays it is widely used in various applications such as cars, televisions, refrigerators, POS systems, and more. It is currently the most popular operating system [2] and is officially developed by the Open Handset Alliance. The source code is released as open-source software [3], and its structure is based on the Linux kernel, with a Java-based framework in its user space.As Android is a system based on Linux, it also supports the development of applications written in C/C++. These are known as native applications because they use libraries compiled specifically for the target system. Some examples of native libraries include libC, OpenGL, WebKit, etc. Since this type of application is closer to the kernel layer, its execution time is usually shorter, but there is a higher complexity in understanding and mastering the syntax of the language.Java is a programming language that utilizes a virtual machine to interact with the system, which results in higher processing costs due to the additional layers of software and this can reduce performance when accessing hardware devices. For this purpose, there is a tool called the Native Development Kit (NDK) [4] that allows communication between a Java application and a native C/C++ application, bringing a considerable performance gain to them.One of the main tools of the NDK is the Java Native Interface [5] (JNI). Applications that use JNI can incorporate native code written in C/C++ while still gaining the advantages of using a higher-level language. Additionally, JNI enables the utilization of native Linux libraries, in conjunction with the benefits of the Android framework simultaneously.

When developing an Android application, it is essential to consider how the system works, and one of the first aspects to evaluate is the execution time. The performance difference between a Java application and a C/C++ application has been a well-established study, but there are few analyses related to this topic applied on an Android platform using the NDK.

In this paper, we evaluate the performance difference between a Java application using JNI and a native C/C++ application. The focus is on testing consolidated algorithms widely used in various areas such as automation, networks, telecommunications, cybersecurity, etc. The main objective of this

work is to establish a comparison between these two development approaches in Android. This comparison provides valuable insights for developers who need to choose between the two approaches to achieve greater efficiency in their applications, either due to hardware limitations or battery consumption.

The article is organized as follows:

- Section II: Review of the algorithms used for performance comparison.
- Section III: Brief description of related works.
- Section IV: Explanation of the development methodology for the test pipeline, metrics, and analysis.
- Section V: Presentation of the test case results.
- Section VI: Analysis of obtained results.
- Section VII: Conclusion of the work and proposals for future research.

II. ALGORITHM DESCRIPTIONS

This section provides a comprehensive overview of the algorithms selected for our performance comparison. These algorithms are widely used across various domains, including data processing, network routing, signal processing, and cryptography. We have carefully chosen algorithms that exhibit different computational complexities and characteristics to ensure a thorough evaluation of the performance differences between Java and C/C++ implementations on Android.

II.1 QUICKSORT

Quicksort is renowned for its efficiency as a sorting algorithm and utilizes a divide-and-conquer strategy to organize data. The core mechanism involves partitioning an array into smaller subarrays around a pivot element. This partitioning step is recursively applied to the resulting subarrays until the entire array is sorted. The selection of the pivot element significantly affects the performance of Quicksort. In the best-case scenario, where the pivot divides the array into nearly equal halves, Quicksort achieves a time complexity of O(n log n). However, in the worst case, where the pivot selection results in highly imbalanced partitions, the time complexity can degrade to $O(n^2)$. To address these performance issues, techniques such as introsort, which combines Quicksort with Heapsort, and three-way partitioning are employed. Introsort ensures that the algorithm's performance remains O(n log n) in the worst case, while three-way partitioning helps improve performance by handling arrays with many duplicate elements more effectively [6].

```
QuickSort(arr, low, high):
    if low < high:
        pivot ← Partition(arr, low, high)
        QuickSort(arr, low, pivot - 1)
        QuickSort(arr, pivot + 1, high)
Partition(arr, low, high):
    pivot ← arr[high]
    i ← low – 1

    for j ← low to high - 1:
        if arr[j] ≤ pivot:
            i ← i + 1
            Swap(arr[i], arr[j])
    Swap(arr[i + 1], arr[high])
    return i + 1
```

Figure 1: Flow of the QuickSort algorithm showing the partitioning process and recursion to sort a list of numbers.
Source: Authors, (2025).

II.2 DIJKSTRA'S ALGORITHM

Dijkstra's algorithm is a fundamental graph search algorithm designed to determine the shortest path between nodes in a weighted graph. The algorithm operates by iteratively exploring neighboring nodes and updating the estimated distance to the destination node. A priority queue, often implemented as a minimum heap, is used to select the node with the smallest known distance for expansion. This approach ensures that the shortest path is identified efficiently.

The time complexity of Dijkstra's algorithm depends on the data structure used for the priority queue. When using a binary heap, the algorithm runs in O((|V| + |E|) log V), where |V| is the number of vertices and |E| is the number of edges in the graph. If a Fibonacci heap is used, the complexity can be reduced to O(|E| + |V| log |V|) [7]. Dijkstra's algorithm is widely applicable, including in network routing protocols, geographic information systems, and robotics for pathfinding.

It is important to note that Dijkstra's algorithm can only be used on graphs that have non-negative edge weights. For graphs containing negative edge weights, the Bellman-Ford algorithm or other techniques may be used [8], [9].

```
Dijkstra(graph, source):
    for each v of V:
        dist[v] ← ∞
    dist[source] ← 0
    priority_queue ← [source]

    while priority_queue is not empty:
        u ← node with smallest dist in priority_queue
        Remove u from priority_queue

        for each neighbor v of u:
            if dist[u] + weight(u, v) < dist[v]:
                dist[v] ← dist[u] + weight(u, v)
                Add v to priority_queue
    return dist
```

Figure 2: Illustration of Dijkstra's algorithm determining the shortest path in a weighted graph, focusing on updating distances and selecting nodes using a priority queue.
Source: Authors, (2025).

II.3 FAST FOURIER TRANSFORM

The Fast Fourier Transform (FFT) is a powerful algorithm for computing the Discrete Fourier Transform (DFT), which decomposes a signal into its constituent frequency components. The FFT is invaluable in various signal processing applications, including filtering, data compression, and spectral analysis. In image processing, FFT is employed for tasks such as convolution, filtering, and edge detection.

The efficiency of FFT arises from its recursive structure, which reduces the computational complexity from $O(n^2)$ for the naive DFT algorithm to O(n log n). This reduction is achieved by recursively dividing the DFT computation into smaller, more manageable subproblems. The FFT's ability to handle large datasets with reduced computational requirements makes it a crucial tool in both theoretical and applied signal processing [10].

```
FFT(A):
   n ← length(A)
   if n = 1:
      return A

   w_n ← e^(2πi/n)  // n^th root of unity
   A_even ← FFT(A[0], A[2], ..., A[n-2])
   A_odd  ← FFT(A[1], A[3], ..., A[n-1])

   for k = 0 to n/2 - 1:
      w ← w_n^k
      A[k] ← A_even[k] + w * A_odd[k]
      A[k + n/2] ← A_even[k] - w * A_odd[k]

   return A
```

Figure 3: Diagram of the FFT decomposition process, showing how the input sequence is divided into even and odd components and processed recursively.
Source: Authors, (2025).

II.4 RIVEST-SHAMIR-ADLEMAN ALGORITHM

The Rivest-Shamir-Adleman (RSA), algorithm is a widely adopted public-key cryptosystem that provides a secure method for encrypting and decrypting information over public channels. The security of RSA is based on the mathematical difficulty of factoring large composite numbers. The algorithm involves generating a pair of keys: a public key used for encryption and a private key used for decryption. Encryption is performed by raising the message to the power of the public key exponent, modulo the product of two large prime numbers.

Decryption, on the other hand, is carried out using the corresponding private key. The computational complexity of RSA encryption and decryption is dominated by the modular exponentiation step, which has a time complexity of $O((\log n)^3)$, where n is the size of the modulus (product of the two primes).

The strength of RSA lies in the size of the keys and the computational challenge associated with factoring the product of large primes. RSA is extensively used in various security protocols, including SSL/TLS for secure web communications and digital signatures for authentication and data integrity [11].

```
RSA Key Generation:
   Choose two large primes p and q
   n ← p * q
   φ(n) ← (p - 1) * (q - 1)

   Choose e such that 1 < e < φ(n) and gcd(e, φ(n)) = 1
   Compute d such that (d * e) % φ(n) = 1
   Public key = (e, n)
   Private key = (d, n)

RSA Encryption(m, e, n):
   c ← (m^e) % n
   return c

RSA Decryption(c, d, n):
   m ← (c^d) % n
   return m
```

Figure 4: Representation of the RSA algorithm, detailing key generation, encryption, and decryption of a message using modular arithmetic.
Source: Authors, (2025).

III. RELATED WORKS

Some work has already been done to measure the performance of Android applications, such as the one by [12], which made comparisons of applications running on an Android emulator under a Linux x86 system. The study concluded that native applications can be up to 30 times faster than a Java application executing the same algorithm, and this time can be improved up to 10 times if the Java application uses JNI. However, since the tests were executed on an emulator, the results may not fully reflect the reality of an embedded system. Additionally, the experiments were limited to calculations with mathematical integers, which may not be sufficient to capture the performance difference.

According to [13] executed 11 algorithms for the comparison between a pure Java application running a shared library via the virtual machine and one running the same library via JNI on specific hardware. In their results, they found that, overall, an application using JNI performs 34.20% better than one using the virtual machine. However, in 3 out of the 11 tests, the Java application performed better. Notably, the author developed their own task execution timer within their Java application, allowing a biased result when the system decides that this is not a priority task.

This paper is based on the work of [14], in which they used 6 algorithms and compared the results between a native application and a Java application with JNI. In contrast to what might be expected, their results indicated that the algorithms called via JNI were faster than those in the native application, except for Dijkstra's algorithm. The authors concluded that native applications were slower due to the native Android library, GNU C, and the compilation done with the GNU Compiler, in comparison with the bionic C/C++ library used in the development of the native layer of their JNI application.

A limitation in the authors' methodology is that each algorithm was executed 15 times, but it is not clear if there was variation in the inputs, as the result graphs are almost constant, with some slight variations that may be related to other processes that the operating system was running at the time. Another limitation is how the test timing was implemented, which was done via software within their target (system). Since Android is not a real-time operating system, this method of timing may lead to biased results when the system determines that certain tasks are not a priority.

IV. MATERIALS AND METHODS

In this work, we developed a pipeline for evaluating the execution time of native and Java applications using a timer external to the device running the application. We chose to use an external timer instead of one programmed within the applications to avoid potential bias caused by the system's task scheduling during the timing of execution. By doing so, we isolated the timer as an external device solely responsible for measuring the time of each execution.

Figure 5 provides a detailed view of the developed pipeline.

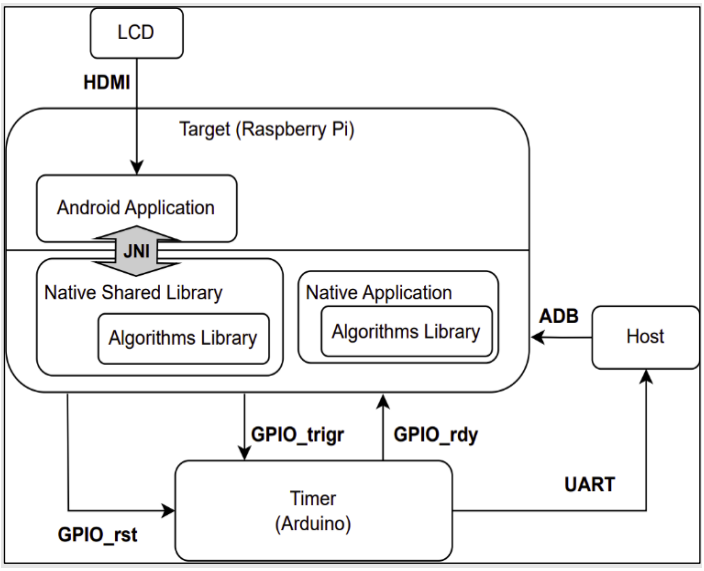

Figure 5: Developed pipeline for algorithm evaluation: the JNI application tests are initiated via LCD, while the native application tests are started through the Android Debug Bridge (ADB); When the target begins executing the algorithm, it triggers the external timer, and at the end of the test, it stops the timer.
Source: Authors, (2025).

The standard way to access a native application on an Android device is through the command line, as it is executed by an external machine referred to as the Host, via ADB. The method used to access the Java application is through a graphical interface, where the Target utilizes an LCD screen to display the options of algorithms to be executed.

When the Host machine or the LCD requests the execution of an algorithm, a sequence of executions is called according to the chosen algorithm. For instance, if the Quicksort algorithm tests are triggered via the LCD, at that moment, tests with 8 different input sizes are programmed, and each of these sizes will be executed 100 times. In other words, the counting is done 800 times in this example of sequence of executions.

When the test initialization is requested, the Target verifies if the timer is available to start the countdown. If it is not available, Target waits for its release; if it is available, it triggers the timer, initiating the countdown and starting the execution of an algorithm. When an algorithm completes its execution, the application triggers the timer again, ending the countdown, and at this moment, the timer sends the test result to the Host and notifies the Target that is available to count again.

For the test execution, the hardware chosen was Raspberry Pi 4B, and the operating system used was Android 13. To measure the time, an external device (Arduino Micro) controlled via General Purpose Input/Output (GPIO) by Target was utilized.

In the following subsections, we will explain each of the modules presented in Figure 5.

IV.1 HOST

For the host machine, represented in Figure 5 as 'Host', was used a computer with Ubuntu 20.04.6 LTS 64-bit system. The Host has two tasks in the developed pipeline, executing tests of the Android Native Layer via ADB and receiving the times of each test, both native and JNI, through Universal Asynchronous Receiver/Transmitter (UART) communication.

IV.2 TIMER

The execution time is calculated using an external hardware, represented in Figure 5 as 'Timer (Arduino)'. The Timer receives a pulse on a GPIO to indicate the start of an execution. During the execution, it signals that it is busy counting through another GPIO. When the execution is completed, another pulse is sent to the same GPIO, indicating that the counting can stop. Upon receiving the second pulse on the first GPIO, the Arduino writes the execution time in microseconds to the serial port, which will be received by the Host. Due to the external communication, this method takes some time that should be disregarded in the algorithm results, referred to as the 'communication offset' between the Target and the Timer.

IV.3 TARGET

The test target, represented in Figure 5 as 'Target (Raspberry Pi)', used Android version 13 ported to the Raspberry Pi 4B [15]. This platform featured the Broadcom BCM2711 SoC, with 4 ARM Cortex-A72 64-bit cores running at 1.8GHz and 8GB of RAM [16]. For cross-compilation, the Low Level Virtual Machine (LLVM) compiler infrastructure, which is the standard in current versions of the Android Open Source Project, (AOSP) was used in conjunction with Clang, the C/C++ compiler present in LLVM, both of which were included in the Android NDK (Native Development Kit). The version of the Android NDK used was r17c [17]. To access the interface of the JNI application, a 7-inch LCD screen with a resolution of 1024x600 pixels was utilized, and to execute the program of the native layer, the Host was used.

As the timer is an external hardware that communicates with Android via GPIO, it was necessary to develop a native library to access it. This library defines a class, called Timer, that encapsulates the management of GPIO in 3 methods that:

1) Indicate whether the timer is available.
2) Trigger and stop the timer.
3) Reset the test counting.

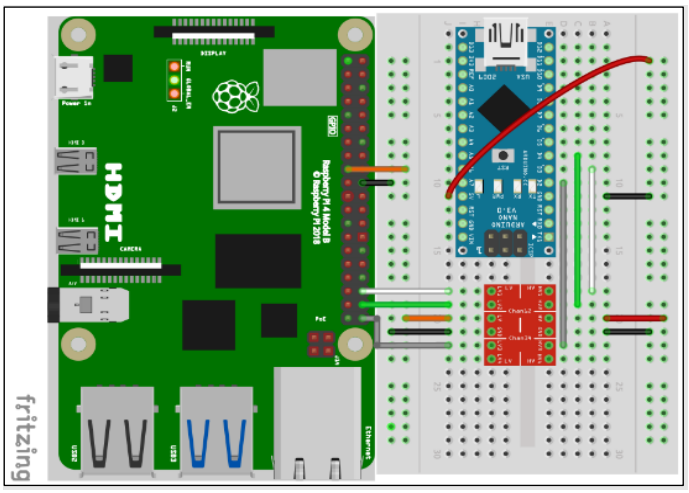

Figure 6: Circuit connections between the target and timer.
Source: Authors, (2025).

Figure 6 represents the circuit connection between the Target and the timer. To make external hardware accessible to the Java application layer on Android, a Hardware Abstraction Layer (HAL) must be created. To access the timer, the implemented HAL utilizes the Timer library mentioned in the previous paragraph and creates a service in the Android framework, enabling access through the JNI application.

IV.4 TARGET ALGORITHM LIBRARY

For the test execution on the target, we selected some well-established algorithms, such as Quicksort, Dijkstra, Fast Fourier Transform (FFT), and the Rivest-Shamir-Adleman (RSA) algorithm, which were implemented in a single library and statically compiled along with the executed binaries. Here is a brief description of the algorithms and how they were executed in this work:

- Quicksort, from the automation category, is an algorithm for sorting arrays. We executed arrays of lengths 1000, 2000, 4000, 6000, 8000, 10000, 12000, and 14000. For each array length, we performed 100 tests with the worst-case scenario for the algorithm, including arrays that are already sorted or have all elements equal.
- Dijkstra's algorithm, from the networks category, calculates the minimum cost between the vertices of a graph. Weighted graphs were run with vertex numbers of 200, 400, 600, 800, 1000, 1200 and 1400, and for each number of vertices 100 different randomly generated graphs with connections and weights were tested.
- Fast Fourier Transform (FFT), from the telecommunication category, decomposes a polynomial signal into the frequency domain. We executed inputs with power of 2, which indicates the degree of the polynomial signal to be transformed. The exponents used in the tests were 14, 15, 16, 17, 18, 19, and 20.
- The Rivest-Shamir-Adleman (RSA) algorithm, from the cybersecurity category, encrypts messages using a private and public key generated from prime numbers. With a fixed key, we encrypted and decrypted texts of lengths 2000, 4000, 6000, 8000, 10000, 12000, and 14000, with any ASCII character. For each length, we tested 100 different strings generated randomly.

IV.5 NATIVE APPLICATION

A Native Application is a type of application that uses native libraries, i.e. libraries that can communicate directly with the system. The Native Application is a type of application that makes use of native libraries, meaning libraries that can communicate directly with the system. As Android is a Linux-based system, this type of application is developed in C/C++, and after compilation, a single binary file is generated that can be executed using the command line provided by adb. Figure 7 represents the binary of the application with algorithm library compiled together with it.

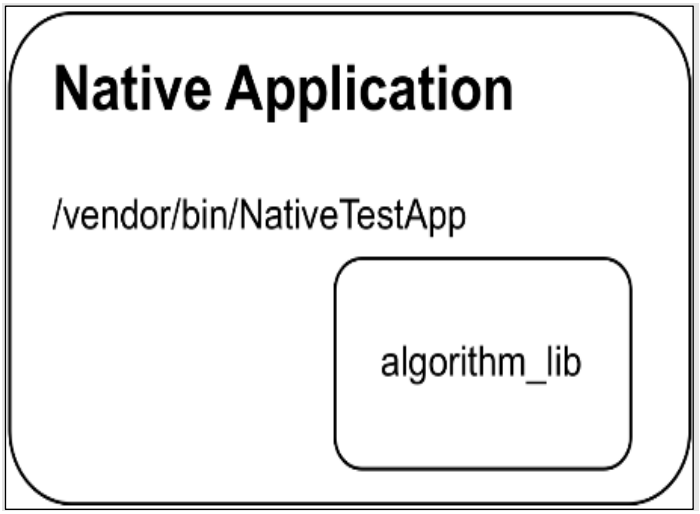

Figure 7: Representation of the native application compiled together with the algorithm library.
Source: Authors, (2025).

IV.6 JAVA APPLICATION USING JNI

Android applications developed in Java and Kotlin are the main ways for users to interact with a device, using a graphical interface. When compiled, the Java application generates a bytecode, which, differently from native applications that are executed directly by the system, requires a virtual machine to translate it. The virtual machine used by Android is called the Android Runtime (ART). Due to the distinct execution and compilation of Java and C/C++, the developed method for communication between these two types of languages is the Java Native Interface (JNI), which integrates a Java method to access functions from a shared native library. Figure 8 illustrates the flow of access by the Java application to the shared library, which, in this case, contains the functions from the algorithm library to be executed.

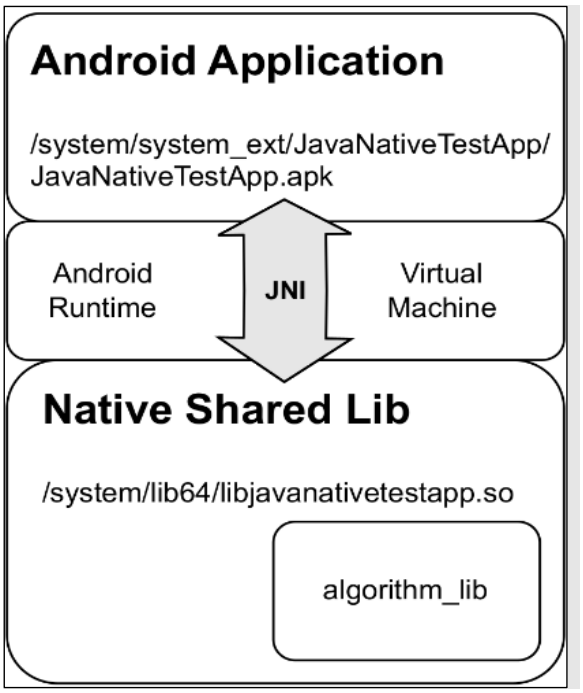

Figure 8: Representation of the communication flow between a Java application and a shared native library using JNI.
Source: Authors, (2025).

V. RESULTS AND DISCUSSIONS

The results were collected from the sequence of executions for each algorithm and plotted in graphs for better visualization. First, it was necessary to calculate the average of the communication offset between the applications and the Timer. This value is subtracted from the algorithm results to obtain a value that closely approximates the real execution time.

V.1 ESTIMANION OF THE COMMUNICATION OFFSET BETWEEN THE SYSTEM AND THE TIMER

Figure 9 shows the difference between the communication offsets for each application and the external timer. This means that the Timer is called without any algorithm running, resulting in only the time taken for the pulse to be sent twice – once to start the counting and another to stop it. The x-axis represents the number of executions, and the y-axis represents the time obtained in each repetition. The average of these times gives the value of the communication offset, which will be subtracted from the execution time of the algorithms.

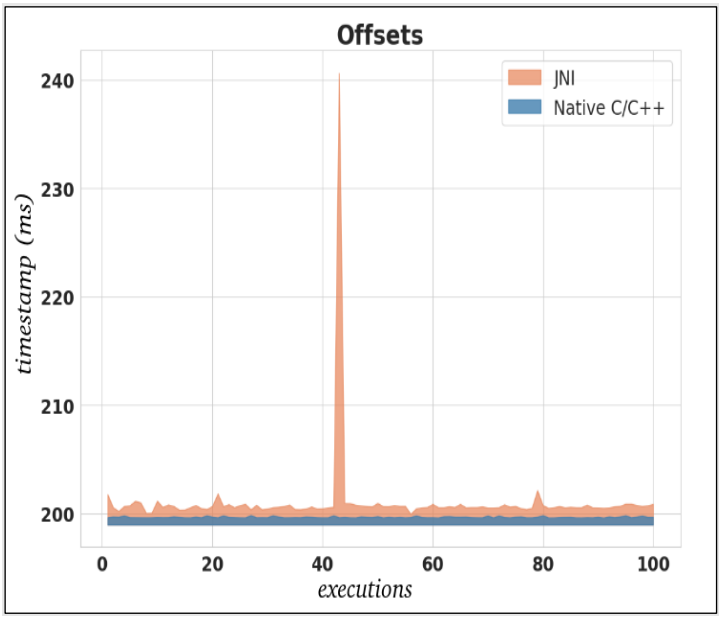

Figure 9: Overhead due to Communication in Java Applications (100 Runs).
Source: Authors, (2025).

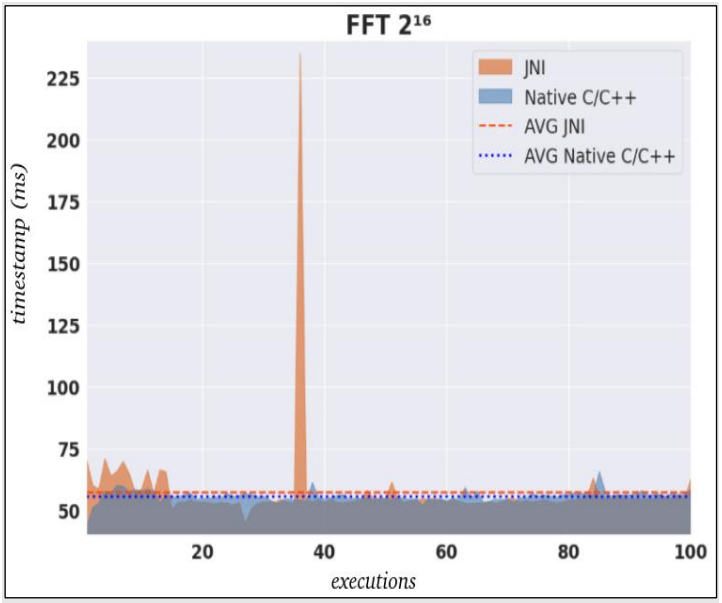

Figure 10: Variation in FFT Algorithm Execution Time for 100 Tests with 2^{16}. Inputs.
Source: Authors, (2025).

As shown, the native application had an average offset of 199.68ms, while the Java application had an average offset of 200.65ms. This small difference is possibly related to the layers that the system needs to pass to communicate with a JNI application.

V.2 CALCULATION OF ALGORITHM EXECUTION TIMES

Figure 11 presents the execution times of various algorithms for different input sizes. The x-axis represents the input size, while y-axis shows the execution time (excluding communication overhead). Each column displays the average execution time across 100 test runs for a specific input size, measured for both the native application and the JNI implementation.

Error bars indicate the standard deviation of these execution times. Figure 11a illustrates that the native application consistently outperforms JNI across all input sizes. Notably, the native application's execution time is between 3% (6,000 inputs) and 20% (2,000 inputs) faster than JNI.

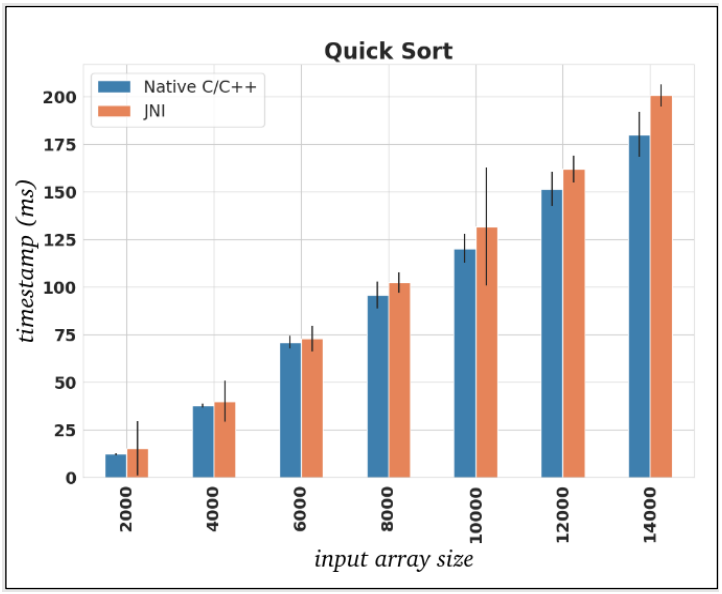

Figure 11a: Result obtained with the *Quick Sort* algorithm for input vectors with sizes ranging between 2000 and 14000.
Source: Authors, (2025).

Similar trends are observed in Figure 11b. The native application generally executes faster than JNI, with an average difference of 4% to 5.5%. In rare instances where JNI is faster, the maximum advantage is around 1.4% compared to the native application's average execution time.

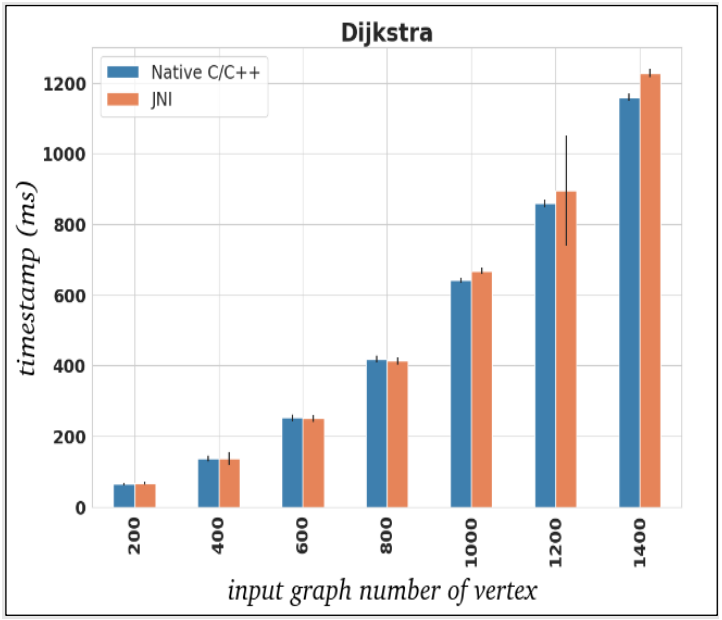

Figure 11b: Result obtained with the Dijkstra algorithm for graphs with number of vertices varying between 200 and 1400.
Source: Authors, (2025).

Figure 11c depicts the performance of the RSA algorithm. The native application demonstrates consistent speedup compared to JNI for all input sizes. However, the performance gap narrows with increasing input size. The native application exhibits a maximum efficiency gain of 6.5% (2,000 inputs) and a maximum of 0.7% (1,200 inputs) over JNI.

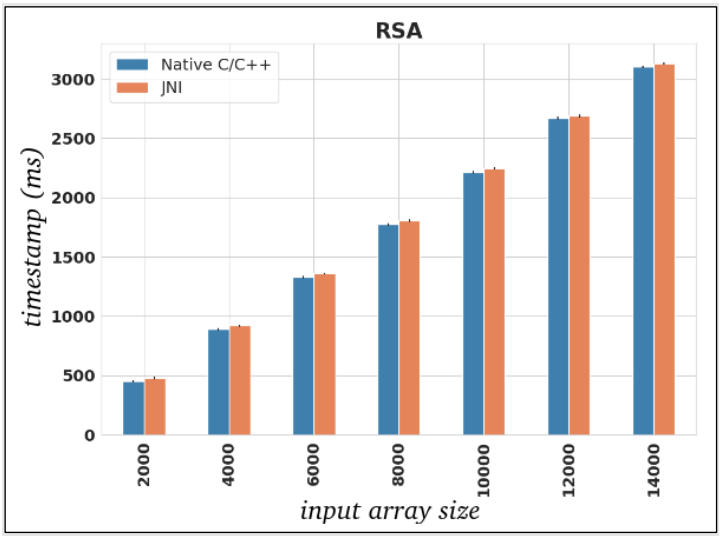

Figure 11c: Result obtained with the RSA algorithm for input vectors with sizes between 2000 and 14000.
Source: Authors, (2025).

In the analysis of the FFT algorithm, it was necessary to make a scale break as shown in Figure 11d, as the time variation according to the inputs was high, varying from 8.4 ms for 2^{14} inputs and 2194 ms for 2^{20} inputs. The native application is faster than JNI at most input sizes, with the average ranging between 3% and 12%. However, in cases where the JNI application is faster, there is a large variation, being 5% to 15% faster than the native one, on average executions.

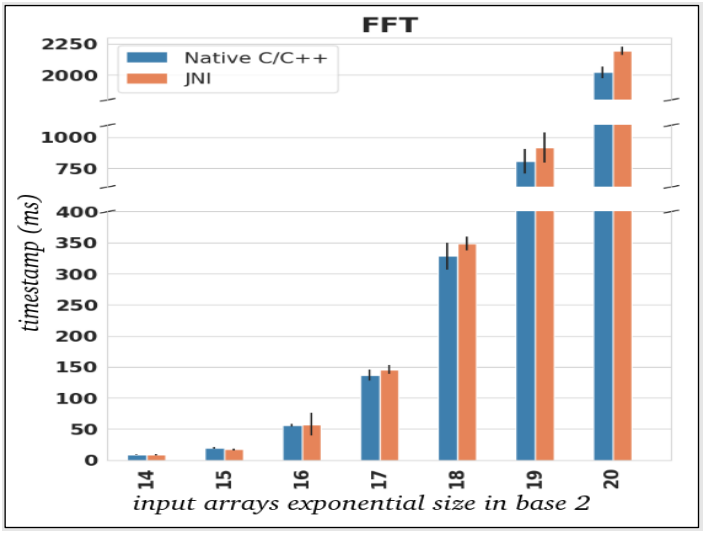

Figure 11d: Results of running the FFT algorithm on vectors size 2^{14} to 2^{20}.
Source: Authors, (2025).

VI. ANALYSIS OF RESULTS

Our experiments show that native applications generally outperform Java applications using JNI, as shown in the graphs of Figure 11. This advantage stems from the way each application interacts with the system. Native applications have built-in algorithm libraries allowing their code to run directly with the system without needing translation. In contrast, Java applications using JNI require an extra layer of communication. This translation process through JNI adds some overhead, slowing down the execution.

These factors not only make native applications faster but also less prone to execution time variations. Figure 10 illustrates this point for the FFT algorithm with a 2^{16} input. The native application's execution time remains consistent, while the Java application's time fluctuates more. Although the Java application might be faster in rare moments, the native application is generally faster and more reliable.

These variations explain the rare instances where the Java application surpassed the native application. Specifically, this occurred with the Dijkstra algorithm for graphs with 600 vertices and de FFT algorithm for a 2^{15} input. The reason for these variations lies in Android. Since Android is a Linux-based system, it doesn't guarantee real-time performance. This means that in some situations, the system might prioritize other tasks, causing temporary slowdowns for the Java application. However, these slowdowns shouldn't be a common occurrence.

VII. CONCLUSIONS AND FUTURE WORKS

This article provides a comprehensive comparison between the performance of native C/C++ applications and Java applications utilizing a shared library accessed via the Java Native Interface (JNI) from the Android Native Development Kit (NDK). Both applications were compiled using the same toolkit to ensure a level playing field for comparison.

The experimental results demonstrate a consistent performance advantage for the native C/C++ application across all tested algorithms. Specifically, the performance improvements were significant, with the native application outperforming the Java application by up to 20% for the Quicksort algorithm. For Dijkstra's algorithm, the performance gain was 5.5%, while for the Fast Fourier Transform (FFT), the improvement was 12%. The RSA algorithm showed a performance enhancement of 6.5%. These results underscore the efficiency of native code execution, particularly in scenarios where computational intensity is high.

However, it is worth noting that for very small input sizes, the execution times for both types of applications were relatively faster and exhibited greater susceptibility to system variations. In these cases, there were instances where the Java application achieved faster execution times, influenced by system fluctuations and variations in processing load.

When comparing the results of this study with those reported by Kim, Cho, Kim, Hwang, Yoon, and Jeon [14], it is evident that the complete migration of AOSP to using the Bionic library and the LLVM compilation toolkit has significantly optimized the performance of native applications. This transition has resulted in native applications consistently outpacing Java applications that use JNI. The improvements in the Bionic library and LLVM toolchain have contributed to this enhanced performance by optimizing low-level operations and compilation processes.

Looking ahead, future research will explore additional performance comparisons by examining Java/native communication via JNI against communication using Binder Inter-Process Communication (IPC). Binder IPC, introduced in Android 10, represents a paradigm shift in the Hardware Abstraction Layer (HAL) development compared to the traditional JNI standard. This investigation will aim to assess how Binder IPC influences performance and efficiency in comparison to JNI, providing further insights into optimizing communication strategies within Android apqplications.

VIII. AUTHOR'S CONTRIBUTION

Conceptualization: Álison de Oliveira Venâncio.
Methodology: Álison de Oliveira Venâncio.
Investigation: Álison de Oliveira Venâncio.
Discussion of results: Álison de Oliveira Venâncio.
Writing – Original Draft: Álison de Oliveira Venâncio.
Writing – Review and Editing: Thales Ruano Barros de Souza, Bruno Raphael Cardoso Dias.
Supervision: Thales Ruano Barros de Souza, Bruno Raphael Cardoso Dias.
Approval of the final text: Álison de Oliveria Venâncio, Thales Ruano Barros de Souza, Bruno Raphael Cardoso Dias.

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CLASSIFICATION OF PROMINENT CACAO POD DISEASES USING MULTI-FEATURE VISUAL ANALYSIS AND K-NEAREST NEIGHBORS ALGORITHM

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ABSTRACT

Cacao has been one of the most promising crops produced in the Philippines due to its increasing demand in various local and international markets. Although cacao production aspired to be heightened to cope with the global trend, several difficulties were still needed to be addressed in crop propagation, mainly due to disruptive diseases and pests. In response to this problem, the study devised an algorithm based on k-Nearest Neighbors that can detect whenever a cacao pod was infected with the three most prominent diseases: black pod rot, Monilia, and pod borer infestations. The machine training model was preceded with visual feature extraction of color and texture parameters representing the cacao pod samples. It was found that the fine k-Nearest Neighbors algorithm achieved the highest validation and testing accuracies of 93.44% and 96.67%, respectively. The study's outcome suggested the continuous practicality of fusing visual feature extraction processes with supervised machine learning to generate models that can be applied to improve agricultural methods.

I. INTRODUCTION

Due to international demand and competitive industry, cacao has been included as one of the crucial crops in the strategic and technology plan for agricultural resources research in the Philippines. It has been recommended that the commercial production of cacao be boosted to accommodate the rising global demand and take advantage of the country's favorable geographic landscape. Although efforts and initiatives are present, the cocoa business in the Philippines still suffers from the risks presented by possible attacks of pests and diseases [1].

The black pod rot disease, caused by Phytophthora species, and the frosty pod rot, also called the Monilia disease, were the most prominent cacao pod ailments worldwide [2]. Regarding pests, the pod borer, Conopomorpha cramerella, significantly contributed to the disruptions in cacao production in Southeast Asia [3]. Small-scale local farmers were projected to face more damaging consequences due to lack of agricultural knowledge and skills in planting and post-harvesting management of cacao crops. Due to the devastations brought by emerging diseases, cacao plantations were expected to decline without appropriate intervention, contributing to significant production losses. In response to these conflicts, national agencies and industry partners have developed programs for disease management and effective resource use. These activities aim to utilize cutting-edge technologies and tools to promote long-term responses for sustainable cacao health and industry firmness over time [2].

Artificial intelligence-based techniques, like deep learning and machine learning, have been infamous for developing programs meant to diagnose plant diseases at their initial stages, paving the way for early preventive maintenance and actions. When complemented by high-resolution photography, these algorithms will break free from the restrictions attributed to the manual classification of diseased crops, often influenced by subjective observations [4].

Neural networks, such as convolutional neural networks (CNNs), and supervised machine learning models were typically applied to tools and gadgets that can perceive the presence of plant defects with high classification accuracy. These approaches heavily depended on data, such as standard pictures or sensor data,

as the number of samples significantly shapes their detection capabilities [5]. For traditional machine learning methods, image processing techniques were preferably embedded for gathering necessary visual features, like shape, color, and texture, which can later be administered to classification algorithms for training.

On the other hand, neural networks can facilitate both feature extraction and classification training processes, making them suitable for more extensive disease differentiation [6]. This ability of the neural networks was showcased in the studies of [7-11] as applied to actual cacao pods and leaves.

Brought by widespread endeavors to combat the implications of unsolicited cacao threats, functional mobile applications have been launched to identify several cacao pests and diseases. [12] created AuToDiDAC, a mobile application aimed at detecting and assessing the level of black pod rot infection in cacao pods. With the application of graph cuts, color balancing, and fast k-means clustering algorithms for processing raw cacao pod images, the SVM classifier incorporated in the tool was found to have a classification accuracy of 84% when evaluated in ten independent pod samples.

Furthermore, [13] designed an image processing application that can identify general initial symptoms of pest and disease infestation in cacao, achieving an accuracy of 100%. The local binary pattern (LBP) and Gabor filter algorithm were utilized for feature extraction, while deep learning methods were used for the classifier.

The resulting mobile application was programmed to use cellphone camera captures as input data. On the other hand, [14] has integrated modified CNN to identify pods infected with swollen shoot disease among cacao trees. According to [15] worked with a CNN-based smartphone application named Cocoa Companion that can detect swollen shoots as well with the addition of black pod diseases, having a maximum accuracy of 80%. SSD MobileNet V2 was selected among the other three options for the CNN architecture: EfficientDetD0, CenterNet ResNet50 V2, and SSD ResNet50 V1 FPN. According to [16] improved the former study by considering a higher sample of cacao pods for training, making the accuracy as high as 88%.

Aside from constructing actual image processing programs, various researchers have chosen to be engaged in finding the perfect combination of feature extraction techniques, supervised machine learning algorithms, and neural networks to form a model that can accurately determine if a cacao pod is healthy or infected by distinct diseases.

Several studies have used conventional image processing techniques to obtain relevant visual information from cacao pod images, then utilized algorithms such as SVM and neural networks for the classification model. According to [17] employed the Haralick algorithm to extract texture features in cacao pods, then used the parameters for the classification training of six machine learning algorithms: Naïve Bayes, Decision Stump, Random Forest, Hoeffding Tree, Multilayer Neural Network, and CNN. CNN achieved 99% accuracy, the highest among the six, in recognizing the Phytophthora palmivora disease or black pod rot infection in cacao pods. Another study of [18] worked with the normalization of RGB (Red, Green, Blue) parameters of cacao pod images to transform them into hue, saturation, and value (HSV) features.

These were then placed into an untrained k-Nearest Neighbors (KNN) classifier to distinguish three class categories: fruit rot disease, fruit-sucking ladybugs, and pod pests. After conducting k-fold cross-validation, the best accuracy attained is 99.33%, at a k-value of 5. According to, [19] created a classification model for detecting if a cacao pod is diseased using a histogram of oriented gradients (HoG) and local binary pattern (LBP) for feature extraction.

Three classification algorithms were trained: SVM, random forest, and artificial neural network (ANN), with ANN attaining the highest classification accuracy of 85%. The study of [20] performed the same procedure with slight modifications of the utilized methods. Color histogram was used instead of HoG, and random forest was replaced by logistic regression (LR). Still, ANN gained the highest classification accuracy of 98.3%.

Pre-existing studies have mostly attempted to devise models for detecting two particular cacao pod diseases. For instance, [21] used five CNN architectures: custom CNN, VGG16, EfficientNetB0, Resnet50, and LeNet-5, as both visual extraction and classification systems for diagnosis of black pod rot or pod borer disease, achieving a maximum accuracy of 91.79%. Conversely, [22] utilized other CNN architectures, with EfficientNetB0 garnering a higher maximum accuracy of 94%. [23] used CNN and the stochastic gradient descent (SGD) algorithm to detect black pod rot and the mistletoe disease. Moreover, [24-26] worked with the identification of the Phytophthora and Monilia diseases.

With these studies as references, a gap can be found in the versatility of the pre-established models in identifying more than two types of disease and pest infestation in cacao pods.

Moreover, image processing techniques in feature analysis were gradually overlooked due to the emergence of different CNN architectures that can facilitate feature extraction and classification. With that, this study utilized conventional visual feature extraction processes to extract RGB, HSV, and gray-level co-occurrence matrix (GLCM) texture parameters from cacao pod samples. Those values were used to model a KNN algorithm for detecting the presence of black pod rot, Monilia, or pod borer disease in cacao pods.

Specifically, it was aimed to: (1) extract numerical parameters representing the RGB, HSV, and texture features of cacao pod images, (2) train a classification model based on three KNN types: fine, cosine, and weighted KNN, and (3) evaluate the KNN models in terms of their accuracy, precision, and recall in identifying specified cacao pod diseases. With the objectives being met, a flexible machine learning model was generated to detect the three most commonly observed illnesses of cacao pods.

II. MATERIALS AND METHODS

This section presents the research methodology employed in the study to classify cacao pod diseases using multi-feature visual analysis and k-nearest neighbor's algorithm. Specifically, MATLAB software was used for performing feature extraction and disease classification.

II.1 MATERIALS

The data used for this study consisted of 800 images of both diseased and healthy cacao pods that were readily obtained from Kaggle. Specifically, a total of 200 images per class for four distinct cacao pod classifications were utilized.

Namely, they are: healthy, infected with black pod rot, infected with pod borers, and Monilia-diseased. Figure 1 presents the sample images of the cacao pods used for the study. To ensure an unbiased model evaluation, the dataset was split into three subsets: training (70%), validation (15%), and testing (15%).

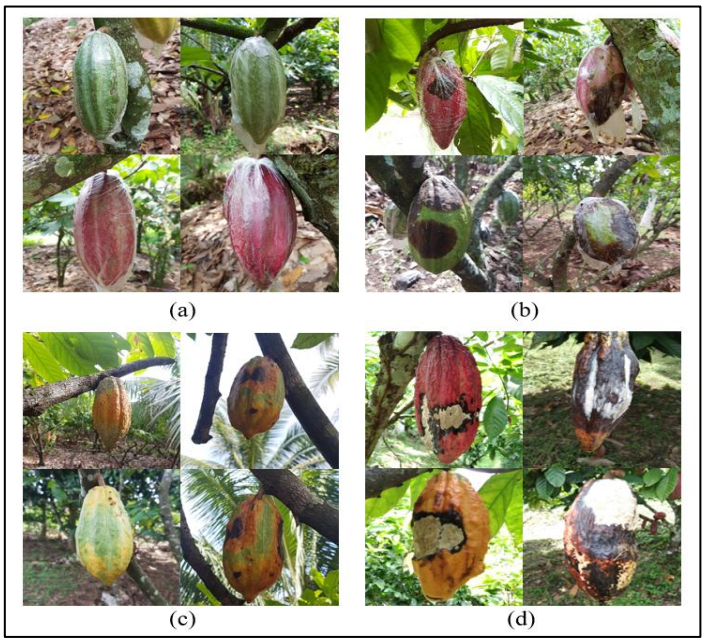

Figure 1: Sample raw cacao pod images: (a) healthy, (b) infected with black pod rot, (c) infested with pod borers, and (d) Monilia-diseased.
Source: Authors, (2025).

II.2 METHODS

Figure 2 shows the overall procedural framework for the study. It consists of four major steps that were followed methodically to ensure proper data acquisition. Specifically, the steps include: (1) image acquisition and pre-processing, (2) visual feature extraction, (3) KNN classification model training, and (4) final testing and evaluation of the model.

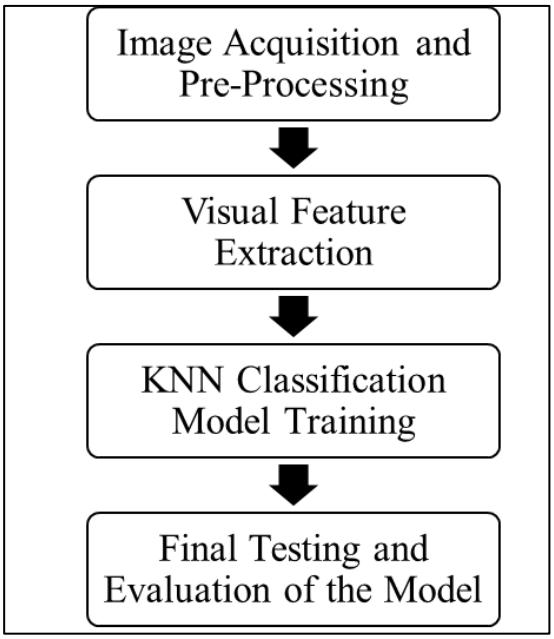

Figure 2: Procedural framework for the study.
Source: Authors, (2025).

II.2.1 IMAGE ACQUISITION AND PRE-PROCESSING

Image pre-processing was done to filter out the data and retain only good-quality images that will be used for the disease classification. Images that were blurry and those that contained multiple diseases were excluded from the data. After that, the filtered images were subjected to pre-processing through background subtraction to separate the target foreground object from the background. Lastly, the resulting images were subjected to ROI (region of interest) selection to ensure that the most significant features of the images were retained and irrelevant information that may affect the classification process was removed. The pre-processing procedures administered were visualized as shown below in Figure 3.

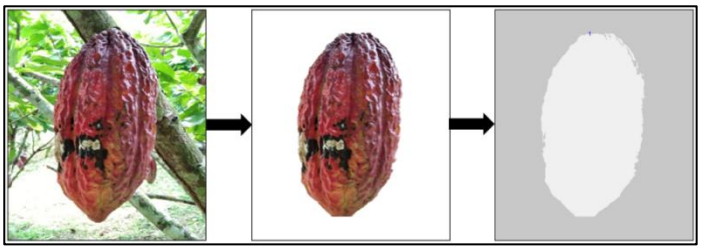

Figure 3: Pre-processing process involving background subtraction and ROI selection.
Source: Authors, (2025).

II.2.2 VISUAL FEATURE EXTRACTION

The visual feature extraction process utilized a combination of color and texture characteristics for a more comprehensive representation of the visual data needed for KNN classification. Color features were extracted by computing the means of the red, green, and blue channels to represent the color distribution of the various images. Similarly, the mean of the hue, saturation, and value channels were also computed to depict the images' perceptual attributes. Figure 4 and Figure 5 show a snippet of the code used to extract the color features.

```
% Compute mean RGB values
meanR = mean(mean(img(:,:,1)));
meanG = mean(mean(img(:,:,2)));
meanB = mean(mean(img(:,:,3)));
```

Figure 4: Snippet of code used for extracting RGB values.
Source: Authors, (2025).

```
% Convert RGB to HSV
imgHSV = rgb2hsv(img);

% Compute mean HSV values
meanH = mean(mean(imgHSV(:,:,1)));
meanS = mean(mean(imgHSV(:,:,2)));
meanV = mean(mean(imgHSV(:,:,3)));
```

Figure 5: Snippet of code used for extracting HSV values.
Source: Authors, (2025).

On the other hand, to characterize the texture of the cacao pods, GLCM was used to extract the following features: energy, entropy, homogeneity, and contrast. These features were extracted to capture and give numerical values to the irregularities and patterns that occur due to cacao pod infections. Figure 6 shows the code used to extract the GLCM-based texture values.

```
% Compute the Gray-Level Co-Occurrence Matrix (GLCM)
glcm = graycomatrix(img, 'Offset', [0 1; -1 1; -1 0; -1 -1], ...
    'Symmetric', true);
stats = graycoprops(glcm, {'Contrast', 'Energy', ...
    'Homogeneity'});

% Compute entropy (from normalized GLCM)
glcmNorm = glcm ./ sum(glcm, 'all');
entropyVal = -sum(glcmNorm(:) .* log2(glcmNorm(:) + eps));
```

Figure 6: Snippet of code used for extracting GLCM-based texture values.
Source: Authors, (2024).

II.2.3 KNN CLASSIFICATION MODEL TRAINING

Following the visual feature extraction of the RGB, HSV, and GLCM-based texture values, the KNN machine learning algorithm was applied to classify the cacao pod diseases. Specifically, the MATLAB's Classification Learner App was used to classify the diseases using three KNN variants, namely: fine KNN, cosine KNN, and weighted KNN. These three variants were used since each offers different metrics and weighting strategies that optimize the classification of the dataset. Lastly, holdout validation was implemented as the validation process to ensure the model's accuracy and generalization capabilities.

II.2.4 FINAL TESTING AND EVALUATION OF THE MODEL

The study employed a dataset splitting of 70-15-15 percent for training, validation, and testing to classify the various cacao pod diseases. Specifically, accuracy, precision, and recall were utilized to assess the performance of the three KNN variants.

Accuracy is defined as the ratio of correctly predicted observations to the total number of observations. It is ideal for symmetric data sets that exhibit virtually equal false positive and false negative values. It quantifies the overall accuracy of the model's classification.

$$Accuracy = \frac{\mathrm{TP} + \mathrm{TN}}{\mathrm{TP} + \mathrm{TN} + \mathrm{FP} + \mathrm{FN}} \quad (1)$$

Precision denotes the accuracy of the positive predictions produced by the mode. It is determined by dividing the total number of data points accurately classified by the model by the number of true positives.

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

The true positive rate, or recall, assesses the classifier's ability to correctly identify all actual positive instances. The calculation involved dividing the overall count of positive data points by the count of actual positive data points.

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

III. RESULTS AND DISCUSSIONS

This section presents the findings and results gathered from the employed methodologies, starting from the visual feature extraction and the cacao pod diseases classification using the KNN algorithm.

III.1 EXTRACTION OF VISUAL FEATURES

Before classifying the various cacao pod diseases, the visual features of each raw cacao pod image were first extracted using the MATLAB code shown in Figures 4 to 6. Running the code facilitated the feature extraction by transforming the image features, such as RGB, HSV, and textures, to numerical representations stored in a table. Figure 7 shows the sample RGB features extracted from the samples. It consists of five columns, with the first column containing the image file name and the second to the fourth column comprising the calculated mean values for red, green, and blue features, respectively. Meanwhile, the last column indicates the class or specific disease of the images. These mean values of each feature served as the predictor for establishing the distinctions between the cacao pod classes to distinguish them from one another.

	ImageName	MeanRed	MeanGreen	MeanBlue	Class
2	blackrot_1.jpg	174.92021	169.985444	166.514708	black_rot
3	blackrot_10.jpg	183.501442	177.102083	130.464263	black_rot
4	blackrot_100.jpg	173.672149	174.843498	158.163681	black_rot
5	blackrot_101.jpg	161.535107	155.974533	158.395814	black_rot
6	blackrot_102.jpg	162.92057	163.94649	143.337524	black_rot
7	blackrot_103.jpg	176.20407	168.867925	158.828487	black_rot
8	blackrot_104.jpg	213.362148	203.584686	168.608157	black_rot
9	blackrot_105.jpg	158.813604	152.971441	148.975583	black_rot
10	blackrot_106.jpg	158.813604	152.971441	148.975583	black_rot
11	blackrot_107.jpg	140.832701	138.565519	135.098278	black_rot
12	blackrot_108.jpg	156.688889	145.839046	144.096673	black_rot
13	blackrot_109.jpg	142.924948	142.399286	129.63372	black_rot
14	blackrot_11.jpg	194.787386	190.761204	190.198213	black_rot
15	blackrot_110.jpg	162.46537	163.494382	142.781598	black_rot
16	blackrot_111.jpg	168.54512	157.216695	161.923801	black_rot
17	blackrot_112.jpg	155.758307	144.350208	124.574117	black_rot
18	blackrot_113.jpg	143.471842	145.613282	133.908678	black_rot
19	blackrot_114.jpg	147.438755	157.166834	154.691432	black_rot
20	blackrot_115.jpg	162.972009	153.58911	147.791718	black_rot

Figure 7: Sample RGB values extracted from the samples.
Source: Authors, (2024).

Consequently, Figure 8 displays the sample HSV values extracted from the different classes. Like the extracted RGB features, it also consists of five columns, with the file name of the images displayed on the first one. Meanwhile, the second, third, and fourth columns display the mean values extracted for hue, saturation, and value, respectively. The class of the images was also indicated in the last column. These extracted features were also used as cacao pod disease classification parameters.

	ImageName	MeanHue	MeanSaturation	MeanValue	Class
2	blackrot_1.jpg	0.197938928	0.114234942	0.689639611	black_rot
3	blackrot_10.jpg	0.107698812	0.338908974	0.724267848	black_rot
4	blackrot_100.jpg	0.17544311	0.165497944	0.703903077	black_rot
5	blackrot_101.jpg	0.390220793	0.132974184	0.647231876	black_rot
6	blackrot_102.jpg	0.126252445	0.270481735	0.653127243	black_rot
7	blackrot_103.jpg	0.151402373	0.167769806	0.701004693	black_rot
8	blackrot_104.jpg	0.164745506	0.237659545	0.841638284	black_rot
9	blackrot_105.jpg	0.144121615	0.117808064	0.627371472	black_rot
10	blackrot_106.jpg	0.144121615	0.117808064	0.627371472	black_rot
11	blackrot_107.jpg	0.187707535	0.109732976	0.556268473	black_rot
12	blackrot_108.jpg	0.187994312	0.192420358	0.618981574	black_rot
13	blackrot_109.jpg	0.247690075	0.208943933	0.577631783	black_rot
14	blackrot_11.jpg	0.231028464	0.082446862	0.773352902	black_rot
15	blackrot_110.jpg	0.126854594	0.271850769	0.651420141	black_rot
16	blackrot_111.jpg	0.395104364	0.143912838	0.669795192	black_rot
17	blackrot_112.jpg	0.077171238	0.335072503	0.61324293	black_rot
18	blackrot_113.jpg	0.202955389	0.207852113	0.589114522	black_rot
19	blackrot_114.jpg	0.282917813	0.115368145	0.625218521	black_rot
20	blackrot_115.jpg	0.153080504	0.180845712	0.644418982	black_rot

Figure 8: Sample HSV values extracted from the samples.
Source: Authors, (2024).

The last set of codes extracted the texture features of the images. The sample extracted values for each of them are displayed in Figure 9. Column one indicates the specific file name of the images, and columns two to five shows the values extracted for the various texture parameters, namely entropy, contrast, energy, and homogeneity. Like the previous features, the last column also indicates the class or specific disease of the images. The numerical representations of the texture extracted from the images enhanced the classification capabilities of the machine learning algorithm by providing more parameters to be fed into the system.

1	ImageName	Entropy	Contrast	Energy	Homogeneity	Class
2	blackrot_1.jpg	5.88264277	0.627607162	0.142402569	0.836931417	black_rot
3	blackrot_10.jpg	5.22315327	0.498099549	0.189491263	0.889756439	black_rot
4	blackrot_100.jpg	5.59336857	0.332917392	0.132674474	0.870545011	black_rot
5	blackrot_101.jpg	5.73904725	0.860616204	0.168875598	0.825329384	black_rot
6	blackrot_102.jpg	5.46394993	0.415148938	0.186113124	0.875376876	black_rot
7	blackrot_103.jpg	5.87713697	0.625541091	0.126421237	0.832169895	black_rot
8	blackrot_104.jpg	5.21568838	0.489077708	0.231795935	0.87438798	black_rot
9	blackrot_105.jpg	5.91299084	0.70921349	0.118900637	0.816637672	black_rot
10	blackrot_106.jpg	5.90856447	0.697451577	0.119176487	0.817153582	black_rot
11	blackrot_107.jpg	5.55044541	0.514322465	0.156201476	0.864463907	black_rot
12	blackrot_108.jpg	5.47662709	0.709734754	0.191581369	0.852680039	black_rot
13	blackrot_109.jpg	5.6511286	0.522071479	0.144276714	0.873185094	black_rot
14	blackrot_11.jpg	5.61144635	0.623425025	0.195588801	0.838544832	black_rot
15	blackrot_110.jpg	5.4737132	0.417277592	0.184152005	0.874862191	black_rot
16	blackrot_111.jpg	5.94956508	0.811224638	0.149636812	0.817202128	black_rot
17	blackrot_112.jpg	5.59322993	0.697644324	0.162633324	0.862538672	black_rot
18	blackrot_113.jpg	5.93341899	0.461326822	0.108322308	0.869319454	black_rot
19	blackrot_114.jpg	5.88644016	0.522268194	0.125385091	0.842533089	black_rot
20	blackrot_115.jpg	5.92623405	0.704857711	0.132831633	0.82970965	black_rot

Figure 9: Sample GLCM-based texture values extracted from the samples.
Source: Authors, (2025).

Table 1: Summary of visual features extracted from the cacao pods.

Visual Features	Cacao Pod Class			
	Healthy	Black Pod Rot	Monilia	Pod Borer
Mean Red	133.468 - 209.654	124.347 - 213.368	108.833 - 224.001	125.189 - 205.783
Mean Green	144.545 - 212.717	124.067 - 207.290	82.547 - 227.259	117.508 - 208.939
Mean Blue	120.550 - 192.781	106.428 - 190.198	73.471 - 225.346	90.109 - 178.892
Mean Hue	0.123 - 0.310	0.077 – 0.510	0.102 - 0.730	0.062 - 0.226
Mean Saturation	0.105 - 0.380	0.074 – 0.341	0.036 - 0.524	0.129 - 0.496
Mean Value	0.568 - 0.841	0.504 – 0.842	0.445 - 0.897	0.495 - 0.838
Entropy	4.713 - 5.716	4.849 - 6.176	4.314 - 6.261	4.331 - 5.774
Contrast	0.216 - 0.531	0.312 - 0.969	0.304 - 1.173	0.234 - 0.668
Energy	0.118 - 0.258	0.100 - 0.306	0.083 - 0.479	0.114 - 0.335
Homogeneity	0.848 - 0.914	0.787 - 0.914	0.778 - 0.904	0.828 - 0.927

Source: Authors, (2025).

Table 1 contains a summary of the visual features extracted for every cacao pod class. These numerical parameters served as inputs for the KNN classification training, specifically using three types of KNN: fine KNN, cosine KNN, and weighted KNN.

III.2 KNN CLASSIFICATION MODEL TRAINING

After acquiring the numerical parameters representing cacao pods' RGB, HSV, and texture features, the KNN machine learning algorithm was trained using MATLAB's Classification Learner App. The classification session was driven by the predictors obtained from the previous procedure. Moreover, a holdout validation scheme was used by setting aside 15% of the original sample for the preliminary assessment of the KNN algorithm. A total of 15% of the dataset was also removed to assess the performance of the KNN classifiers in classifying cacao pod diseases.

For the KNN training, the study utilized three models, namely: fine KNN, cosine KNN, and weighted KNN. This is to provide insights regarding which model classifies the cacao pod diseases more accurately.

Each of their figure of merits was obtained after subjecting the extracted features to the various KNN training models. Specifically, their validation confusion matrices were consolidated to collect the numerical parameters needed to calculate the other figure of merits. Table 2 summarizes the results of the model evaluation in terms of accuracy, precision, and recall.

Table 2: Validation results for the KNN classification models.

Model	Accuracy	Precision	Recall
Fine KNN	93.44%	93.57%	93.41%
Cosine KNN	68.85%	67.69%	68.68%
Weighted KNN	91.80%	91.99%	91.85%

Source: Authors, (2025).

Table 2 shows that the fine KNN model performed the best in classifying various cacao pod diseases among all other models during the validation phase. It showed accuracy, precision, and recall of 93.44%, 93.57%, and 93.41%, respectively. To further elaborate, the corresponding confusion matrix for the Fine KNN model is shown in Figure 10. Out of 30 cacao pods with black pod rot disease, 25 were classified correctly, one was misclassified as healthy, and four were misclassified as being infected by Monilia disease. Likewise, for those 31 healthy cacao pods, 29 were correctly labeled, one was misclassified as having black pod rot, and one was misclassified as being infected with pod borers. Among 31 monilia-diseased pods, 30 were correctly identified, and only one was miscategorized as having black pod rot. Lastly, all 30 pods infested with pod borers were correctly categorized by the fine KNN algorithm.

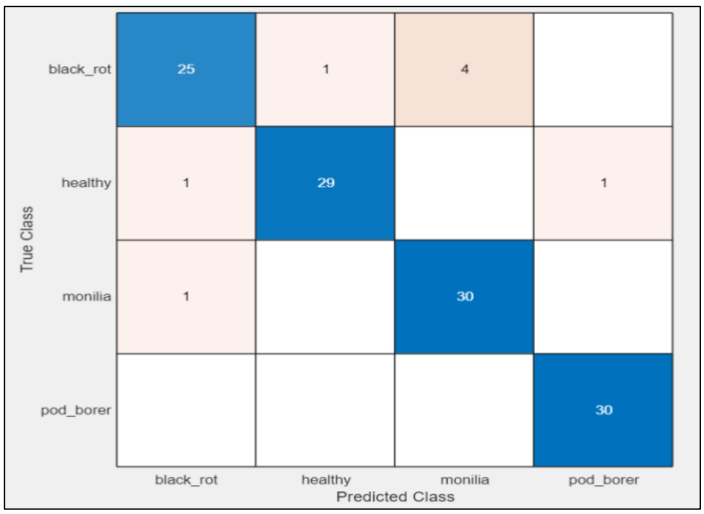

Figure 10: Confusion matrix for the validation results of the fine KNN algorithm.
Source: Authors, (2025).

III.3 EVALUATION OF THE PROPOSED CLASSIFICATION MODEL

In addition to the initial evaluation of the KNN machine learning algorithm model's performance, the holdout validation method assisted the further optimization of the algorithms to adapt better and adjust to new data. Upon finalizing the classification models, each was independently subjected to testing using the remaining samples. Like the holdout validation, the accuracy, precision, and recall of the KNN models were assessed in the final performance evaluation. Table 3 shows the summary of the evaluation of the results.

Table 3: Evaluation results for the KNN classification models.

Model	Accuracy	Precision	Recall
Fine KNN	96.67%	96.67%	96.67%
Cosine KNN	78.33%	77.84%	78.33%
Weighted KNN	95.83%	95.86%	95.83%

Source: Authors, (2025).

Similar to the validation findings, the fine KNN model performed best in classifying the different cacao pod diseases. Table 3 shows that it now has an accuracy, precision, and recall of 96.67% for all three figures of merits. The confusion matrix provided in Figure 11 shows the correctness of the model in classifying each class. For 30 cacao pods with black pod rot, 28 were correctly classified, and two were mislabeled as infected with monilia disease. Among the 30 healthy pods, all of them were classified correctly. Meanwhile, for those that are infected with monilia disease, 28 were correctly labeled, and two were miscategorized as having black pod rot. Finally, all 30 pods with pod borer disease were correctly labeled by the fine KNN classifier.

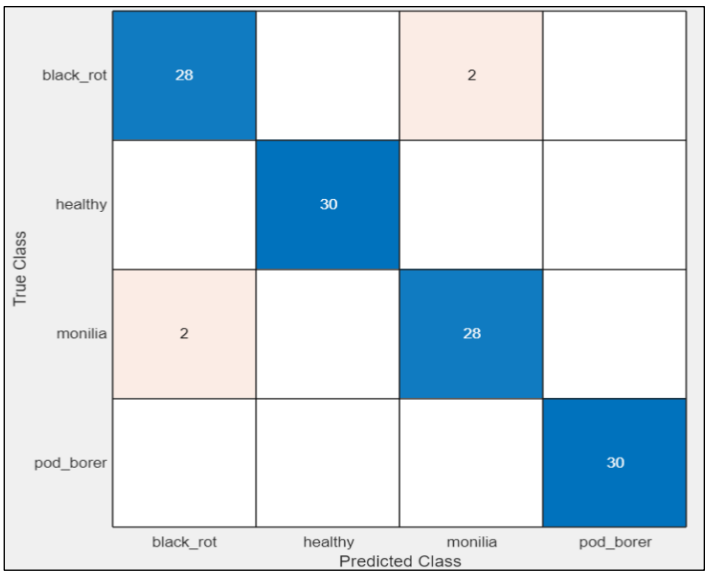

Figure 11: Confusion matrix for the evaluation results of the fine KNN algorithm.
Source: Authors, (2024).

IV. CONCLUSIONS

The present study focused on identifying prominent cacao pod diseases through multi-feature visual analysis combined with the KNN machine learning algorithm. Specifically, the RGB, HSV, and GLCM-based texture features were considered for the visual analysis of 800 cacao pod images that were classified into four classes: healthy, black pod rot-infected, pod borer-infested, and monilia-diseased. The numerical representations of each feature were then fed as predictors for the training of the KNN classifier using three models evaluated to identify the most optimum result. From the three KNN models, it was revealed that fine KNN achieved the highest accuracy for both the validation and testing stages, recording 93.44% and 96.67%, respectively. These results highlight the effectiveness and reliability of combining multi-feature visual analysis and KNN algorithms to distinguish between cacao pod diseases. This approach provides a valuable contribution to agriculture, especially in cacao disease management, as a tool for early disease detection and monitoring. For further improvements in the research, future researchers may add other cacao pod diseases and pests, such as swollen shoots, to further expand the diagnosing capabilities of the model. Likewise, other KNN models or variants not used in the study may be evaluated for their potential to enhance the accuracy of the overall classification scheme. In addition, additional relevant cacao-related applications may be explored, including cacao bean grading and quality assessment, whereby the combination of multi-feature visual extraction and KNN algorithms can be implemented.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Earl Clarence S. San Diego and Seph Gerald C. Rodrin.
Methodology: Earl Clarence S. San Diego and Seph Gerald C. Rodrin.
Investigation: Earl Clarence S. San Diego and Edwin R. Arboleda.
Discussion of results: Earl Clarence S. San Diego and Seph Gerald C. Rodrin.
Writing – Original Draft: Earl Clarence S. San Diego and Seph Gerald C. Rodrin.
Writing – Review and Editing: Earl Clarence S. San Diego and Seph Gerald C. Rodrin.
Resources: Earl Clarence S. San Diego and Seph Gerald C. Rodrin.
Supervision: Earl Clarence S. San Diego, Seph Gerald C. Rodrin, and Edwin R. Arboleda.
Approval of the final text: Earl Clarence S. San Diego, Seph Gerald C. Rodrin, Edwin R. Arboleda.

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RESEARCH ARTICLE OPEN ACCESS

DEVELOPMENT OF MALARIA DIAGNOSIS WITH CONVOLUTIONAL NEURAL NETWORK ARCHITECTURES: A CNN-BASED SOFTWARE FOR ACCURATE CELL IMAGE ANALYSIS

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ABSTRACT

This study emphasizes that early diagnosis and treatment of malaria is critical in reducing health problems and mortality from the disease, especially in developing countries where the disease is prevalent. Malaria is a potentially fatal disease transmitted to humans by mosquitoes infected by a blood parasite called Plasmodium. The traditional method of diagnosis relies on experts examining red blood cells under a microscope and is inefficient as it is dependent on expert knowledge and experience. Nowadays, machine learning methods that provide high accuracy are increasingly used in disease detection. In this paper, a Convolutional Neural Network (CNN) architecture is proposed to distinguish between parasitized and non-parasitized cells. In addition, the performance of the proposed CNN architecture is compared to pre-trained CNN models such as VGG-19 and EfficientNetB3. The studies were carried out using the Malaria Dataset supplied by the National Institute of Health (NIH), and our proposed architecture was shown to function with 99.12% accuracy. The results of the study reveal that it is effective in improving the accuracy of cell images containing Plasmodium. In addition, a software that predicts whether cell images are noisy or not has been developed.

I. INTRODUCTION

Malaria is a disease that threatens health systems and affects millions of people, especially in developing countries [1]. Caused by Plasmodium parasites spread through mosquito bites, this disease can kill many people, especially children, if not treated in time. According to the World Health Organization (WHO), the majority of malaria cases occur in Africa and mortality rates are quite high. Children under five are particularly vulnerable to the disease [2]. Therefore, rapid and accurate diagnosis is crucial to prevent the spread of malaria and save lives.

Traditional methods of malaria diagnosis, such as microscopic examination and laboratory tests, are laborious and costly. Furthermore, as the clinical symptoms of malaria are non-specific, they can be confused with other diseases and lead to misdiagnosis [3],[4]. Therefore, early diagnosis and treatment are critical for assessing the severity of the disease and preventing fatal outcomes. However, factors such as limited resources, lack of information and insufficient scientific research pose serious challenges in malaria treatment, especially in developing countries [5]. At this point, computer-aided systems, artificial intelligence and open-source technologies are emerging as a unique tool to assist experts in the diagnosis and evaluation of malaria [6],[7].

Today, Deep Learning (DL) and Machine Learning (ML) techniques offer great potential in malaria diagnosis thanks to their ability to process large datasets, recognize complex patterns, and make rapid diagnoses [8]. Deep learning models are able to identify Plasmodium parasites in medical images, minimizing human error and speeding up the diagnosis process, thus providing an important second opinion in medical diagnosis processes and helping doctors. In this context, Computer Aided Diagnosis (CAD) and deep learning-based models in medical images have attracted much attention from researchers in recent years [9]. Such models can be trained on large datasets to recognize Plasmodium parasites, thus enabling faster and more accurate malaria diagnosis [10].

The aim of this study is to go beyond traditional malaria diagnosis methods and evaluate the performance of deep learning architectures in malaria diagnosis. A comprehensive review is

presented on how these technologies can be used in clinical applications and how they can improve accuracy in malaria diagnosis. For this purpose, a cell image analysis application was developed with models trained on the dataset. This application aims to make a significant contribution to the early diagnosis and control of malaria by providing experts with a real-time and accurate diagnosis.

This paper aims to show how convolutional neural networks (CNNs), a deep learning architecture, can be used effectively and reliably in malaria detection from cell images and how a software application can support experts in diagnosis. This research demonstrates the potential of artificial intelligence in malaria diagnosis, providing a faster, reliable and cost-effective alternative to current diagnostic methods.

The rest of the paper is organized as follows: Section 2 is the literature review; Section 3 presents the dataset and methods used in the study; Section 4 presents the experimental results obtained; and Section 5 contains conclusions and general remarks.

II. LITERATURE REVIEW

Addressed the problem of misdiagnosis in malaria diagnosis in Nigeria and applied various machine learning models with age, gender and 15 symptom data of 337 patients. The Adaboost model showed the best performance with 98.2% accuracy and 96.6% precision; they concluded that this model can be used in decision support systems [11]. Aimed to overcome the limitations of traditional methods by using artificial neural networks and especially CNN for early diagnosis of malaria. With 1,920 blood smear images from 84 patients, CNN showed the highest success with 99.59% accuracy. The study reveals that CNN is an effective method for accurate diagnosis of malaria [12]. Developed an artificial intelligence-based system for the detection of malaria parasites with microscopic images. MobileNetV2 achieved the highest accuracy and ResNet152V2 achieved the lowest loss value. DenseNet121 provided the best results in terms of precision, recall and F1 score [13].

Developed a model using Inception and Capsule networks to detect malaria parasites from microscopic images. The system provides faster and more accurate results than conventional microscopy [14]. Used machine learning methods for malaria and breast cancer detection in this study. CNN, ResNet50 and VGG16 models were used for malaria detection and the highest accuracy was 94.73% with CNN. For breast cancer detection, the highest accuracy was found in ResNet50 with 95.53% in tests with the same models [15].

In this study, Anita et al. combined the Deep-CNN model with Random Forest (RF) for the detection of malaria parasites. By using Global Average-Pooling (GAP) layer and Canny edge detection, they better visualized the interference areas. Experimental results showed that the proposed model outperformed existing methods on malaria parasite datasets [16]. Alessandra et al. used machine learning to predict clinical outcomes in imported malaria patients. In their analysis, AST, platelet count, total bilirubin and parasitemia were associated with adverse outcomes. These parameters are not included in the WHO criteria for severe malaria. The study demonstrates the potential of ML algorithms to provide clinical decision support [17].

Developed a NASNet-based model for early diagnosis of malaria. The model combines NASNet and Random Forest methods for feature engineering, working with images of parasitized and healthy red blood cells. Support vector machines showed the best performance with 99% accuracy. This approach can help reduce mortality rates by improving malaria diagnosis [18]. Propose an IoT-based system for malaria detection. The system collects real-time symptom data with wearable sensors, processes the data using edge computing and cloud infrastructure, and analyzes it with machine learning. Four machine learning techniques were compared and Support Vector Machines (SVM) achieved 98% training accuracy, 96% testing accuracy and 95% AUC score with the highest accuracy. This system promises to accurately diagnose malaria cases [19]. Developed ML methods to predict clinical outcomes in imported malaria patients.

The study found that AST, platelet count, total bilirubin and parasitemia were associated with adverse outcomes, and aminotransferase and platelet were not included in the WHO criteria [20]. Propose a deep learning based method called EfficientNet for malaria detection. This approach detects malaria parasites using red blood cell images. Experiments showed that the proposed method is effective in malaria detection with 97.57% accuracy [21].

Succeeded in identifying malaria parasites in microscopic blood images with 96.73% accuracy using a CNN model called MozzieNet. Using data augmentation and hyperparameter optimization, the model demonstrated strong performance and was designed to help malaria diagnosis in remote areas [22]. According to [23] developed the miLab™ device, which achieved 98.86% accuracy in malaria diagnosis.

This device consistently prepared blood films with digital microscopy and detected malaria parasites with deep learning. It achieved 92.21% agreement in clinical tests. Evaluated the use of machine learning and deep learning methods in malaria diagnosis by reviewing 50 articles between 2015 and 2023. While most of the research focused on binary classification, multi-stage classification and dataset cross-validation were missing.

This study provides classification models that can accurately predict malaria types and recommendations for future research [24]. According to [25] improved the YOLOv5 framework, achieving 99.2% accuracy, 98.7% precision and 98.5% sensitivity in malaria diagnosis.

They replaced the C3 module with C3TR structure and improved PANet with Bi-directional Feature Pyramid Network, which outperformed existing methods. Developed MILISMA, a deep learning-based model, for the diagnosis of malaria anemia (SMA) in sub-Saharan Africa. The model detected morphologically altered red blood cells (RBCs), achieving 83% accuracy, 87% AUC and 76% precision-recall AUC. MILISMA helps to improve diagnostic and prognostic processes by identifying SMA-related RBC alterations [26].

III. MATERIALS AND METHODS

In this study, a model based on convolutional neural networks is proposed for the classification of malaria disease, consisting of two classes. The National Institutes of Health (NIH) in the United States provided an open-access dataset from which the photos used to validate the suggested method were taken. 27,558 cell pictures in all, including equal numbers of cells with and without parasites, are included in the dataset [27]. The Mahidol-Oxford Tropical Medicine Research Unit experts annotated every photograph included in the dataset.

The dataset is randomly divided into 80% for training and 20% for test samples of each class. Table 1 shows the distribution of images for each class for training, validation, and testing. Figure 1 shows randomly selected parasitized cell samples from the dataset, while Figure 2 shows images of unparasitized cell samples.

Table 1: Distribution of training, validation, and test sets.

Dataset Type	Number of Parasitised Sample	Number of Unarasitised Sample	Total
Training	8818	8818	17636
Validation	2205	2205	4410
Test	2756	2756	5512
Total Data			27558

Source: Authors, (2024).

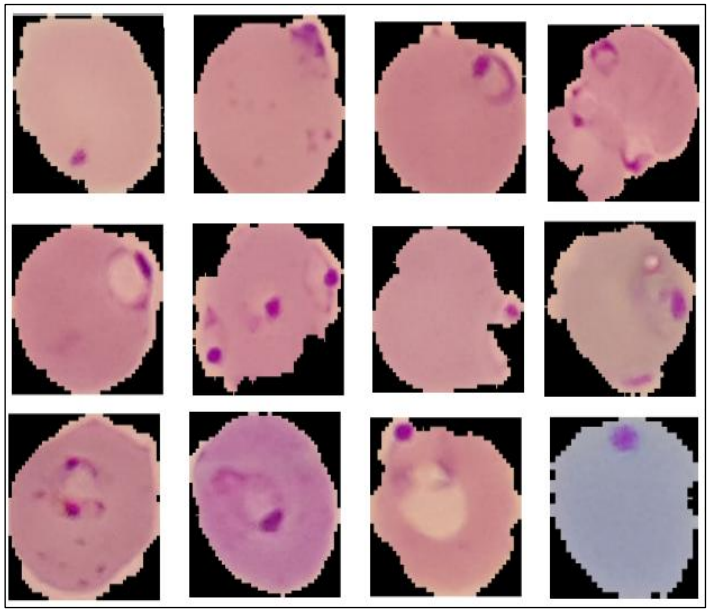

Figure 1: Parasitized cell samples.
Source: Authors, (2024).

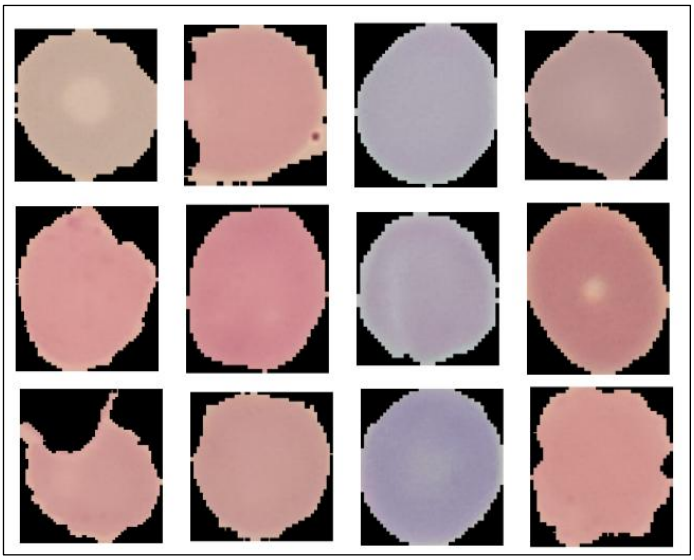

Figure 2: Unparasitized cell samples.
Source: Authors, (2024).

III.1 CONVOLUTIONAL NEURAL NETWORKS

Convolutional Neural Networks (CNN) are one of the deep learning models used in computer vision and pattern recognition. Basically, it is a specialized neural network architecture that can work effectively on visual data. CNNs consist of a series of convolutional layers that divide an image into small, overlapping regions and learn the features in these regions. These features represent specific patterns in the input images. The convolution and pooling layers create the feature maps and reduce their size. This allows the network to learn more complex features using fewer parameters in the learning process. CNNs are often successfully used in object recognition, face recognition, and other visual tasks [9],[28]. Figure 3 shows the architecture of a convolutional neural network.

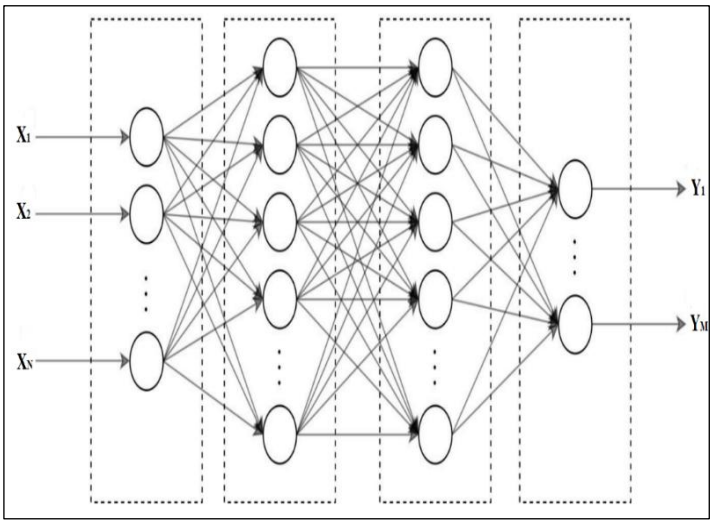

Figure 3: Convolutional Neural Network Architecture.
Source: Authors, (2023).

VGG19, developed by the Visual Geometry Group (VGG), is one of the most prominent convolutional neural network (CNN) models in deep learning. It was widely recognized for its impressive performance at the ImageNet Large Scale Visual Recognition Challenge in 2014. VGG19 has a deep architecture with a total of 19 layers. The main features of the architecture are a recurrent structure consisting of successive convolution layers followed by pooling layers. In particular, convolution layers with 3x3 filter sizes increase the ability to learn more complex features through the sequential use of small-sized filters. The VGG19 model has a structure that terminates with fully connected layers, which are used to classify the learned features. Furthermore, ReLU activation functions are generally preferred in VGG19. This model was one of the initial and referenced models in the deep learning community. However, due to its large parameter count and computational intensity, VGG19 has played a critical role in the evolution of deep learning architectures, although nowadays lighter and morescalable models have grown in popularity [29].

EfficientNetB3 is a high-performance neural network model designed for computer vision tasks in the deep learning domain. The EfficientNet series aims to provide efficient and scalable models, especially by using a scaling strategy that optimizes factors such as model size, depth, and width in a balanced way. EfficientNetB3 is a version that follows this strategy and has a larger size than previous EfficientNet models. The model includes specialized components such as convolution layers, mobile learning blocks, and expanding blocks. This enables the network to gain more learning capacity and extract visual features more effectively. EfficientNetB3 has achieved high accuracy rates on the ImageNet dataset and other visual recognition tasks. This model is considered an important step in the effort to optimize the size and performance trade-off of deep learning models [6].

III.2 PROPOSED MODEL

The three steps of the suggested method are feature extraction, data preparation, and classification. Figure 6

graphically depicts these phases. Preprocessing data is a useful tactic for enhancing image quality. Numerous noise sources, such as camera angle and microscope position, might contaminate images. To lessen picture noise, images were cleaned using a variety of techniques. In order to effectively categorize infected and non-infected photos for malaria detection, we have developed a CNN model. First, 4 convolutional layers with 2x2 filter sizes were used to process the 50 × 50 × 3 dimensional input images, followed by 4 maximum pooling layers of size 2x2. ReLU was chosen as the activation function. Finally, 1 Flatten layer, 2 Dropout layers, and 2 Dense layers were used to smooth the data. A Sigmoid activation function is applied to the output layer. It is seen that all of these parameters are trained. The block diagram of the proposed method is given in Figure 4.

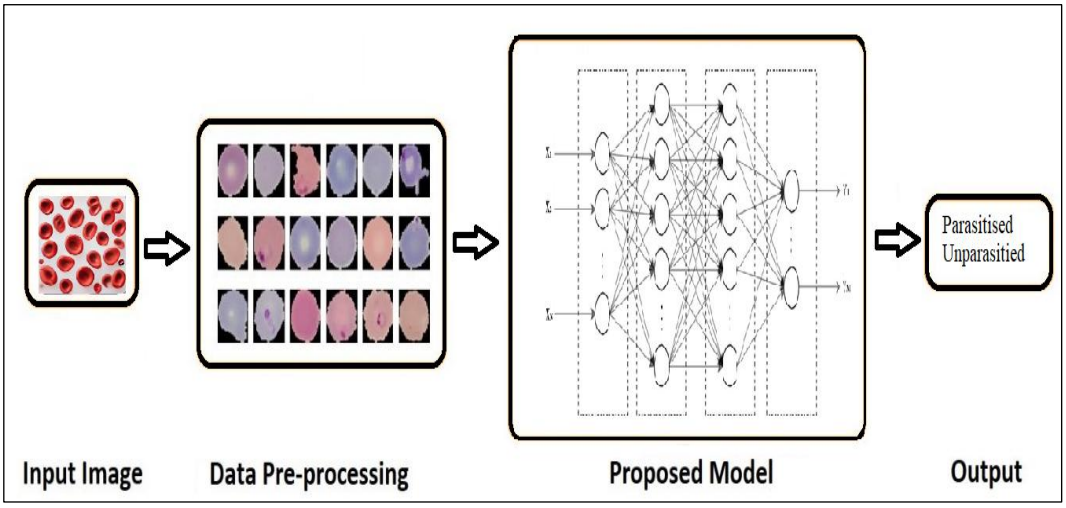

Figure 4. Block diagram of our proposed model.
Source: Authors, (2024).

The confusion matrix and classification assessment criteria derived from the confusion matrix are used to assess the classification performance of the suggested approach. The evaluation criteria consist of F1-score, recall, accuracy, and precision. The criteria are as follows: True Positive (TP), True Negative (TN), False Negative (FN), and False Positive (FP) numbers make up a confusion matrix. In this work, TP happens when a certain parasitic cell's class is accurately predicted by the classifier. When a cell picture is determined by the classifier to not be a member of a particular class of parasitic cells, TN happens. FP happens when a negative sample is mistakenly predicted as positive by the classifier. When a positive sample is mistakenly predicted as negative by the classifier, FN occurs.

The ratio of the number of test samples correctly classified according to each cell type to the total number of test samples is denoted by accuracy and calculated as in Equation (1).

$$\text{Accuracy} = \frac{TP+TN}{TP+FP+FN+TN} \quad (1)$$

The ratio of the number of positive samples correctly classified by each cell type to the number of actual observed positive samples is denoted by recall, and calculated as in Equation (2).

$$\text{Recall} = \frac{TP}{TP+FN} \quad (2)$$

The number of positive samples correctly classified by each cell type and the number of samples classified as positive samples are determined by precision and calculated as in Equation (3).

$$\text{Precision} = \frac{TP}{TP+FP} \quad (3)$$

The F1-score corresponds to the harmonic mean of the precision and recall ratios. The F1-score takes a value between 0 and 1. The better performance of each cell classification model corresponds to a higher F1-score and is calculated as in Equation (4).

$$\text{F1} = 2\text{x}\frac{Precision\ x\ Recall}{\text{Precision+Recall}} \quad (4)$$

IV. EXPERIMENTAL RESULTS

This chapter presents the results obtained using the materials and methods presented in the previous chapter. The study involves the classification of human red blood cell images as parasitized or unparasitized by the Plasmodium parasite. CNN architectures are used to detect whether the blood cell is parasitized or not. In this study, experiments were conducted with the pre-trained CNN architectures VGG-19, EfficientNetB3, and our proposed CNN model. The confusion matrices for each model as a result of the experiments are given in Figure 5-7 respectively.

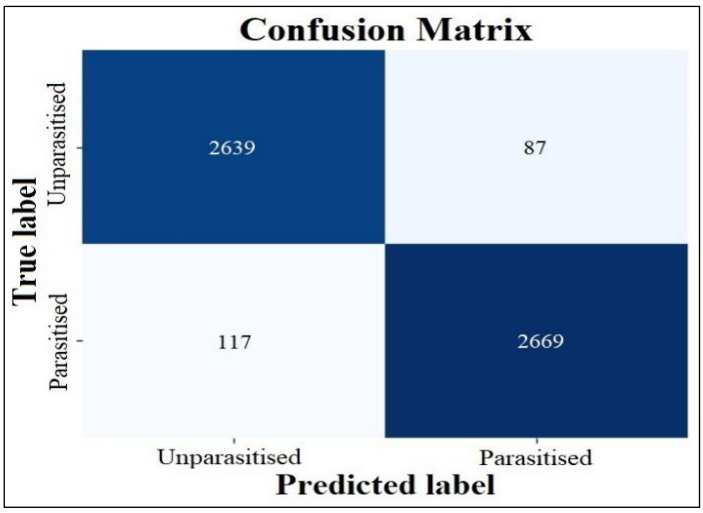

Figure 5: VGG19 Confusion Matrix.
Source: Authors, (2024).

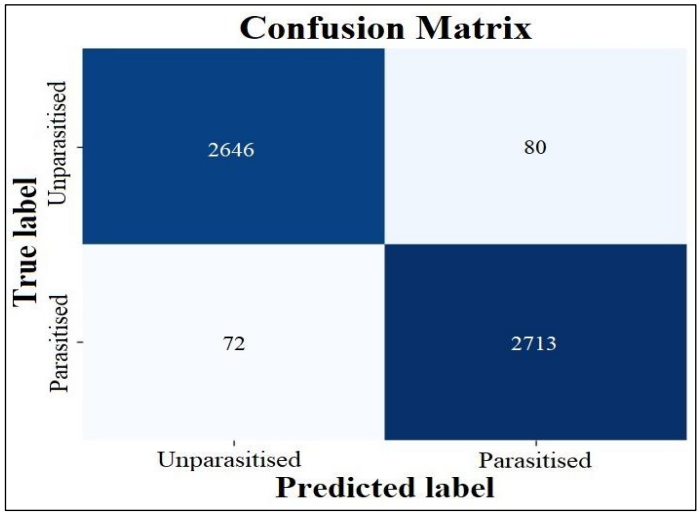

Figure 6: EfficientNetB3 Confusion Matrix.
Source: Authors, (2024).

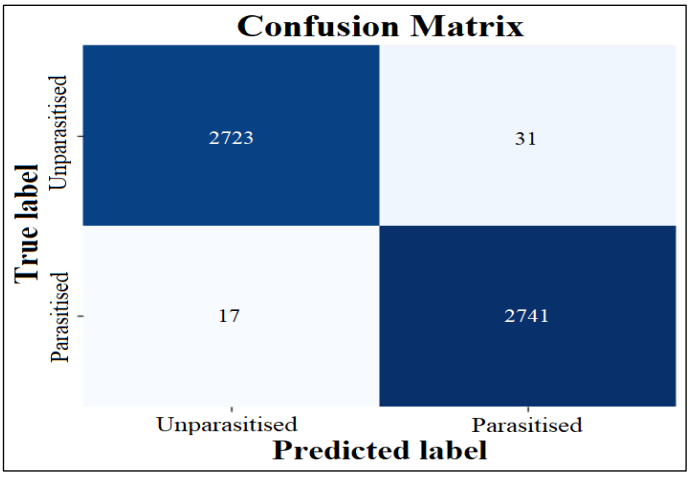

Figure 7: Proposed Model Confusion Matrix.
Source: Authors, (2024).

In this study, we conducted a comparative analysis to evaluate the performance of various deep learning-based classification methods for malaria cell categorization. The pre-trained architectures considered for evaluation include VGG19, InceptionResNetV2, DenseNet121, EfficientNetB3, and our proposed CNN model. Each model was fine-tuned and assessed using the National Institutes of Health open-access dataset, a widely recognized benchmark in the field of malaria diagnosis. The classification performance of the proposed image classification method is compared with pre-trained CNN-based methods in terms of accuracy, precision, recall, and F1-score as shown in Table 2.

Table 2: Comparison of the model results

Methods	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1 (%)**
VGG19	96,28	96,79	95,73	96,26
EfficientNetB3	97,23	97,70	97,33	97,20
Proposed Model	**99,12**	**98,87**	**99,37**	**99,12**

Source: Authors, (2024).

Table 2 compares the performance metrics of different deep learning models used for malaria diagnosis. This table shows that the proposed model has a significant advantage over popular pre-trained models such as VGG19 and EfficientNetB3 that have been previously used for malaria diagnosis. The performance evaluation is based on critical metrics such as accuracy, precision, recall and F-score. Firstly, it can be seen that the VGG19 model achieved 96.28% accuracy, 96.79% precision, 95.73% sensitivity and 96.26% F-score in malaria diagnosis. Although these results show that VGG19 performs well in malaria diagnosis, it still has some limitations. EfficientNetB3 outperforms VGG19 with 97.23% accuracy, 97.70% precision, 97.33% sensitivity and 97.20% F-score. EfficientNetB3, thanks to its advanced architecture, improved diagnostic accuracy and provided a more balanced performance. Although these two models have high accuracy in malaria diagnosis, they are still not competitive enough compared to the proposed model.

The proposed model achieved 99.12% accuracy, surpassing other models developed for malaria diagnosis. It also has extremely high values of 98.87% precision, 99.37% sensitivity and 99.12% F-score. These results show that the proposed model offers a more accurate and reliable performance in the diagnosis of malaria parasites compared to other models. The high sensitivity rate of the model (99.37%) reveals that it is highly successful in detecting true positive samples and minimizes the false negative rate. This is critical in a disease such as malaria that requires rapid response. The precision value of the proposed model (98.87%) shows that the false positive rate is low and the model avoids misdiagnosing healthy cells. This provides a significant advantage in reducing the false positive diagnosis rate in an infectious and widespread disease such as malaria, thereby reducing unnecessary treatment and resource utilization.

In conclusion, the proposed model outperforms other models in the literature with its high accuracy, precision and sensitivity rates in malaria diagnosis. Thanks to this superior performance, it offers a more reliable alternative in malaria diagnosis and enables earlier intervention by accelerating the diagnosis process. Especially in resource-limited regions, the rapid and accurate diagnosis of the proposed model has the potential to improve disease control and public health.

The comparative analysis revealed that our proposed CNN model outperforms all other architectures across key performance metrics, including accuracy, precision, recall, and F1-score. Specifically, the proposed model achieved an accuracy of 99.12%, which is significantly higher than the other models. Furthermore, our model maintained a compact architecture with only 620,441 parameters, demonstrating efficiency without compromising performance. The training-validation accuracy is shown in Figure 8, and the training-validation loss is shown in Figure 9 for 50 epochs. As the epoch value increases, the accuracy values in both the training set and the validation set increase. Simultaneously, the training and validation loss curves decrease as the epoch value increases. Figure 10 shows a screenshot where a randomly selected cell is predicted to be parasited or unparasited.

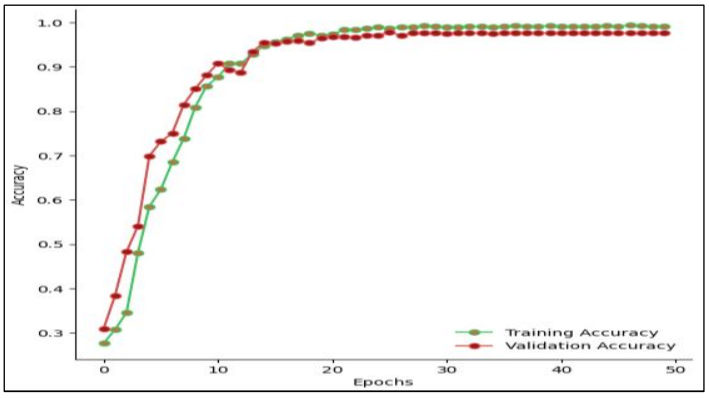

Figure 8: Training-validation accuracy curve.
Source: Authors, (2024).

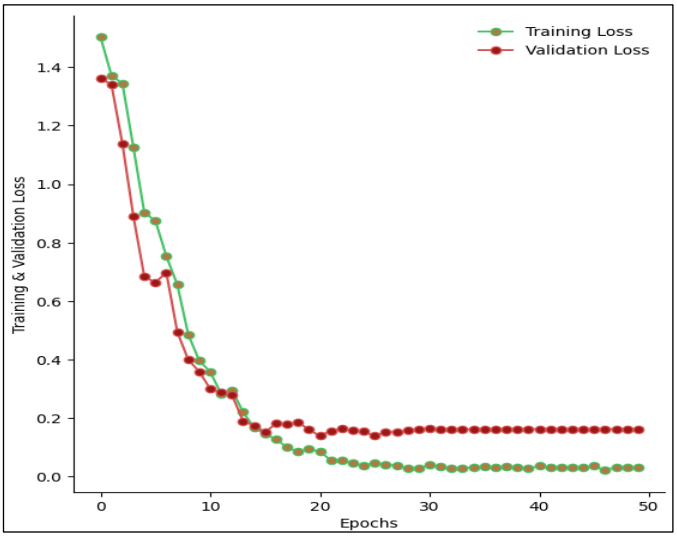

Figure 9: Training-validation loss curve.
Source: Authors, (2024).

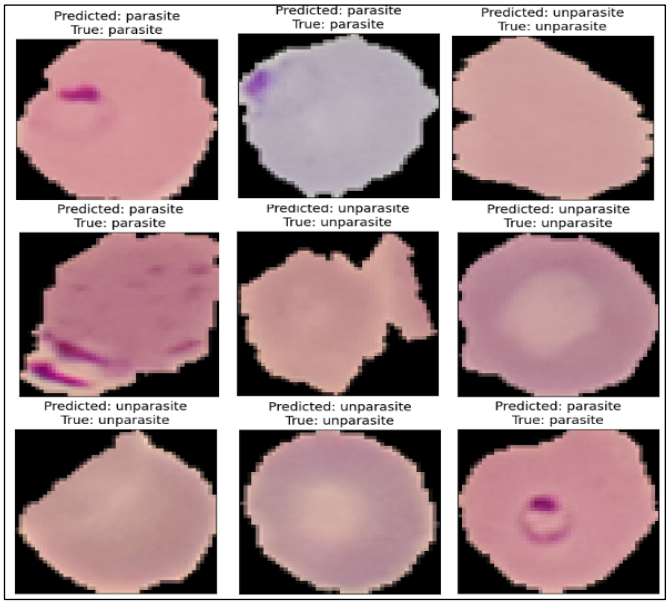

Figure 10: Estimation of the parasitic status of randomly selected cells.
Source: Authors, (2024).

The superior performance of the proposed CNN model underscores its potential as a reliable and efficient alternative for malaria diagnosis. This remarkable accuracy can significantly enhance diagnostic accuracy, particularly in resource-limited settings where timely and accurate diagnosis is crucial for effective treatment and control of the disease. The integration of our CNN model into a user-friendly software application further amplifies its impact, offering healthcare professionals a valuable tool for real-time malaria diagnosis. As such, our findings pave the way for advancements in malaria diagnosis through the fusion of artificial intelligence and medical science, marking a significant stride towards combating malaria and improving global health outcomes. A simple and fast to use desktop software that detects whether the cell is malarial or not when the blood cell image is uploaded has been realised. The application was implemented using Python programming language. The user can determine the status of the cell by uploading the blood cell image to the application and pressing the guess button. Figure 11 and Figure 12 show the screenshots of the application.

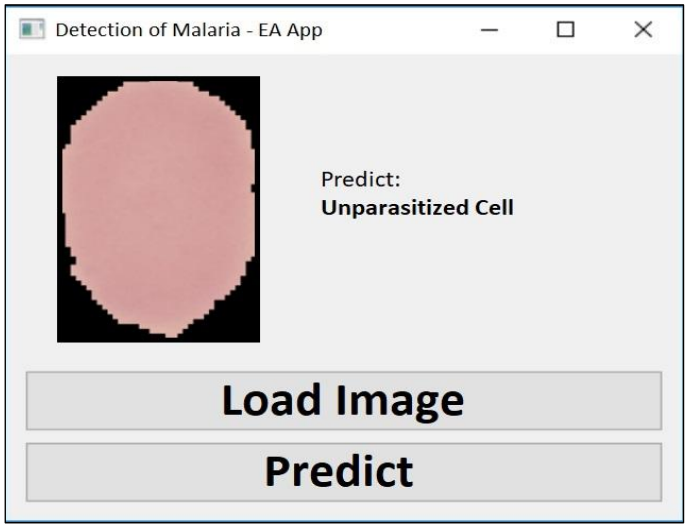

Figure 11: Screenshots of the application showing predictions of actual cell images 1.
Source: Authors, (2024).

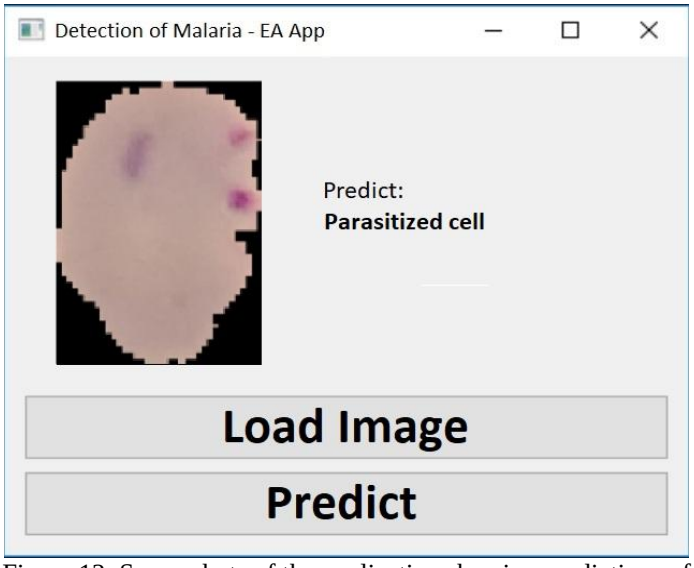

Figure 12: Screenshots of the application showing predictions of actual cell images 2.
Source: Authors, (2024).

V. CONCLUSIONS

This study demonstrates the innovative potential of deep learning-based approaches in malaria diagnosis. Our CNN-based architecture, which was developed to overcome the difficulties of traditional diagnostic methods, has achieved a high accuracy rate of 99.12%, which is a remarkable achievement, especially in the rapid and reliable diagnosis of a common disease such as malaria. The 98.87% precision and 99.37% recall values of our model support its diagnostic performance and reveal that it has the capacity to produce high accuracy results by minimizing human error in the malaria detection process. These high-performance values demonstrate the applicability and effectiveness of CNN-based deep learning models in the diagnosis of a common and potentially fatal disease such as malaria. The developed software platform accelerates the diagnosis of malaria while at the same time minimizing the possibility of misdiagnosis by increasing diagnostic accuracy, thus enabling rapid and accurate diagnosis of malaria. The results of this study offer an innovative approach to malaria diagnosis that is independent of traditional methods and

opens the door to a new era in healthcare by bringing artificial intelligence-supported solutions to the diagnostic process. Especially in diseases that threaten public health such as malaria, artificial intelligence applications for early diagnosis and treatment have great potential to improve health outcomes and reduce disease-related mortality rates. In this context, the convergence of AI and medicine is an important step that will shape the future of global healthcare.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Emrah ASLAN
Methodology: Emrah ASLAN
Investigation: Emrah ASLAN
Discussion of results: Emrah ASLAN
Writing – Original Draft: Emrah ASLAN
Writing – Review and Editing: Emrah ASLAN
Resources: Emrah ASLAN
Supervision: Emrah ASLAN
Approval of the final text: Emrah ASLAN

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A THREE PHASE INDUCTION MOTOR DYNAMIC FRAMEWORK REGULATED BY PREDICTIVE AND INTELLIGENT OPTIMIZATIONS

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ABSTRACT

The role of Model Predictive Control (MPC) as a fundamental optimization tool in modern control systems is increasingly emphasized. In this context, the paper presents Predictive Current Control (PCC) strategies for a three-phase inverter-fed induction motor drive (IM), focusing on two core approaches: the Finite Control Set (FCS) and the Integral Finite Control Set (IFCS). The FCS-MPC algorithm is based on the evaluation of a cost function, selecting a control signal from a finite set that satisfies the minimum value of the cost function. This cost function is calculated based on the squared error between the reference current and the measured stator current. Conversely, the I-FCS-MPC uses a cascade feedback structure with an appropriately adjusted controller gain to determine the optimal set of control variables. Using a minimization principle, these methods manage the switching states for reversal, causing the inverter to generate appropriate voltage signals for the induction motor. This article compares IM electromagnetic torque and load currents under each control technique to determine the most flexible and robust prediction strategy. All these methods were studied in the MATLAB/Simulink environment. In addition, the paper uses Gravitational Search Algorithm (GSA) and Genetic Algorithm (GA) as benchmarks and shows that the results of FCS and I-FCS methods have superior performance.

I. INTRODUCTION

In electrical engineering applications, MPC has proven to be more effective for utilizing and controlling the switching of power converters, synchronous and induction machine drives, as well as for controlling various power system parameters. Many researchers have implemented a wide range of predictive control algorithms. MPC has attracted wide attention due to its flexibility, robustness and fast dynamic response. The MPC topology can switch to two modes, i.e., depending on its operation and control actions and named as continuous control set (CCS), and finite control set (FCS). Predictive current control schemes for power converters and electric drives were proposed in [1], which demonstrates the CCS-MPC algorithm, the principle of receding horizon control with forward Euler approximation and cost function for a discrete-time load model of PMSM (permanent magnet synchronous motor) for switching states selection of the inverter. The introduction of Integral FCS is intended to minimize the steady-state error, which cannot be significantly reduced by FCS.

The implementation of IFCS in AC motor drives to analyze the steady-state error in d and q-axis currents was presented in [2]. Before the development of MPC techniques, conventional controllers such as PI, PD and PID were commonly used. In [3], the algorithms of the FCS and IFCS-MPC topologies for controlling various synchronous and asynchronous motor drives were designed and compared with conventional controllers.

A new FCS-MPC technique is proposed to regulate the flux dynamics of an induction motor [4]. In this control approach, the PWM technique is implemented to minimize the problems associated with the switching frequency. A comparative study between FCS and CCS method was highlighted in [5]. In this work, the execution methodology of both FCS and CCS action has been

discussed, such as modulation control and SVPWM control scheme, respectively. A predictive control strategy of an inverter-fed IM drive can be designed with current evaluation or with flux/torque evaluation [6].

This study provides the practical perception of MPC for inverter-fed drive systems. To diagnose the performance of IM, various strategies have been included, including field-oriented control, direct torque control, and predictive controllers [7]. Basically, optimization problems are assigned with specific cost functions depending on system parameters. In order to achieve fast dynamic behavior of the induction machine, innovative control strategies with two different objective functions for both torque and flux were defined [8]. In [9], an MPC scheme for direct flux control of induction motors with multiple three-phase structures was proposed to improve the fault-tolerant behavior of the drives by independently controlling the three phases.

The IFCS-MPC strategy for a single-phase Z-source inverter was implemented in [10] to compensate for the steady-state error caused by the FCS method.

FCS MPC has proven to be a promising control method for converter-powered IM drives. Two case studies of a converter-fed induction machine with and without an LC filter were analyzed in [11]. In [12], a predictive control approach is proposed to determine the length of the control horizon of an induction motor drive. As already discussed in previous literature, predictive control can be a fast-acting measure for optimal control of the switching states of inverters [13]. In general, a finite rule set based controller provides fast dynamic response and overcomes the limitations of traditional PI controllers. In [14], a deadbeat FCS topology was proposed for predictive current control to improve IM dynamics.

The adaptability, robustness and flexibility of the FCS technique has been compared with classical controllers [15] and a sliding mode based MPC method has been introduced for torque and flux control of induction motors [16],[17]. The field-oriented control of a three-phase induction motor by the FCS-MPC method with integrated forced control and DC control strategy is demonstrated in [18]. This algorithm can minimize the deviations between desired currents and predicted currents. Apart from single- or three-phase IM, the prediction mechanism has also provided a real control algorithm for multi-phase machines such as five-phase or six-phase machines [19-21] to optimize the machine performances.

A predictive phase angle controller was used to control the phase angles of the stator phase currents [22] and the overall properties of the machine were analyzed. The main aspects of controlling the dynamics of an induction machine are monitoring the flux and current behavior. Accordingly, observer-based predictive flux control [23] and various flux control strategies [24],[25] were implemented to observe and control the variations of machine parameters.

The development of MPC methods has increased much faster due to their reputation for responding quickly and providing a simple system algorithm. The many advantages of this novel technique include minimizing harmonic current and torque distortions [26], multi-objective optimization, and a fast fault-tolerant approach [27]. In the current scenario, predictive controls are significantly used in high-performance drive systems such as induction machines, synchronous machines, linear motors, reluctance motors and multi-phase machine drives [28]. In [29], a total disturbance observer-based PCC model of IM was presented, which directly incorporates the disturbance into the prediction mechanism, thus eliminating the need for a separate controller. The most recent advancement of MPC action features the fast-acting control mechanism of multi-phase induction motor drives [30],[31]. The application of model predictive control in power electronics increases the flexibility, robustness and speed of designed control architectures. To increase the dynamics, various predictive controllers are used, such as: Deadbeat controllers, hysteresis current controllers (HCC) and trajectory-based controllers. Predictive controls of machine drives are based on current or torque/flow control[32-34]. Although the FCS-MPC method adopted by researchers has largely improved the dynamic response of the system, the technique has drawbacks in terms of minimizing the steady-state error. Therefore, this work is motivated to apply the finite control set model (I-FCS-MPC) predictive control with integral action to further minimize the steady-state error and with a fast dynamic response. Therefore, two integral gain constants Kd and Kq are introduced in the control structure for direct and quadrature axis currents. Therefore, it is necessary to have the correct values of these two parameters to obtain a system with minimum steady state error and acceptable switching losses.

However, to evaluate the efficacy of IFCS-MPC and FCS-MPC, we have applied the Genetic Algorithm (GA) [35-37] and Gravitational Search Algorithm (GSA) [37-40] for comparison. The results show that both FCS-MPC and I-FCS-MPC methods exhibit superior performance in comparison to the GSA and GA algorithms. Despite the evolution of control strategies and the introduction of new techniques, the application of model predictive control in power electronics continually enhances the robustness, flexibility, and speed of designed control architectures. This work aims to build upon this foundation, exploring the potential of I-FCS-MPC in the realm of induction motor drives [41]. The optimal values for these parameters depend greatly on the specific problem being solved. However, here are some general guidelines for selecting the parameters: Inertial Mass: The inertial mass is typically calculated from the agent's fitness, so there's no initial value to set. However, it is common to normalize the fitness values so that the sum of all agents' inertial mass equals 1 at each iteration. Diminishing Gravitational Constant: The gravitational constant G is often initialized to a value such as 100 or 1 and reduced over time. A common approach is to decrease G linearly over the iterations.

The article is structured in the following manner to facilitate a comprehensive exploration of the implemented techniques. Section 2 introduces related reviews and research literature, setting a rich backdrop for the study. Moving ahead, Section 3 elaborates on the inverter topology, dynamic model, control methodologies, and the crucial algorithms designed for the proposed predictive controllers for an Induction Motor (IM) drive. This section also ventures into the structure and implementation of the Gravitational Search Algorithm (GSA) and the Genetic Algorithm (GA).

Section 4 is devoted to presenting and discussing the responses of torque, currents, and speeds with respect to step changes of the various proposed control actions. In Section 5, a comparative analysis is performed on the designed Model Predictive Controls (MPCs) with a focus on their torque and current dynamic characteristics. The paper finally concludes with Section 6, summarizing the main conclusions drawn from the study along with relevant references.

II. RELATED REVIEWS

In recent years, predictive control methods have become a pivotal area of interest for induction motor drives due to their

superior dynamic response and simplified implementation over traditional methods. [2] first introduced integral FCS predictive current control of induction motor drives, providing a basis for improving dynamic response and static error performance [2]. Subsequent research by introduced the application of PID and predictive control methods using MATLAB/Simulink, affirming the advantages of these predictive control approaches [3]. However, this work lacked an in-depth exploration of practical implementation challenges. Advancements in this field continued, who explored direct flux and current vector control, as well as Finite Control Set-Model Predictive Speed Control, respectively [4,5]. These studies validated the control principles and applications for high-performance drive systems [5].

The literature further expanded with comparative studies and explorations into various predictive control methods. contrasted current-based and flux/torque-based model predictive control methods for open-end winding induction motor drives, ultimately favoring the flux/torque-based method for its efficiency in reducing current ripple and improving dynamic response [6]. Advancing the topic, further explored advanced control strategies of induction machines: Field Oriented Control, Direct Torque Control, and Model Predictive Control [7]. The authors provided a detailed analysis and comparison of these strategies, indicating the dominance of Model Predictive Control in terms of performance. Similarly, presented a simple strategy for high-quality performance of AC machines using model predictive control [8], emphasizing the simplicity and effectiveness of Model Predictive Control. Concurrently, offered an in-depth analysis and comparison of advanced control strategies: Field Oriented Control, Direct Torque Control, and Model Predictive Control, with the latter emerging dominant [7]. This was further substantiated by, who touted the simplicity and effectiveness of Model Predictive Control [8].

More recently, research began exploring the intersection of predictive control methods with computational intelligence techniques, hybrid approaches, and innovative concepts. This includes studies such as those by F. Yahiaoui et al.[32], R. Venayagamoorthy et al.[33], Mehedi Ibrahim Mustafa et al. [34], T. Jalil et al.[35], J. Senthil Kumar et al.[36] and PA Naidu, V Singh[37] who utilized Genetic Algorithms and Gravitational Search Algorithm for optimizing the nonlinear control of induction motors. The introduction of these techniques has shown significant efficacy in performance enhancement. Meanwhile, , and Stando have extended model predictive control's application to power electronics, providing comprehensive design guidelines, exploring long-horizon control, and examining the constant switching frequency predictive control scheme [11,12,13,14]. Lastly, showcased an extended application of the predictive control concept to multi-phase systems [9]. In conjuction to this integration of predictive and optimal control algorithms for drive control established as a worthy dynamic platform [42],[43]. In essence, the ongoing research in the field emphasizes the diverse applications and continual advancements in predictive control methods for induction motor drives.

III. PROPOSED CONTROL METHODS

The working principle of model predictive control (MPC), where the variable of interest is the finite horizon control and is compared with the desired reference value to obtain the required command signal. This proposed work is based on simplifying the optimization of inverter states without PWM technique. Here, eight combinations of inverter states are formed as constraints for the control design. To better predict future behavior, the load model is used, hence the variables, which is why the name model predictive control arises. The optimization technique works on the principle of controlling the receding horizon. We can say that a constraint-free FCS-MPC method is similar to the discrete-time deadbeat feedback system, where the controller gain varies with time under the condition that the poles in the closed loop are at the origin of the complex plane.

To improve the steady-state behavior of the normal FCS-MPC method, an integral effect is added via a cascade control structure. The minimized objective function in the normal FCS-MPC method is just the squared difference between the predicted current and the measured current in the d-q reference frame. The main utility of the objective function in an I-FCS-MPC method is explicitly related to the sampling time Δt. Further two intelligent techniques such as Genetic Algrithm(GA) and Gravitational Search Algorithm(GSA) are introduced to evaluate the dynamic characteristics of designed Induction motor.

III. 1. MPC METHODOLOGY

MPC works with a finite horizon control principle. The controller or MPC block carries out the evaluation of control signals for a specific future point in time. Over time, the finite prediction horizon is updated by incorporating a future period and leaving behind a past period. Based on the predicted performance of the system, MPC generates a control sequence that is only applicable at the current sampling time.

After a sampling interval, the control sequence is changed based on the new measurements. In Figure 1, the red trajectory is the reference signal to follow. The green trajectory is the controlled signal obtained after proper measurements and manipulations at time k. The yellow curve is the past measure used to predict the future.

In the current state k, the MPC evaluates the control sequence for the prediction horizon, as indicated by the purple line. Similarly, at sampling time k+1, k+2, etc., MPC generates different sets of controlled sequences for their respective prediction horizons.

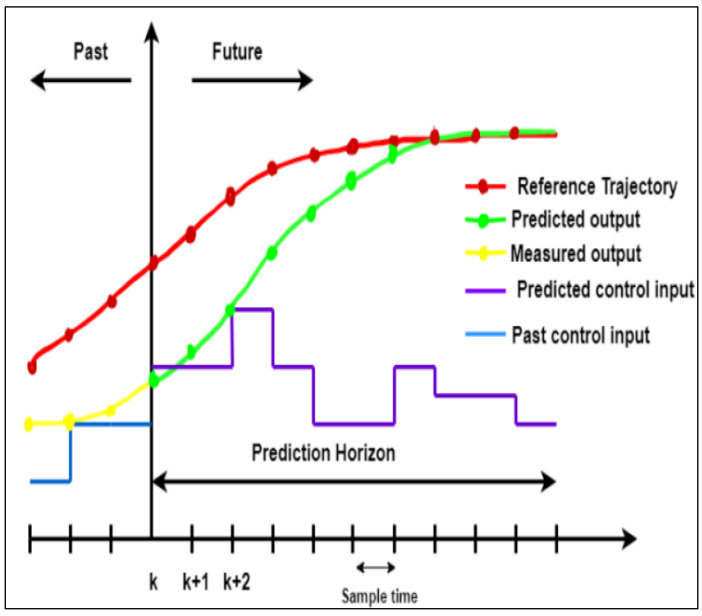

Figure 1: MPC with Predictive Horizon
Source: Authors, (2025).

III. 2. DYNAMIC FRAMEWORK OF IM

For our experimental setup in a simulation environment, we took a case of a squirrel cage type induction motor. The current and

torque dynamics are represented in the following mathematical equations with respect to the d-q reference frame [3].

$$\frac{di_{sd}}{dt} = -\frac{1}{\tau_\sigma} i_{sd} + \omega_s i_{sq} + \frac{k_r}{r_\sigma \tau_\sigma \tau_r} \varphi_{rd} + \frac{1}{r_\sigma \tau_\sigma} \quad (1)$$

$$\frac{di_{sq}}{dt} = -\omega_s i_{sd} - \frac{1}{\tau_\sigma} i_{sq} - \frac{k_r}{r_\sigma \tau_\sigma} \omega_e \varphi_{rd} + \frac{1}{r_\sigma \tau_\sigma} \quad (2)$$

$$\omega_s = \omega_e + \frac{L_h}{\tau_r} \quad (3)$$

$$\omega_s = \omega_e + \frac{1}{\tau_r} \frac{i_{sq}}{i_{sd}} \quad (4)$$

Where

i_{sd} & i_{sq} are the measured currents on the d-axis, q-axis, expressed in Ampere (A)

v_{sd} & v_{sq} are the measured voltages on the d-axis, q-axis, expressed in Volt (V)

ω_s, ω_e are the angular speed of the stator and rotor, expressed in rad/sec

φ_{rd}= d-axis Rotor flux (Wb)

All other parameters used in the IM drive dynamic equations are defined below[41-42].

Leakage factor:

$$\sigma = 1 - \frac{L_h^2}{L_s L_r} \quad (5)$$

Stator time constant:

$$\tau_s = \frac{L_s}{R_s} \quad (6)$$

Rotor time constant:

$$\tau_r = \frac{L_r}{R_r} \quad (7)$$

Coefficients:

$$k_r = \frac{L_h}{L_r} \quad (8)$$

$$r_\sigma = R_s + R_r k_r^2 \quad (9)$$

$$\tau_\sigma = \frac{\sigma L_s}{r_\sigma} \quad (10)$$

The torque produced by the magnetic field, commonly known as electromagnetic torque, is proportional to, $\varphi_{rd} i_{sq}$, which is expressed as

$$T_e = \frac{3}{2} Z_p \frac{L_h}{L_r} \varphi_{rd} i_{sq} \quad (11)$$

The mechanical parameters of the induction motor must be taken into account and derived from the general motor equation for rotation, which is given as follows:

$$J_m \frac{d\omega_m}{dt} + f_d \omega_m = T_e - T_L \quad (12)$$

Where $\omega_m(t)$, the mechanical Speed of the rotor ($\omega_m = \frac{\omega_e}{Z_p}$), J_m, the inertia of the motor and f_d, the coefficient of friction, T_e & T_L the torque in the electromagnetic field and the load. With consideration of the dynamics, the model and using the above in to the motion equation, representing in (12),

$$\frac{d\omega_m}{dt} = \frac{-f_d}{J_m} \omega_m + \frac{3}{2} \frac{Z_p L_h}{L_r J_m} \varphi_{rd} i_{sq} - \frac{T_L}{J_m} \quad (13)$$

The electrical speed of the rotor can be expressed as,

$$\frac{d\omega_e}{dt} = \frac{-f_d}{J_m} \omega_e + \frac{3}{2} \frac{Z_p^2 L_h}{L_r J_m} \varphi_{rd} i_{sq} - \frac{Z_p T_L}{J_m} \quad (14)$$

The physical and technical parameters previously defined and used in the IM model were considered and tabulated below for the evaluation of the system performance.

Table 1: 3-Φ IM model parameters.

Parameters	Values
Winding resistance offer to Stator(R_s)	111.2 Ohms
Winding resistance offer to Rotor(R_r)	88.3 Ohms
Winding inductance offer by Stator (L_s)	00.6155 Henrys
Winding inductance offer by Rotor (L_r)	00.6380 Henrys
Mutual inductance of Machine (L_h)	00.57 Henrys
Moment of inertia (J_m)	0.00176 Kgm^2
Friction viscous gain (f_d)	0.00038818 Nm/rad/sec
Number of Pole pairs(Zp)	2nos

Source: Authors, [3].

III. 3. MODELLING OF THREE PHASE INVERTER

We consider a 3φ inverter that converts 520V to 3φ AC for a squirrel cage type induction motor, whose physical parameters are shown in Table 1. The inverter operates in non-linear mode, discrete time system with 180° operating mode, 7 outputs and 8 configuration states. For simplicity and rounding, we ignore the IGBT saturation voltage and diode forward voltage drop when modeling and mathematically calculating the simulation. The schematic circuit as a voltage source and inverter to the 3-φ IM is shown below in Figure 2.

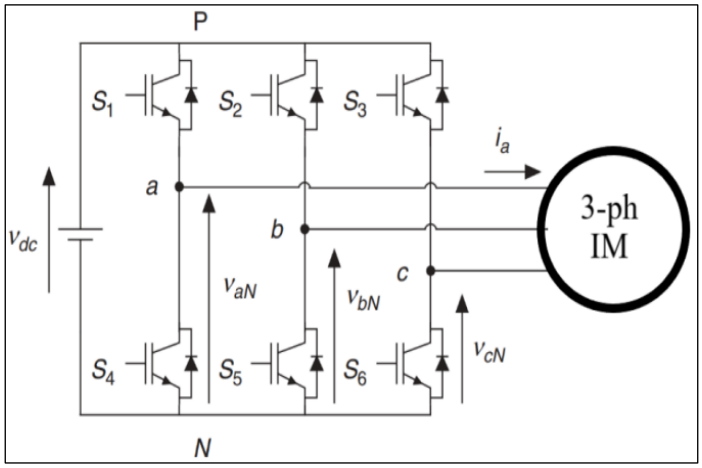

Figure 2: VSI fed 3-Φ IM.
Source: Authors, (2025).

The switching states for inverter action is specified with the reference of the gating signals *Sa*, *Sb*, *Sc* and can be represented as follows[1]:

$$S_a = \begin{cases} 1, \text{if } Switch_1 \text{ on and } Switch_4 \text{ off} \\ 0, \text{if } Switch_1 \text{ off and } Switch_4 \text{ on} \end{cases}$$

$$S_b = \begin{cases} 1, \text{if } Switch_2 \text{ on and } Switch_5 \text{ off} \\ 0, \text{if } Switch_2 \text{ off and } Switch_5 \text{ on} \end{cases}$$

$$S_c = \begin{cases} 1, \text{if } Switch_3 \text{ on and } Switch_6 \text{ off} \\ 0, \text{if } Switch_3 \text{ off and } Switch_6 \text{ on} \end{cases}$$

The concept of space vector modulation was adopted for voltage vectors with regard to optimal switching states [41],[42].

The generation of switching states results in eight voltage vectors listed in Table 2, which can be predicted by equation (15) as follows:

$$v = \frac{2}{3} V_{dc}(S_a + aS_b + a^2 S_c) \text{ Where, } a = e^{-j(2\pi/3)} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}, \quad (15)$$

with a phase displacement of 120° , between any two phases.

Table 2: Switching states with voltage vectors.

Sa	Sb	Sc	Voltage Vector(v)
0	00	00	$\overrightarrow{v_0} = 0$
1	00	00	$\overrightarrow{v_1} = \frac{2}{3} v_{dc}$
1	11	00	$\overrightarrow{v_2} = \frac{1}{3} v_{dc} + j\frac{\sqrt{3}}{3} v_{dc}$
0	11	00	$\overrightarrow{v_3} = -\frac{1}{3} v_{dc} + j\frac{\sqrt{3}}{3} v_{dc}$
0	11	11	$\overrightarrow{v_4} = -\frac{2}{3} v_{dc}$
0	00	11	$\overrightarrow{v_5} = -\frac{1}{3} v_{dc} - j\frac{\sqrt{3}}{3} v_{dc}$
1	00	11	$\overrightarrow{v_6} = \frac{1}{3} v_{dc} - j\frac{\sqrt{3}}{3} v_{dc}$
1	1	1	$\overrightarrow{v_7} = 0$

Source: Authors, (2025).

The simple mathematical model of a three-phase inverter circuit that defines the generated output voltages (phase to neutral) by applying switching signals is shown in Figure 3. The optimal operation of prediction algorithms leads to the switching state listed in the Table. 2.

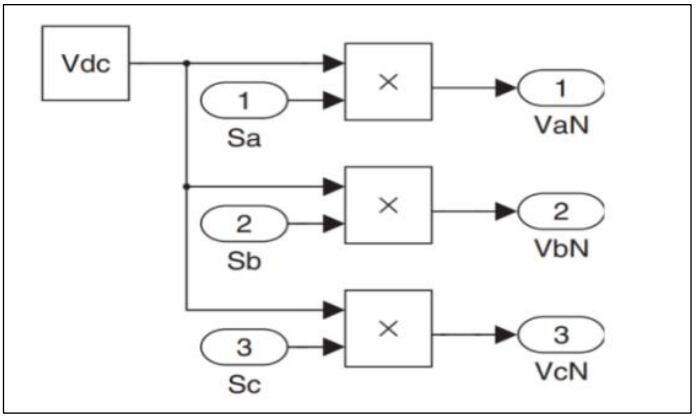

Figure 3: Generated Voltage of VSI.
Source: [1].

III. 3. PREDICTIVE CURRENT CONTROL

The predictive control algorithm can be organized in the following way.

1) The measurement of the reference current i*(ti+1) is carried out via the outer control loop, while the measurement of the load current i(t) must be carried out in each state with respect to the sampling interval.
2) The evaluation and prediction of the load current value for each upcoming sampling interval i(ti+1) taking into account the different voltage vector.
3) The cost function J uses the difference between the reference and the predicted currents of upcoming scanning frames with the corresponding voltage vector for the error calculation.

$$J=\{i_d^*(t_i)-i_d(t_{i+1})\}^2+\{i_q^*(t_i)-i_q(t_{i+1})\}^2 \quad (16)$$

4) The switching status signals generated minimize the current error and must be listed and taken into account for use.

In this algorithm, the previous value of the load current and the next state of the current leads to the prediction of 7 different states and 8 configurations for the operation of the inverter circuit. For each discrete state, we need to calculate the current value, predict it and compare it with the reference current to detect minimal errors and changes. We need to calculate for all 8 values listed in the table above and record the errors. The optimal operating states are fed to the inverter, which serves as a voltage source inverter. The flowchart of the above process is shown in Figure 4.

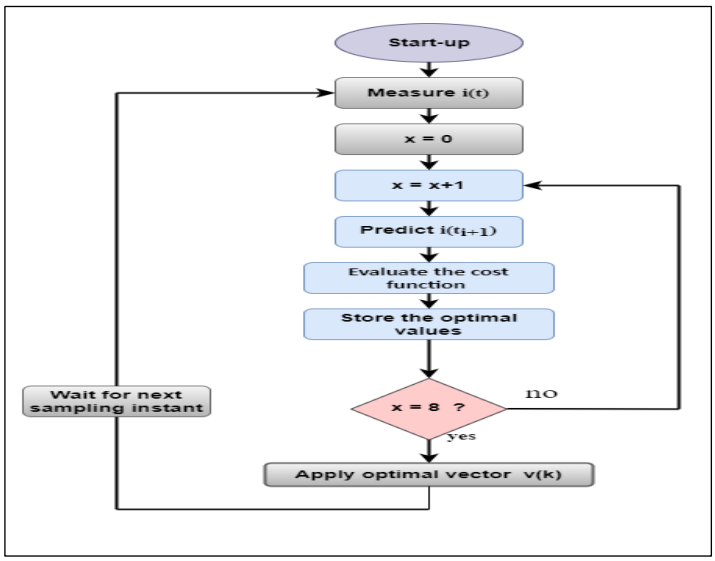

Figure 4: Flow Chart for Predictive Current Control.
Source: [41].

III. 4. FCS-MPC METHOD FOR IM

When generalizing the equations, predicted load currents in the d-q frame for sampling time ti can be derived from forward Euler approximations [1].

$$\frac{di_{sd}(t)}{dt} \approx \frac{i_{sd}(t_{i+1}) - i_{sd}(t_i)}{\Delta t} \quad (17)$$

$$\frac{di_{sq}(t)}{dt} \approx \frac{i_{sq}(t_{i+1}) - i_{sq}(t_i)}{\Delta t} \quad (18)$$

Where, Δt is the sampling interval,

$i_d(t_{i+1})$ and $i_q(t_{i+1})$ are predicted values of current on d-q frame, i_d^* and i_q^* are the desired values of current on the d-q frame.

Now by blending Equations (17) & (18) in Equations (1) & (2) respectively, the discrete differential equations transform as the difference equations and can be represented as follows:

$$i_{sd}(t_{i+1}) = i_{sd}(t_i) + \Delta t(-\frac{1}{\tau_\sigma} i_{sd}(t_i) + \omega_s i_{sq}(t_i) + \frac{k_r}{r_\sigma \tau_\sigma \tau_r} \varphi_{rd}(t_i) + \frac{1}{r_\sigma \tau_\sigma} u_{sd}(t_i)) \quad (19)$$

$$i_{sq}(t_{i+1}) = i_{sq}(t_i) + \Delta t(-\omega_s i_{sd}(t_i) - \frac{1}{\tau_\sigma} i_{sq}(t_i) - \frac{k_r}{r_\sigma \tau_\sigma} \omega_e(t_i)\, \varphi_{rd}(t_i) + \frac{1}{r_\sigma \tau_\sigma} u_{sq}(t_i)) \quad (20)$$

The prediction equations for current forecasting corresponding to Equation (19) and (20) can be presented in matrix form.

$$\begin{bmatrix} i_{sd}(t_{i+1}) \\ i_{sq}(t_{i+1}) \end{bmatrix} = (\mathrm{I} + \Delta t A_m(t_i)) \begin{bmatrix} i_{sd}(t_i) \\ i_{sq}(t_i) \end{bmatrix} + \Delta t B_m \begin{bmatrix} u_{sd}(t_i) \\ u_{sq}(t_i) \end{bmatrix} + \begin{bmatrix} \frac{k_r \Delta t}{r_\sigma \tau_\sigma \tau_r} \varphi_{rd}(t_i) \\ -\frac{k_r \Delta t}{r_\sigma \tau_\sigma} \omega_e(t_i)\, \varphi_{rd}(t_i) \end{bmatrix} \quad (21)$$

Where,

I is a 2*2, identity matrix and

$$A_m(t_i) = \begin{bmatrix} -\frac{1}{\tau_\sigma} & \omega_s(t) \\ -\omega_s(t) & -\frac{1}{\tau_\sigma} \end{bmatrix}$$

$$B_m = \begin{bmatrix} \frac{1}{r_\sigma \tau_\sigma} & 0 \\ 0 & \frac{1}{r_\sigma \tau_{\sigma_q}} \end{bmatrix}$$

The block diagram of FCS-MPC Model used for 3-ph induction motor is illustrated in Figure 5.

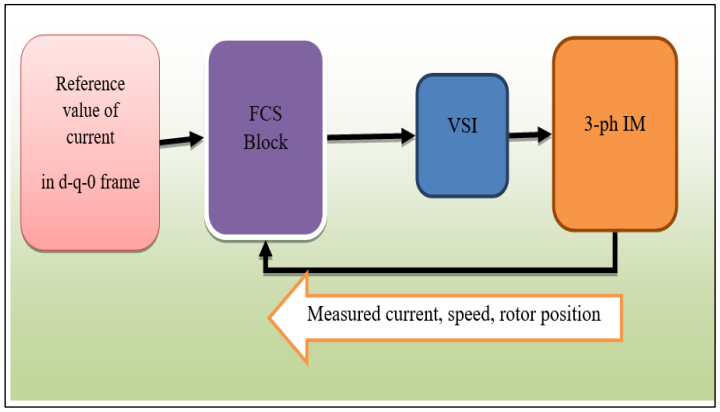

Figure 5: FCS-MPC Structure for IM Control.
Source: [41].

This method is processed in the following way.

1) The reference value is represented in d-q frame (idref and iqref).

2) Measured currents in d-q frame, velocity in radians per second and rotor angle position in radians are used as input to FCS control block .

3) The output of the FCS block is the switching states to the voltage link inverter.

4) The control output of the inverter is fed to the IM model as a voltage source.

5) In this article, a two-stage three-phase VSI is considered for the application of prediction schemes. Since all modeling and calculation is done in the d-q-0 reference frame, the generated stress vectors must be transformed from the a-b-c coordinate to the d-q-0 coordinate using the Park transform.

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (22)$$

Where,

u_{sd} = d-axis Voltage,

u_{sq} = q-axis Voltage,

θ = Rotor angle

V_{an} ,V_{bn},V_{cn} are the phase to neutral voltages,

V_{dc} = Input DC voltage to VSI

In the FCS-MPC approach, there are seven sets and values are presented based on the rotor angular position and sampling time. In this control strategy, we employ the objective function, which is defined as the sum of the square of the error difference between the desired and predicted current values in the d-q frame. The objective function J takes into account the variables measured with the sampling time and the manipulated variables. Equation (16) can be expressed as follows:

$$\mathrm{J_K} = \left(\mathrm{i^*_{sd}(t_i) - i_{sd}(t_i) - \Delta t(-\frac{1}{\tau_\sigma} i_{sd}(t_i) + \omega_s i_{sq}(t_i) + \frac{k_r}{r_\sigma \tau_\sigma \tau_r} \varphi_{rd}(t_i) + \frac{1}{r_\sigma \tau_\sigma} u_{sd}(t_i))} \right)^2 + \left(\mathrm{i^*_{sq}(t_i) - i_{sq}(t_i) - \Delta t(-\omega_s i_{sd}(t_i) - \frac{1}{\tau_\sigma} i_{sq}(t_i) - \frac{k_r}{r_\sigma \tau_\sigma} \omega_e(t_i)\, \varphi_{rd}(t_i) + \frac{1}{r_\sigma \tau_\sigma} u_{sq}(t_i))} \right)^2 \quad (23)$$

Where ,

φ_{rd} = d-axis rotor flux and

K = index from 0 to 7.

The principle of declining horizon control is used here, which is based on feedback parameters such as: $i_{sd}(t_i)$, $i_{sq}(t_i)$, ω_e and θ_e, and the 3-ph IM model predicts a value for one step ahead. The objective function is calculated based on the above feedback values, parameters of the 3-ph IM model and the $u_{sd} - u_{sq}$ value pair. Seven sets of objective functions are calculated based on seven pairs of $u_{sd} - u_{sq}$ values. The index value is 0 or 7, it is determined based on the previous states of the inverter. The switching combinations and corresponding voltage vectors used in the FCS-MPC technique are listed in Table 3.

Table 3: Switching States and Voltage Vectors of FCS Block.

Switching State			Voltage Vector	Phase Voltage		
Sa	Sb	Sc	v	V_{an}	V_{bn}	V_{cn}
0	0	0	$\vec{v_0}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
1	0	0	$\vec{v_1}$	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
1	1	0	$\vec{v_2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
0	1	0	$\vec{v_3}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
0	1	1	$\vec{v_4}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$
0	0	1	$\vec{v_5}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$
1	0	1	$\vec{v_6}$	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$
1	1	1	$\vec{v_7}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$

Source: Authors, (2025).

The phase-neutral voltages of each phase can be defined in relation to the switching states and the DC input voltage of the inverter as follows:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} S_a - \frac{1}{2} \\ S_b - \frac{1}{2} \\ S_c - \frac{1}{2} \end{bmatrix} \mathrm{V_{dc}} \quad (24)$$

III. 5. IFCS-MPC METHOD FOR IM

The IFCS-MPC method uses the same concept as the normal FCS-MPC method, but different in control effect, so in the I-FCS-MPC method the objective function is variable with respect to voltage signals, while in the normal FCS -MPC method the same applies was formed in relation to current signals. The optimal control signals obtained from the feedback control framework are given as follows:

$$\begin{bmatrix} u_{sd}(t_i)^{opt} \\ u_{sq}(t_i)^{opt} \end{bmatrix} = K_{fcs} \left(\begin{bmatrix} {i_{sd}}^*(t_i) \\ {i_{sq}}^*(t_i) \end{bmatrix} - \begin{bmatrix} i_{sd}(t_i) \\ i_{sq}(t_i) \end{bmatrix} \right) \quad (25)$$

Where, K_{fcs} is the gain of the controller and can be calculated from Equation (21) as:

$$K_{fcs}(t_i) = (\Delta t^2 \mathrm{B_m^T B_m})^{-1}\, \mathrm{B_m^T} \Delta t\, (\mathrm{I} + \Delta t A_m(t_i)) \quad (26)$$

Further modifying by putting the matrix form of A_m & $\mathrm{B_m}$,

$$K_{fcs}(t_i) = \begin{bmatrix} \frac{r_\sigma \tau_\sigma}{\Delta t}(1 - \frac{\Delta t}{\tau_\sigma}) & \omega_s(t_i) r_\sigma \tau_\sigma \\ -\omega_s(t_i) r_\sigma \tau_\sigma & \frac{r_\sigma \tau_\sigma}{\Delta t}(1 - \frac{\Delta t}{\tau_\sigma}) \end{bmatrix} \quad (27)$$

Utilizing the integral action in discrete time control system, Equation (25) can be updated as:

$$\begin{bmatrix} u_{sd}(t_i)^{opt} \\ u_{sq}(t_i)^{opt} \end{bmatrix} = K_{fcs}(t_i) \begin{bmatrix} \frac{K_d}{1-q^{-1}} ({i_{sd}}^*(t_i) - i_{sd}(t_i)) \\ \frac{K_q}{1-q^{-1}} ({i_{sq}}^*(t_i) - i_{sq}(t_i)) \end{bmatrix} - \begin{bmatrix} i_{sd}(t_i) \\ i_{sq}(t_i) \end{bmatrix} \quad (28)$$

Where 'K_d' and 'K_q' are the of integral gains selected for current error at both d-axis and q-axis respectively, and $0 < Kd \leq 1$ and $0 < Kq \leq 1$ and $\frac{1}{1-q^{-1}}$ represents an integrator.

Now at sampling time t_i the optimum voltage signals are evaluated as:

$$\begin{bmatrix} u_{sd}(t_i)^{opt} \\ u_{sq}(t_i)^{opt} \end{bmatrix} = \begin{bmatrix} u_{sd}(t_{i-1})^{opt} \\ u_{sq}(t_{i-1})^{opt} \end{bmatrix} + K_{fcs}(t_i) \begin{bmatrix} K_d\, ({i_{sd}}^*(t_i) - i_{sd}(t_i)) \\ K_q\, ({i_{sq}}^*(t_i) - i_{sq}(t_i)) \end{bmatrix} - K_{fcs}(t_i) \begin{bmatrix} \Delta i_{sd}(t_i) \\ \Delta i_{sq}(t_i) \end{bmatrix} \quad (29)$$

The upgraded objective function for I-FCS-MPC is defined as

$$J_K = \frac{\Delta t^2}{(r_\sigma \tau_\sigma)^2} (u_{sd}(t_i)^K - u_{sd}(t_i)^{opt})^2 + \frac{\Delta t^2}{(r_\sigma \tau_\sigma)^2} (u_{sq}(t_i)^K - u_{sq}(t_i)^{opt})^2 \quad (30)$$

This is the objective function that is calculated for each control with index K = 0, 1, 2, ……, 6. The index value and the corresponding control set for which the target function is minimal are selected for generating the respective switching pulse to the inverter. The schematic of I-FCS-MPC for IM is shown in Figure 6.

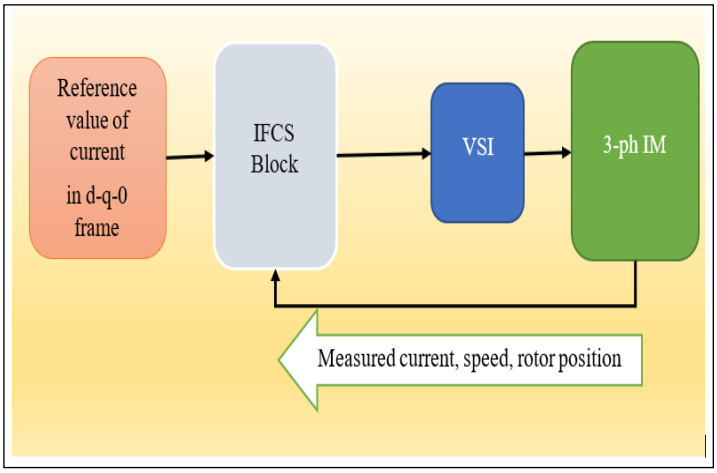

FIgure 6: Structure of I-FCS-MPC for IM.
Source: [43].

The control architecture of I-FCS-MPC for a three-phase induction motor with integral gain parameters and optimal voltage vectors is shown in Figure 7. From the block diagram shown below, we can visualize the control structure of the predictive current controller in the d-q reference frame. In addition, the mathematical representation of the previously defined equation (28) is demonstrated. By further modifying with gain parameters, equation (29) is extracted for optimal evaluation of the integral FCS control mechanism. In the implemented control algorithm, the values of the integral gain parameters *Kd* and *Kq* are set to 0.1 [3]. Further analysis can also be performed by using different values of the gain parameters ranging from 0 to 1.

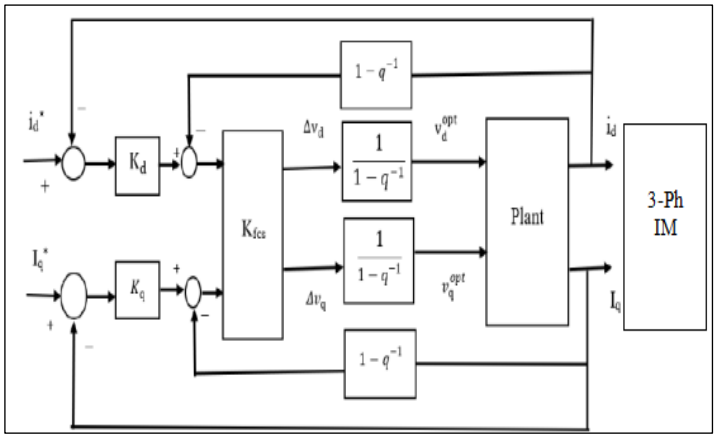

Figure 7: Control Architecture of Proposed I-FCS-MPC.
Source: [42].

III. 6. STRUCTURING GSA & GA FOR IM

The application of metaheuristic algorithms such as the Gravitational Search Algorithm (GSA) and Genetic Algorithm (GA) to the problem of induction motor control brings an innovative approach to system optimization. In GSA, the search agents are considered as objects and their performance is measured by their masses, which directly influence the gravitational attraction. This provides a balance between exploitation and exploration capabilities, thereby facilitating effective search of the optimal solution space.

In comparison, the GA employs biological evolutionary concepts including selection, crossover, and mutation to explore the solution space. The effectiveness of GA lies in its ability to handle a diverse population and evolve it over time to find optimal

or near-optimal solutions. Both GSA and GA, due to their stochastic nature, have the potential to avoid being trapped in local minima, making them particularly suitable for the nonlinear and complex problem of induction motor control. Their effectiveness is deeply tied to the proper tuning of algorithmic parameters those are mentioned in Table. 4.

Table 4.Parameter constraints used for GSA and GA.

GSA Parameters	GA Parameters
Population size (pop_size) = 50	Population size (pop_size) 50
Gravitational constant (G) = set to 100 or 1	Number of generations (ngen) = 100-500
lower and upper bounds = [0,0]-[10/400,10/400]	lower and upper bounds = [0,0]- [10/400,10/400]
Masses of agents = fitness function	Crossover rate = 0.5
Inertia weight = 0.4	Mutation rate (mutpb) =0.2
Diminishing gravitational constant = G	Crossover operator = *(DEAP library)
Distance calculation = Euclidean distance	Selection method
	Tourn-size = 3

Source: Authors, (2025).

III. 7. APPLYING ALGORITHMSON IM DYNAMICS.

1. GSA Algorithm

Step-1: Initialize a population of agents with random positions and velocities in the search space (problem space).
Step-2: Compute the fitness of each agent by taking motor dynamic parameters.
Step-3: Based on the fitness, assign a mass value to each agent - the better the fitness, the higher the mass.
Step-4: Calculate the force between each pair of agents/pop.
Step-5: Update the velocity and position of each agent based on the computed forces.
Step-6: Repeat these steps until a termination criterion is met (such as a maximum number of iterations or an acceptable solution has been found).

2. GA Algorithm

Step-1: Initialize a population of individuals with random genotypes.
Step-2: Define a fitness function of each particle by taking motor dynamic parameters.
Step-3: Select individuals for reproduction based on their fitness - the better the fitness, the higher the probability of selection.
Step-4: Apply crossover and mutation operators to the selected individuals to generate offspring for the next generation.
Step-5: Replace the current population with the offspring to form a new generation.
Step-6: Repeat these steps until a termination criterion is met.

Gravitational Search Algorithm (GSA) and Genetic Algorithm (GA) have gained prominence as effective strategies in the intelligent control methodologies for induction motor drives. GSA functions through initializing a population of agents, each with random velocities and positions, within the problem space. An assigned mass value to each agent, proportional to its fitness, facilitates the inter-agent dynamics based on gravitational forces, thereby updating their velocities and positions. This algorithm persists until meeting a termination criterion, such as finding an acceptable solution or reaching a maximum iteration limit. Simultaneously, GA operates by initiating a set of individuals with random genotypes. A predefined fitness function evaluates these individuals' problem-solving proficiency. Individuals with higher fitness have an increased likelihood of reproduction selection. The offspring, derived from crossover and mutation operations, create the new generation, and this algorithm also continues until a termination criterion is met. When applied to induction motors, these algorithms can optimize performance parameters like minimizing energy consumption, enhancing response times, or refining speed and torque control precision.

Nevertheless, the performance of these algorithms relies on the unique characteristics of the induction motor and the specifics of the control problem, necessitating careful tuning and adaptation of these methodologies for optimal induction motor drive control.

IV. RESULTS AND DISCUSSIONS

The previously mentioned three-phase induction motor with the specified parameters was modeled and executed with the FCS, I-FCS, GSA and GA control algorithms applied to the inverter circuit. The dynamic characteristics of currents, torque and angular velocity of IM were analyzed for different prediction schemes implemented here. The total simulation and sampling time is set to 0.2 s and 80 μs, respectively.

IV. 1. CURRENT DYNAMIC CHARACTERISTICS

The reference currents in d-q frame for dynamic analysis have been depicted in Figure 8. The d-axis current is set to be a constant value of i_{sd} = 0.8A and q-axis current is taken to be a step signal of amplitude i_{sq}=3A with step changes at 0.1 sec to fix the value as 1A.

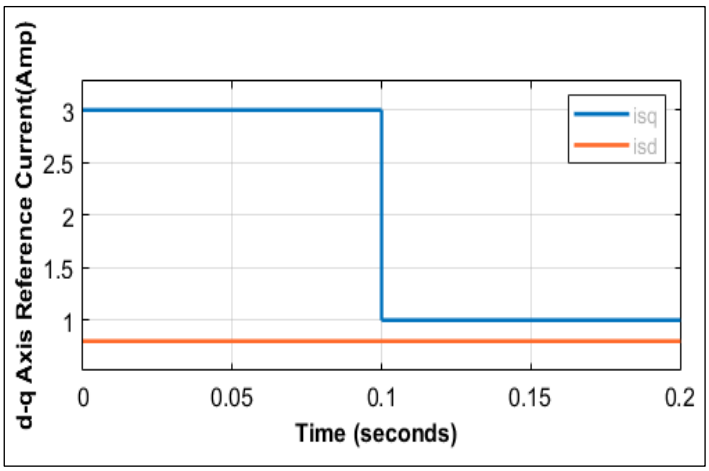

Figure 8: Three phase reference current in d-q frame.
Source: Authors, (2025).

Regarding the d-q axis currents and the change of rotor angle (θ), the characteristics of the desired currents in three phase sizes also change at a given time. These flows can be set as a reference for the flows in the next execution cycle and are used as a benchmark for all proposed approximations. The output currents

in d-q form obtained by the implemented MPC techniques are shown in Figure 9 and Figure 10, respectively.

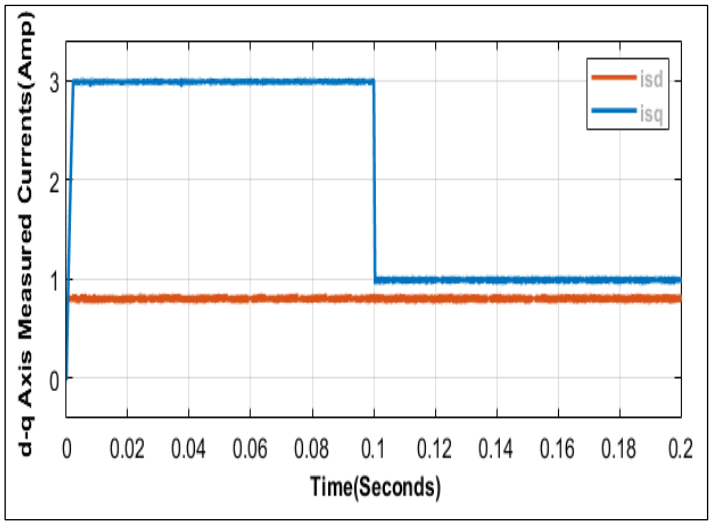

Figure 9: d-q axis currents of FCS-MPC Method.
Source: Authors, (2025).

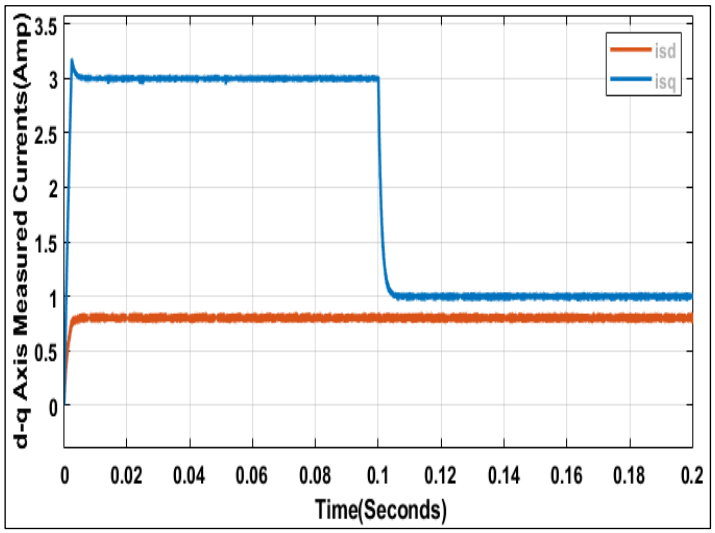

Figure 10: Output Currents of IFCS-MPC Method.
Source: Authors, (2025).

In the study of rotor angle (θ) dynamics and d-q axis currents, the use of the Gravitational Search Algorithm (GSA) and the Genetic Algorithm (GA) plays in meta-heuristic way. The intricacy of this dynamic is found in the immediate effect that the shifts in θ have on the characteristics of the currents in the three-phase quantities. For the subsequent execution cycle, a fundamental assumption is put forward: the currents as determined by the model will act as the reference point.

This benchmark is based on the results derived from the application of the GSA and GA techniques. To present a more tangible understanding of the impact of these methodologies, the output currents are visually represented. Figure 11 illustrates the output currents in d-q form, a result of applying the GSA technique, while Figure 12 displays thed-q form of output currents, an outcome attributed to the GA technique. Consequently, these figures offer a clearer comprehension of the influence of GSA and GA in the modelling of currents with comparison of FCS and I-FCS method.

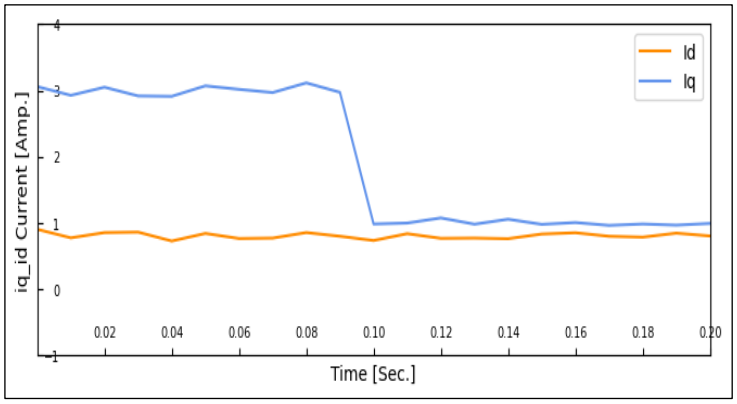

Figure 11: d-q axis currents of GSA Method.
Source: Authors, (2025).

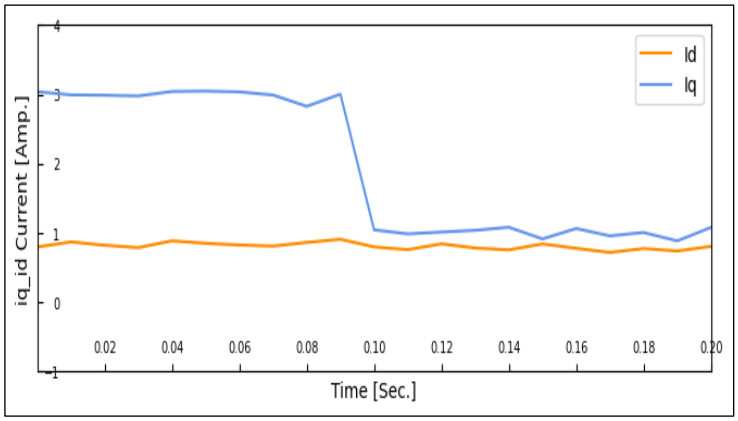

Figure 12: d-q axis currents of GA Method
Source: Authors, (2025).

IV.2. TORQUE & SPEED CHARACTERISTICS

Equation. (11) clearly demonstrates that electrical torque output (T_e) is a function of q-axis current and rotor flux of an induction motor. Hence it can be stated that the behaviour of q-axis current controls the torque characteristics. The plots of reference load torque (Figure 13) and output torque obtained from FCS and I-FCS predictive control schemes are depicted in Figure 14 & Figure 15 respectively. The load torque applied to the induction motor drive is a step signal of amplitude 2Nm with step changes at time 0.1second to 1Nm .

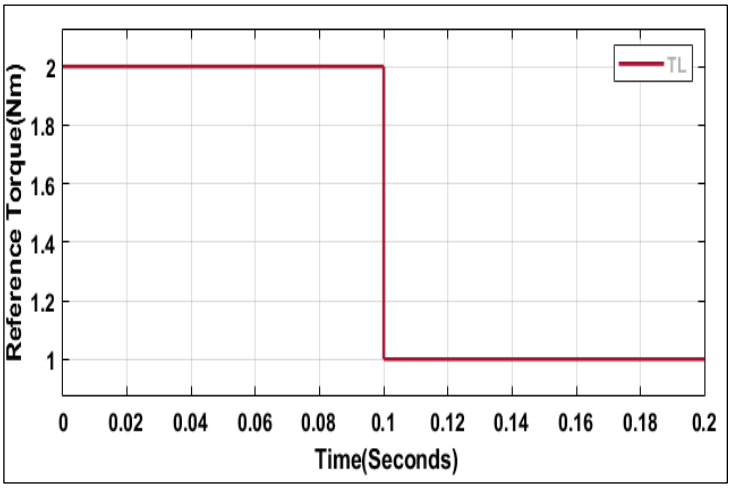

Figure 13: Load toque applied to the 3-ph IM model.
Source: Authors, (2025).

From the previous analysis, we can see that the electromagnetic torque output, quadrature axis current, rotor flux and angular velocity are dependent parameters. A change in the behavior of one of the mentioned parameters changes the properties of others, which directly affects the machine performance. Therefore, by controlling the current, we can regulate the torque and thereby also control the angular velocity of the motor in coordination with other dependent parameters. This concept can be defined mathematically by equations (13) and (14). Below, the angular velocity response of the induction motor is presented by corresponding step change in load torque and q-axis current for both proposed predictive controllers.(Figure 18).

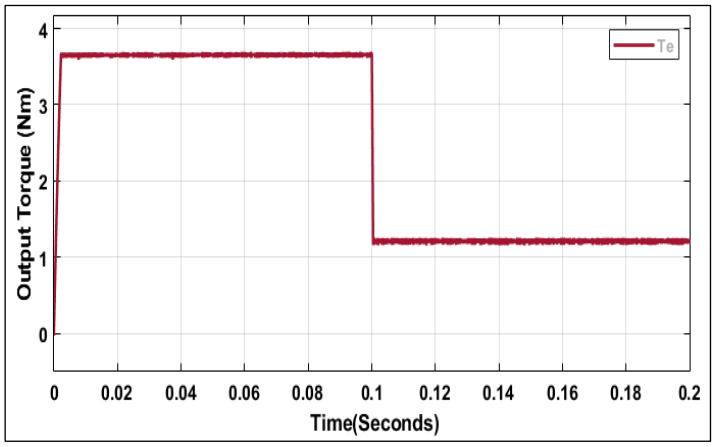

Figure 14: Torque output of FCS-MPC Method.
Source: Authors, (2025).

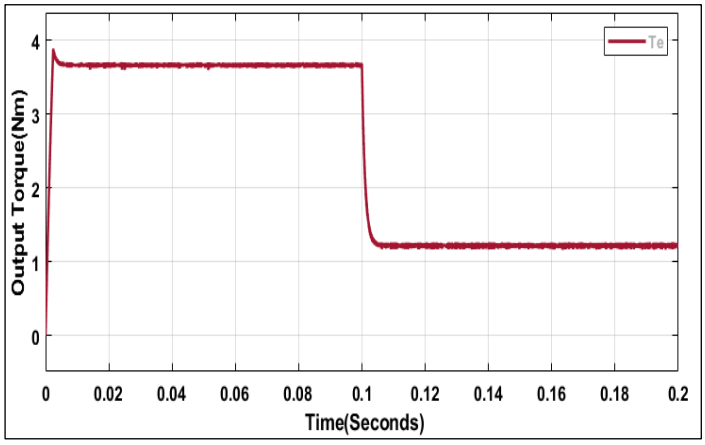

Figure 15: Torque output of I-FCS-MPC Method.
Source: Authors, (2025).

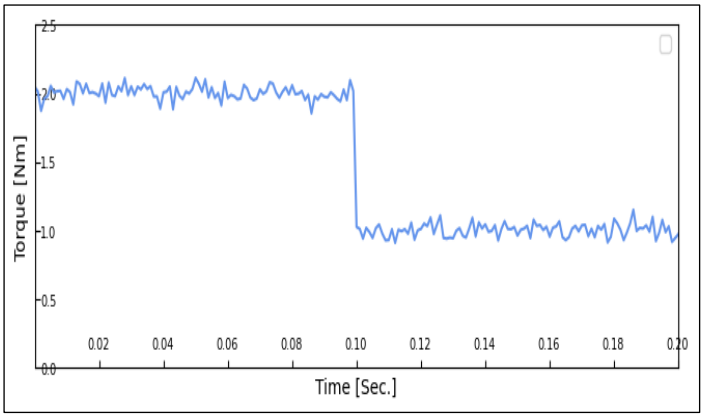

Figure 16: Torque output of GSA method.
Source: Authors, (2025).

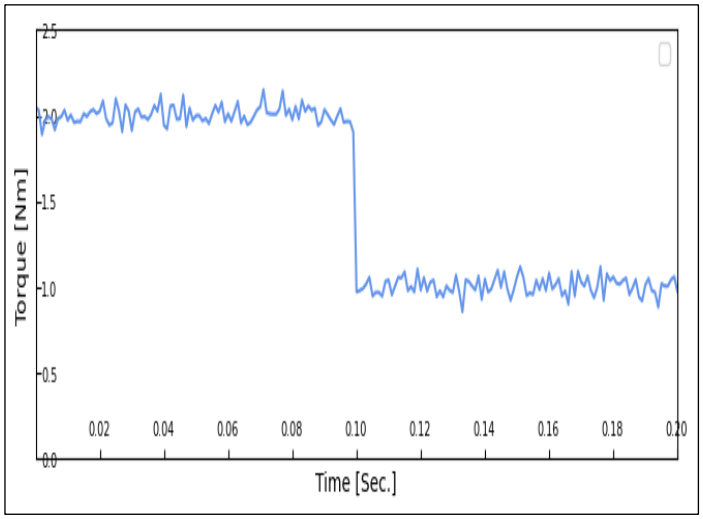

Figure 17: Torque output of GA method.
Source: Authors, (2025).

In our prior analysis, a change in one parameter invariably affects the others, setting off a cascade of impacts that influence the overall motor performance. This understanding introduces a strategic opportunity to manipulate the current and thus regulate torque as you can visualize on Figure 16 & Figure 17, and by extension, the angular speed of the motor. However, this control isn't a standalone process; it works in tandem with other dependent parameters, as succinctly demonstrated by Equations (13) & (14).

Implementing advanced algorithms such as the Gravitational Search Algorithm (GSA) and the Genetic Algorithm (GA) illuminates these complex dynamics, allowing for a deep exploration of the angular speed response of the induction motor to respective changes in load torque and q-axis current. Yet, it is worth noting that the Finite Control Set (FCS) and Integral Control Set (I-FCS) methods produce even more favorable results than the GSA and GA methods.

This observation is clearly visualized in Figure 18, which showcases the angular speed characteristics achieved by the GSA, GA, FCS, and I-FCS control approaches. Thus, these visualizations emphasize the superior efficacy of the FCS and I-FCS methods in optimizing motor performance through the effective management of interconnected parameters.

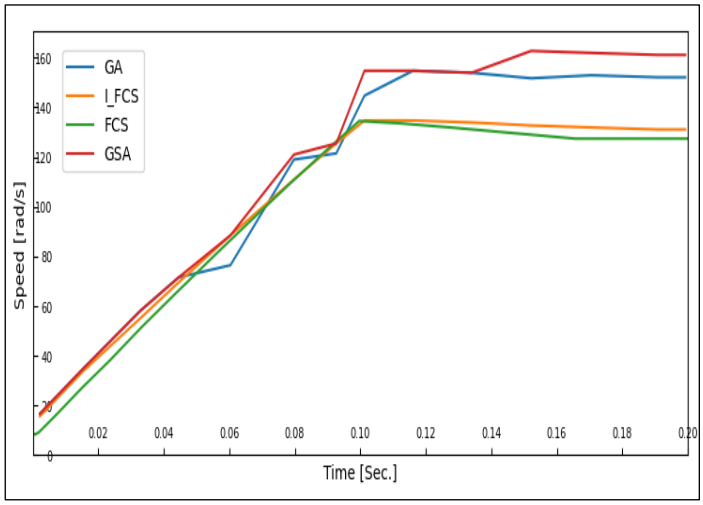

Figure 18: Angular Speed of FCS-MPC, I-FCS, GSA and GA.
Source: Authors, (2025).

The model outputs of currents, torque, angular velocity and rotor angle (Figure 19) of the designed induction motor drive were collected for optimal performance evaluation. The current dynamics are studied using a reference step signal of the quadrature axis current. Accordingly, the machine's electromagnetic torque output also follows the applied step load torque since the output torque is a function of the q-axis current and rotor flux defined in the equation. (11). Since the rotor position angle is updated after each point in time, the corresponding angular velocity also changes. Here, the step responses of current, torque and speed achieved by FCS and I-FCS control strategies were demonstrated. Currents and torque ripples can be visualized from the output reactions. It can be found that the ripple magnitudes for both current and torque output are lower for I-FCS-MPC compared to FCS-MPC, GSA and GA. Compared to the integral FCS technique, somewhat larger fluctuations in the speed response are also observed with FCS. Based on the model results of the implemented MPC strategies, a performance comparison was carried out in terms of d and q axis current responses, torque & speed trajectories and rotor angle deviations w.r.t step input signal. Further controller selection can be done by observing the current errors noted.

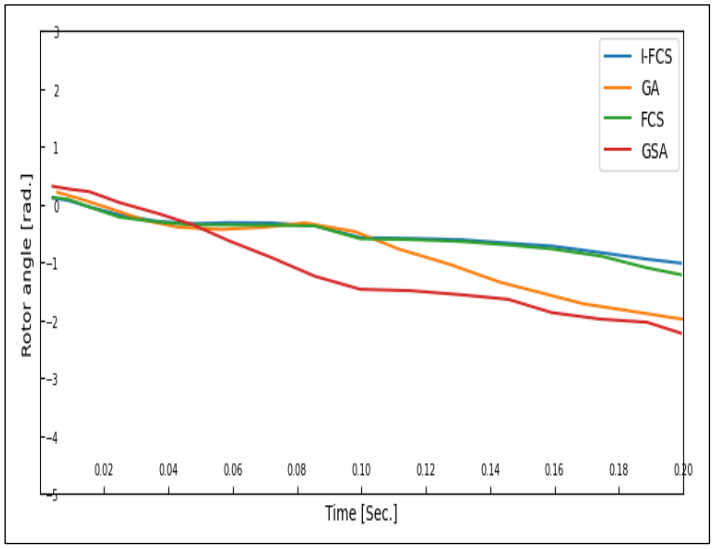

Figure 19: Rotor angle of FCS-MPC, I-FCS, GSA and GA.
Source: Authors, (2025).

In the pursuit of optimal performance, a thorough evaluation of the designed induction motor drive model reveals the significance of certain parameters - currents, torque, angular speed, and most importantly, the rotor angle (θ). These variables play pivotal roles in the complex dynamics of motor operation. The study of current dynamics, undertaken via a reference step signal of the quadrature axis current, emerges as a particularly engaging aspect. Notably, this signal has a profound influence on the rotor angle output of the machine, painting a picture of the intricate interdependency within the system. Furthermore, every update to the rotor position angle induces a corresponding shift in the angular speed, highlighting the delicate balance within these dynamics.

Crucially, when we employ the Integral Finite Control Set Model Predictive Control (I-FCS-MPC) approach, we observe a superior level of control over these dynamics when compared to the Finite Control Set Model Predictive Control (FCS-MPC), Gravitational Search Algorithm (GSA), and Genetic Algorithm (GA) methods. This key observation underscores the outstanding efficacy of the I-FCS-MPC approach in optimizing both the rotor angle control and the overall performance of the induction motor drive, thereby proving it to be a preferred strategy for motor control.

IV.3. COMPARISON OF PROPOSED CONTROLLERS

The simulation of FCS-MPC, I-FCS-MPC, GA and GSA optimized models is implemented with a sampling time of 80 microseconds. Two main factors that determine the characteristic results of the predictive controllers are the sampling time and an integral gain constant *Kd* and *Kq*. The integral gain is only applicable to the I-FCS-MPC method. At higher values of the integral gains, the current curves will overshoot in steady state with good performance. If we keep the integral gain low, dynamic overshoot can be compensated. Here the value of the integral profits is assumed to be 0.1. The sampling time does not have a large impact on dynamic performance. Its effect mainly concerns the steady state ripple. With a higher sampling time, the ripple is larger and therefore it is necessary to shorten the sampling time. However, the computing effort and switching losses of the inverter limit the sampling time to fall below a certain value. Therefore, a compromise is made between the allowable ripple and the computing time and the switching loss.

Table 5: Absolute Current Error.

	Absolute Current Error (in Amp)	
Control Technique	$\lvert I_{dRef} - I_{dMeas} \rvert$	$\lvert I_{qRef} - I_{qMeas} \rvert$
FCS-MPC	0.05226	0.06012
I-FCS-MPC	0.01641	0.02693
GA	0.44594	0.37549
GSA	0.36649	1.07919

Source: Authors, (2025).

From the obtained characteristics of currents and torque by the simulated control algorithms the responses of d and q axis current can be specified. As discussed earlier the ripples contents are observed to be significantly less in case of predictive controllers as compared to GA & GSA methods. Also it can be clearly demonstrated from Table 5 regarding the absolute current errors measured by different control techniques applied. Integral FCS scheme inherently performs superior to other intelligent techniques such as GA & GSA.

IV. CONCLUSIONS

The utility of induction motor drives in various industries such as traction, process, manufacturing and mining is significant. They play a central role in these areas due to their integral role in the development of electromagnetic torque and the dynamics of the converter-fed voltage. While there are several methods for speed and torque control, such as traditional PI, PID and hysteresis controllers, the Finite Control Set Model Predictive Control (FCS-MPC) method has a significant improvement in handling non-linear loads due to its predictive properties shown. This already promising method has been further improved with the implementation of the Gravitational Search Algorithm (GSA) and Genetic Algorithm (GA), adding another dimension to the study of the dynamics of 3-phase induction motors (IM). By adjusting the reference current in the q-axis and the reference load torque as step functions, we can observe the dynamic behavior of the 3-phase IM in more detail.

Although FCS-MPC, GSA and GA have shown notable strengths in IM control, Integral Finite Control Set Model

Predictive Control (IFCS-MPC) has shown superior performance in several aspects. With its similar control strategy to FCS-MPC, IFCS-MPC inherently reduces steady-state errors, improves slew rates, and provides superior trajectories with respect to the step input signal. Although the velocity responses of FCS-MPC and IFCS-MPC are similar, IFCS-MPC has fewer waves compared to FCS-MPC. The adaptive and flexible nature of MPC methods makes these controllers superior options in the modern control landscape. With just a few changes, IFCS-MPC outperforms GSA and GA, cementing its place as the preferred choice for modern control systems. Extending this predictive control approach can potentially revolutionize applications in electric vehicles, FACTS devices, and various energy system controls.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Shaswat Chirantan, Bibhuti Bhusan Pati
Methodology: Shaswat Chirantan, Bibhuti Bhusan Pati
Investigation: Shaswat Chirantan, Bibhuti Bhusan Pati
Discussion of results: Shaswat Chirantan, Bibhuti Bhusan Pati
Writing – Original Draft: Shaswat Chirantan
Writing – Review and Editing: Shaswat Chirantan, Bibhuti Bhusan Pati
Resources: Shaswat Chirantan, Bibhuti Bhusan Pati
Supervision: Shaswat Chirantan, Bibhuti Bhusan Pati
Approval of the final text: Shaswat Chirantan, Bibhuti Bhusan Pati

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THE INFLUENCE OF THE GEOMETRIC FEATURES OF PROCESSED SURFACES ON CONTACT INTERACTION AND PROCESS PERFORMANCE DURING MACHINING WITH ELASTIC POLYMER-ABRASIVE WHEELS

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ABSTRACT

The automation of finishing and deburring operations remains a highly relevant task for modern mechanical engineering. This article examines the study of the influence of the specifics of contact interaction between various polymer-abrasive wheels on the productivity of the machining process in order to determine the relationship between the geometric shape of the processed surface and the productivity of the processing process. For theoretical calculations and experimental studies, elastic polymer-abrasive discs from 3M, models FS-WL, DB-WL, and CF-FB were used. The experimental research was conducted using a modern robotic complex based on the KUKA KR 210 R2700 EXTRA industrial robot. Interaction schemes of wheels with different surfaces are considered, and formulas are determined for each of them that allow calculating the average deformation and the length of the contact area. The effect of the average deformation and length of the contact zone on the efficiency of the treatment process is proven. These results should be taken into account when optimizing the operations under consideration, as well as when designing technological processes for finishing parts using elastic polymer-abrasive tools.

I. INTRODUCTION

At present, the role of transport in the Russian economy is very significant. This is due to the volume of passenger, cargo, and baggage transportation in Russia, the longest country on Earth. Transport is a crucial element in ensuring the welfare of both the state and its population, making the development of a medium-haul narrow-body aircraft an important direction for the transport engineering industry in the Russian Federation.

The MC-21 aircraft (Figure 1) belongs to the family of modern Russian mainline airliners developed by the Yakovlev Corporation under the framework of the Russian Federal Government program “Development of the Aviation Industry for the period 2013-2025.”

The MC-21-300 aircraft modification has a seating capacity ranging from 163 to 211 passengers. It is designed for the most popular segment of the passenger transportation market in the Russian Federation and boasts the largest cabin width and aisle width in its class. The MC-21 fully meets high international standards and industry requirements in terms of safety.

Flight performance characteristics	
Aircraft length, m	42,3
Wingspan, m	35,9
Aircraft height, m	11,5
Cabin width, m	3,81
Fuselage width, m	4,06
Maximum takeoff weight, kg	79 250
Maximum landing weight, kg	69 100
Maximum commercial load, kg	22 600
Maximum fuel capacity, kg	20 400
Maximum range in two-class configuration, km	5 900

Figure 1: General appearance and flight performance characteristics of the MC-21-300 aircraft.
Source: Authors, (2025).

An analysis of the nomenclature of fuselage parts of this aircraft showed that it contains more than 500 different parts made of aluminum and titanium alloys, on which finishing and polishing operations are carried out.

Currently, the share of manual labor involved in performing these operations remains significant, negatively affecting labor productivity and, consequently, the cost of the final product.

Almost all structural parts of the aircraft made of aluminum alloys require smoothing to reduce roughness to required values. The need for this operation often arises at transition points, when changing the feed direction, or when processing curved surfaces because the required surface roughness specified in the drawings is not achieved. It should be noted that the dimensions of these parts reach 500...2000 mm or more, and it is advisable to perform their processing in a fixed and oriented position. Examples include stringers, rims, sections of skin between frames, hull skin sections, profiles, etc. (Figure 2).

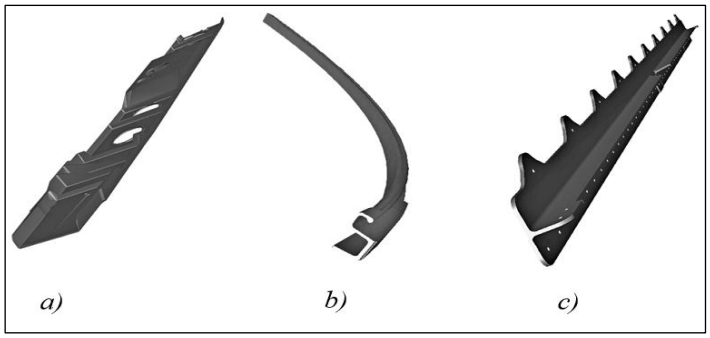

Figure 2: Examples of complex-profile, large-sized aircraft frame parts: a) stringer; b) rim; c) profile.
Source: Authors, (2025).

It should be noted that when using rigid tools, it is difficult to smooth a thin surface layer to reduce roughness (especially for parts made of aluminum alloys, widely used in aerospace construction) due to the possibility of removing a certain amount of material and compromising the required dimensional accuracy.

Methods of bulk vibration and magnetic-abrasive processing, as well as other well-known methods, are very effective and actively applied for the finish processing of metal parts with overall dimensions up to 300 mm [1-3]. However, applying these methods to large-scale and long-length parts shown in Figure 2 is economically impractical since they require bulky and expensive equipment, as well as extensive preparatory and concluding work.

Based on the above, it can be concluded that the most promising approach capable of effectively addressing these issues related to ensuring the quality of finish processing for large-scale, complex-profiled, and long-length parts considering their size and design features, is processing with polymer-abrasive wheels bonded with non-woven materials and brushes (radial and end-face), which possess high flexibility. A similar situation is observed in other areas of mechanical engineering production.

Thus, there exists a serious technological challenge associated with the necessity to automate finishing and deburring operations in serial production environments.

Numerous works [4-13] have been dedicated to the topics of contact interaction, process efficiency, formation of the surface layer, and the quality of the processed surface in various types of mechanical processing. Currently, attempts have been made to automate these technological operations using cutting tools [14], [15] and flap discs [16],[17]. However, these well-known technologies and recommendations are difficult to apply when processing parts made from aluminum alloys where it is necessary to smooth a thin surface layer. This is especially true for shaped surfaces, where the use of absolutely rigid tools or flexible tools with relatively high rigidity (such as flap discs) leads to a high percentage of defects and significant economic losses for the production.

II. MATERIALS AND METHODS

One of the most promising directions capable of efficiently addressing these problems is processing with polymer-abrasive wheels with nonwoven bonding and solid-bristle brushes (both radial and end-facing), which exhibit high flexibility. At present, the processing with such tools is insufficiently studied, and corresponding theoretical and experimental investigations to determine process efficiency indicators and the quality of processed surfaces in relation to the specifics of contact interactions between these tools and various surfaces and geometrical features of the parts being processed are lacking. To make a scientifically sound choice of flexible polymer-abrasive tools and processing regimes, knowledge about their influence on process efficiency and the quality of the surface layer taking into account the geometrical peculiarities of the surfaces being processed is essential.

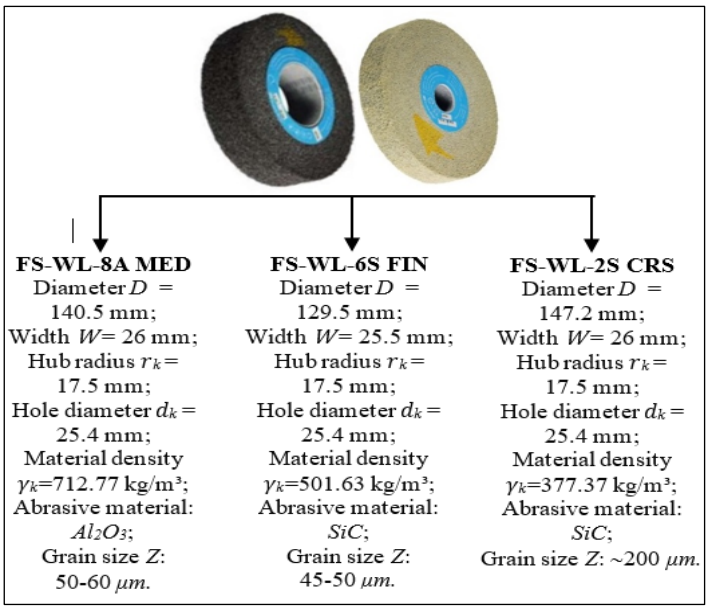

Figure 3: Molded wheels brand FS-WL.
Source: Authors, (2025).

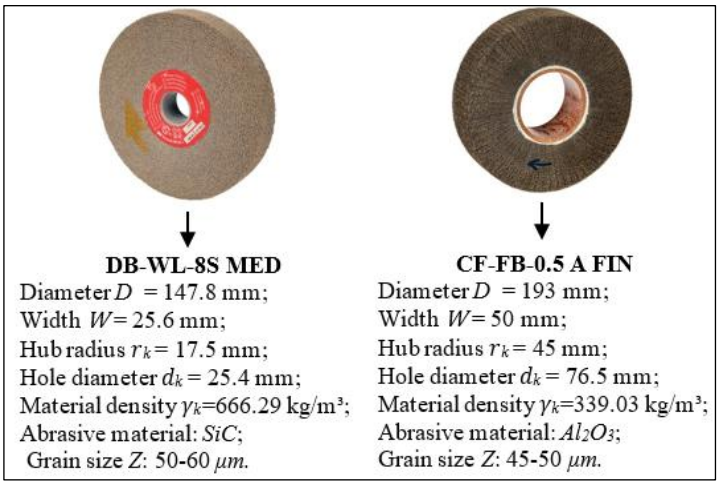

Figure 4: Molded wheel brand DB-WL and flexible wheel consisting of lamellae brand CF-FB.
Source: Authors, (2025).

The experimental part of this work was carried out using elastic polymer-abrasive wheels from the company 3M, shown in Figures 3-4. These wheels are made of non-woven abrasive material Scotch-Brite™.

III. RESULTS AND DISCUSSIONS

Features of contact interaction between elastic polymer-abrasive tools and processed surfaces

Analysis of the designs of MC-21 aircraft frame parts allowed us to identify three variants that determine the features of tool-part contact interaction: contact with a flat surface, as well as contact with surfaces rounded along an external radius and internal radius. For a given circle deformation ΔY in all cases of circle contact with different surfaces (flat, rounded along the outer radius, rounded along the inner radius), the angle α (Figures 5, 6, 7) will be determined as:

$$\cos\alpha = 1 - \frac{\Delta Y}{R}$$

In the case of contact interaction between an elastic polymer-abrasive wheel and a flat surface: $\Delta Y = \Delta Y_w$.

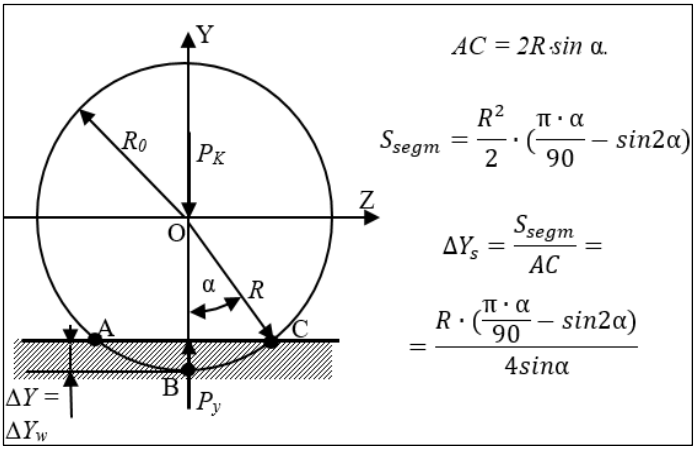

Figure 5: Interaction scheme with a flat surface.
Source: Authors, (2025).

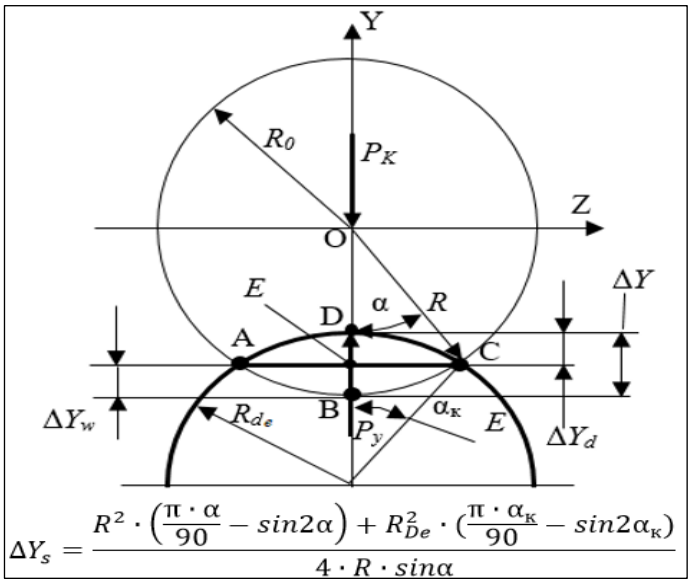

Figure 6: Interaction scheme with a surface rounded along the outer radius.
Source: Authors, (2025).

In Figure 5: S_{segm} is the area of segment ABC; ΔY_w is the average weighted deformation of the circle. The angle α here is in degrees.

For the case of contact between the circle and the surface rounded along the outer radius (Figure 6):

$$\Delta Y = \Delta Y_w + \Delta Y_d$$

For the case of contact between the circle and the surface rounded along the inner radius (Figure 7):

$$\Delta Y = \Delta Y_w - \Delta Y_d$$

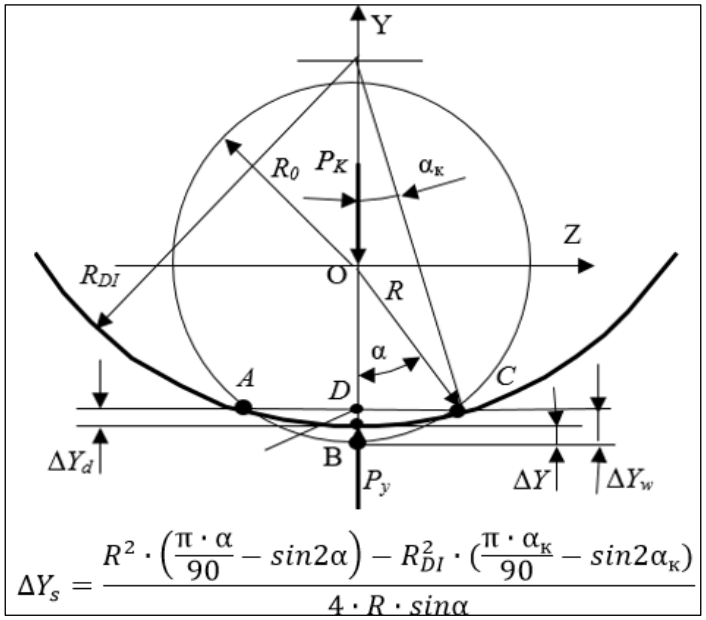

Figure 7: Interaction scheme with a surface rounded along the inner radius.
Source: Authors, (2025).

The length of the contact zone between the wheel and the workpiece surface

The length of the contact zone between the wheel and the workpiece surface depends on the specified wheel deformation ΔY and the geometric shape of the workpiece surface.

For the case of contact between the wheel and a flat surface *(see Figure 5)*, the length of the contact zone for a given wheel deformation ΔY is calculated using the formula:

$$L_c = 2\sqrt{\Delta Y \cdot R - \Delta Y^2} \quad (1)$$

For the case of contact between the wheel and the surface rounded along the outer radius *(see Figure 6):*

$$L_c = \alpha_k \cdot R_{de} \quad (2)$$

where $\alpha_к$ is the contact angle between the part and the wheel in radians, defined by the condition that $\Delta Y = \Delta Y_w + \Delta Y_d$, since $\Delta Y_w \cdot R = \Delta Y_d \cdot R_{de}$, and $\Delta Y_d = R_{de} \cdot (1 - cos\ \alpha_к/2)$.

After transformation:

$$cos\frac{\alpha_к}{2} = 1 - \Delta Y \cdot \frac{R}{(R_{de}+R) \cdot R_{de}},$$

where R – is the radius of the elastic polymer-abrasive wheel, mm; R_{de} – is the rounding radius of the workpiece surface, mm.

For the case of contact between the wheel and the surface rounded along the inner radius (see Figure 7):

$$L_c = \alpha_k \cdot R_{DI}\,, \tag{3}$$

where $cos\frac{\alpha_к}{2} = 1 - \Delta Y \cdot \frac{R}{(R_{DI}-R)\cdot R_{DI}}$.

Determination of the processing performance using elastic polymer-abrasive wheels in relation to the geometrical characteristics of the machined surfaces

Material removal during the studied processing method occurs through the interaction of abrasive grains from the elastic polymer-abrasive wheel with the workpiece surface. It includes both the volume of material displaced in the form of chips and the material destroyed due to repeated plastic and elastic deformation (poly-deformation), which results from numerous overlapping impacts of the abrasive particles.

It is known that the volume of elastically and plastically deformed material is negligible compared to the volumes of chips.

Therefore, the formula for material removal per unit area per unit time can be written as follows:

$$Q = W \cdot l_{ws} \cdot Q_v \cdot T \cdot n, \tag{4}$$

where: W – width of processing, mm; l_{ws} – length of the workpiece surface, mm; n – rotational speed of the wheel, rpm; T – processing time for length l_{ws}, min.:

$$T = \frac{l_{ws}}{F_R}\,, \tag{5}$$

where F_R – longitudinal feed rate, mm/min; Q_v – volume of material removed by the elastic polymer-abrasive wheel per single revolution per unit width (1 mm) when moving into contact with the workpiece over a distance of 1 mm.

$$Q_v = C_S \cdot N_g \cdot 2\pi \cdot R \cdot L_c\,, \tag{6}$$

where: C_S – cross-sectional area of the chip on a single grain; N_g – number of grains of the elastic polymer-abrasive wheel in contact on an area of 1 mm²; L_c– length of the contact zone at a given wheel deformation ΔY, which depends on the geometric shape of the workpiece surface (see equations (1-3)); R – radius of the wheel, mm.

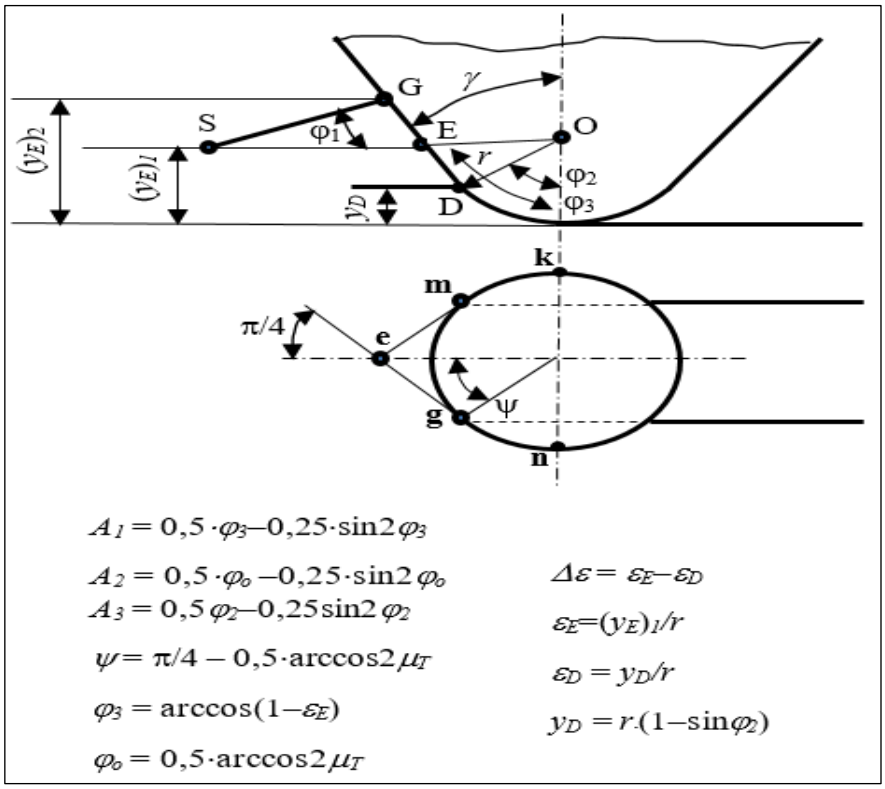

Figure 8: Interaction of a single-grain model with the workpiece surface.
Source: Authors, (2025).

The cross-sectional area of the chip on a single grain (*Cs*) and the number of grains of the elastic polymer-abrasive wheel in contact on an area of 1 mm² (*Ng*), which need to be determined for calculating the material removal per unit area per unit time, are calculated taking into account the specific physical and mechanical properties of the thin near-surface layer of the material, and the determination of micro-relief parameters of real elastic polymer-abrasive wheels according to a specially developed methodology [18]. When a grain penetrates the surface at an angle, a bulge forms ahead of it (Figure 8), which under certain conditions may turn into a chip. Plastically pushed aside material flows around the grain without separating from the main mass, forming a buildup on its sides.

In Figure 8, the following notations are used: $(y_E)_1$ – depth of penetration of the elastic polymer-abrasive wheel grain; *mg* – section where chip formation occurs; *D* – point where the spherical part transitions into the conical part; *mk* and *gn* – sections where, upon movement of the grain, the material is plastically pushed aside to form a build-up. Angles φ_2, φ_3 and φ_o are in radians.

Cross-sectional area of the chip on a single grain:

$$C_S = 2r^2 \cdot sin\psi \cdot (A_1 - A_2), \text{ when } (y_E)_1 \le y_D; \tag{7}$$

$$C_S = 2r^2 \cdot sin\psi \cdot [A_3 + A_2 + \Delta\varepsilon \cdot (0{,}5 \cdot \Delta\varepsilon \cdot ctg\varphi_2 + sin\varphi_2)], \text{ when } (y_E)_1 > y_D, \tag{8}$$

where r is the radius of curvature of the abrasive grain throughout the entire cutting microrelief, and ψ is the angle of the stalled section on a spherical abrasive grain.
After transformations, we obtain:

$$C_S = 0{,}864 \cdot r^2 \cdot [0{,}5\varphi_3 + 0{,}25 sin2\varphi_3 - 0{,}5617], \quad (9)$$

when $(y_E)_1 \leq y_D$;

$$C_S = 0{,}864 \cdot r^2 \cdot \left[0{,}5 \left(\frac{(y_E)_1}{r}\right)^2 + 0{,}414 \left(\frac{(y_E)_1}{r}\right) - 0{,}1642\right], \quad (10)$$

when $(y_E)_1 > y_D$,

Here $(y_E)_1$– the expected value of the penetration depth of plastically deforming material protrusions of grains.

To determine $(y_E)_1$, the dependencies of the cutting force components for a single grain are used. These issues are discussed in more detail in works [19], [20]. It should be noted that when dealing with small depths of penetration of the cutting microrelief during processing with elastic polymer-abrasive wheels, it is virtually impossible to take into account all factors related to the constantly changing microgeometry due to tool wear and self-sharpening. In light of this, for elastic polymer-abrasive wheels, the decision was made to experimentally determine the actual radius r_1 based on the level of convergence γ_k, and consequently, on the processing parameters — ΔY, V, and F_R. The experimentally obtained dependence of the radius of curvature of the grain vertices on the treatment modes (ΔY, V and F_R) takes the form:

$$r_1 = a_1 \cdot \Delta Y^2 + a_2 \cdot V^2 + a_3 \cdot F_R{}^2 + a_4 \cdot \Delta Y + a_5 \cdot V + a_6 \cdot F_R + a_7 \cdot \Delta Y \cdot V + a_8 \cdot \Delta Y \cdot F_R + a_9 \cdot V \cdot F_R + a_{10} \cdot \Delta Y \cdot V \cdot F_R + a_{11}. \quad (11)$$

The values of the coefficients a_1 through a_{10} and the free term a_{11} for equation (11) are given in Table 1. The cutting speeds V are in m/s, wheel deformation ΔY is in mm, and feed rate F_R is in m/min.

Thus, in equations (9) and (10), one should assume: $r = r_1$.
To confirm the adequacy of the developed theoretical propositions, corresponding experimental studies were conducted. In these experiments, elastic polymer-abrasive wheels from 3M, shown in Figures 3–4, were used.

The results of calculating the processing productivity Q according to formula (4), as well as the contact length L_c according to formulas (1-3) for various wheels, are presented in Tables 2-6. As an example, cases of wheel contact with a flat surface, a surface rounded by the outer radius R_{de}=120 mm, and a surface rounded by the inner radius R_{DI}=120 mm are considered.

Table 1: Values of coefficients and free term in formula (11).

Coefficient	Wheels brand FS-WL			Wheel brand DB-WL 8S MED	Wheel brand CF-FB 0,5A FIN
	8A MED	6S FIN	2S CRS		
a_1	$6{,}01 \cdot 10^{-4}$	$5{,}503 \cdot 10^{-3}$	$6{,}448 \cdot 10^{-4}$	$4{,}99 \cdot 10^{-5}$	$3{,}599 \cdot 10^{-5}$
a_2	–	$5{,}56 \cdot 10^{-9}$	$1{,}389 \cdot 10^{-9}$	–	–
a_3	$-1{,}39 \cdot 10^{-8}$	$-1{,}1 \cdot 10^{-9}$	–	$-1{,}01 \cdot 10^{-8}$	$-2{,}5 \cdot 10^{-9}$
a_4	$4{,}002 \cdot 10^{-3}$	–0,01445	$1{,}488 \cdot 10^{-4}$	$3{,}99 \cdot 10^{-3}$	$9{,}005 \cdot 10^{-5}$
a_5	–	$8{,}331 \cdot 10^{-7}$	$8{,}333 \cdot 10^{-7}$	$3{,}332 \cdot 10^{-7}$	$1{,}667 \cdot 10^{-8}$
a_6	$-1{,}51 \cdot 10^{-6}$	$-4{,}98 \cdot 10^{-8}$	–	$-1{,}01 \cdot 10^{-6}$	$-4{,}99 \cdot 10^{-8}$
a_7	–	$1{,}167 \cdot 10^{-9}$	$1{,}167 \cdot 10^{-9}$	–	–
a_8	$4{,}995 \cdot 10^{-7}$	$-5{,}01 \cdot 10^{-6}$	–	$4{,}99 \cdot 10^{-7}$	$2{,}501 \cdot 10^{-8}$
a_9	–	$6{,}665 \cdot 10^{-9}$	–	–	–
a_{10}	–	$1{,}66 \cdot 10^{-11}$	–	–	–
a_{11}	$1{,}404 \cdot 10^{-3}$	0,0147	$2{,}01 \cdot 10^{-4}$	$-1{,}29 \cdot 10^{-3}$	$3{,}004 \cdot 10^{-5}$

Source: Authors, (2025).

Table 2: Results of calculating contact length L_c and process productivity Q when processing surfaces with an elastic polymer-abrasive wheel FS-WL 8A MED.

V, m/min	F_R, mm/min	ΔY, mm	Flat surface		Surface rounded along the outer radius R_{de}=120 mm	
			L_c, mm (1)	Q, µm/min (4)	L_c, mm (2)	Q, µm/min (4)
220,7	130	1,5	28,88	52,94	23,068	50,881
441,4				87,35		80,147
551,7				101,11		92,569
706,2				101,44		97,668
441,4	130	0,5	16,733	25,89	13,315	23,14
		1,0	23,622	58,14	18,832	55,98
		1,5	28,88	87,35	23,068	80,147
		2,0	33,287	120,1	26,64	101,86
441,4	42	1,5	28,88	27,39	23,068	19,45
	130			87,35		80,147
	255			207,82		174,12
	395			278,17		223,57
V, m/min	F_R, mm/min	ΔY, mm	Surface rounded along the inner radius R_{DI}=120 mm			
			L_c, mm (3)		Q, µm/min (4)	
220,7	130	1,5	45,159		62,4	
441,4					134,76	
551,7					158,11	
706,2					169,62	
441,4	130	0,5	26,047		34,19	
		1,0	36,854		65,56	
		1,5	45,159		134,76	
		2,0	52,171		171,12	
441,4	42	1,5	45,159		40,12	
	130				134,76	
	255				256,55	
	395				377,12	

Source: Authors, (2025).

Table 3: Results of calculating contact length L_c and process productivity Q when processing surfaces with an elastic polymer-abrasive wheel FS-WL 6S FIN.

V, m/min	F_R, mm/min	ΔY, mm	Flat surface		Surface rounded along the outer radius R_{de}=120 mm	
			L_c, mm (1)	Q, µm/min (4)	L_c, mm (2)	Q, µm/min (4)
203,4	130	1,5	27,713	5,075	22,473	4,975
406,8				7,446		7,120
508,5				8,45		8,147
650,9				8,665		8,415
406,8	130	0,5	16,062	1,456	12,972	1,411
		1,0	22,672	3,62	18,347	3,15
		1,5	27,713	7,446	22,473	7,120
		2,0	31,937	10,443	25,953	9,812
406,8	42	1,5	27,713	3,937	22,473	3,737
	130			7,446		7,120
	255			11,889		10,802
	395			16,105		15,455
V, m/min	F_R, mm/min	ΔY, mm	Surface rounded along the inner radius R_{DI}=120 mm			
			L_c, mm (3)		Q, µm/min (4)	
203,4	130	1,5	41,131		6,274	
406,8					10,567	
508,5					12,642	
650,9					13,046	
406,8	130	0,5	23,727		1,921	
		1,0	33,569		4,971	
		1,5	41,131		10,567	
		2,0	47,513		16,264	
406,8	42	1,5	41,131		5,012	
	130				10,567	
	255				17,802	
	395				25,456	

Source: Authors, (2025).

Table 4: Results of calculating contact length L_c and process productivity Q when processing surfaces with an elastic polymer-abrasive wheel FS-WL 2S CRS.

V, m/ min	**F_R, mm/min**	**ΔY, mm**	**Flat surface**		**Surface rounded along the outer radius R_{de}=120 mm**	
			L_c, mm (1)	**Q, µm/ min (4)**	**L_c, mm (2)**	**Q, µm/ min (4)**
231,2	130	2,5	38,039	25,856	30,226	22,801
464,4				44,962		40,116
578,1				55,569		49,802
739,9				61,475		57,027
464,4	130	1,5	29,567	8,980	23,407	8,205
		2,0	34,082	21,746	27,031	19,106
		2,5	38,039	44,962	30,226	40,116
		3,0	41,598	77,591	33,115	69,997
464,4	42	2,5	38,039	39,006	30,226	37,201
	130			44,962		40,116
	255			54,522		50,964
	395			66,749		59,427
V, m/ min	**F_R, mm/min**	**ΔY, mm**	**Surface rounded along the inner radius R_{DI}=120 mm**			
			L_c, mm (3)	**Q, µm/ min (4)**		
231,2	130	2,5	61,871	34,124		
464,4				55,455		
578,1				70,229		
739,9				84,023		
464,4	130	1,5	47,872	12,101		
		2,0	55,309	29,789		
		2,5	61,871	55,455		
		3,0	67,814	97,199		
464,4	42	2,5	61,871	46,102		
	130			55,455		
	255			64,106		
	395			75,991		

Source: Authors, (2025).

Table 5: Results of calculating contact length L_k and process productivity Q when processing surfaces with an elastic polymer-abrasive wheel DB-WL 8S MED.

V, m/ min	**S, mm/min**	**ΔY, mm**	**Flat surface**		**Surface rounded along the outer radius R_{de}=120 mm**	
			L_k, mm (1)	**Q, µm/ min (4)**	**L_k, mm (2)**	**Q, µm/ min (4)**
232,2	130	1,5	29,628	61,010	23,436	56,809
464,3				103,11		94,996
580,4				123,98		111,28
742,9				126,97		118,21
464,4	130	0,5	17,164	38,225	13,527	32,882
		1,0	24,232	44,623	19,133	41,113
		1,5	29,628	103,11	23,436	94,996
		2,0	34,153	136,4	27,065	121,78
464,4	42	1,5	29,628	31,5	23,436	29,105
	130			103,11		94,996
	255			199,03		182,22
	395			299,93		256,11
V, m/ min	**S, mm/min**	**ΔY, mm**	**Surface rounded along the inner radius R_{DI}=120 mm**			
			L_k, mm (3)	**Q, µm/min (4)**		
232,2	130	1,5	48,126	70,104		
464,3				135,99		
580,4				154,41		
742,9				176,19		
464,4	130	0,5	27,755	50,447		
		1,0	39,273	66,601		
		1,5	48,126	135,99		
		2,0	55,602	178,64		
464,4	42	1,5	48,126	40,221		
	130			135,99		
	255			246,97		
	395			386,02		

Source: Authors, (2025).

Table 6: Results of calculating contact length L_k and process productivity Q when processing surfaces with an elastic polymer-abrasive wheel CF-FB-0,5AFIN.

V, m/ min	**F_R, mm/min**	**ΔY, mm**	**Flat surface**		**Surface rounded along the outer radius R_{de}=120 mm**	
			L_c, mm (1)	**Q, µm/ min (4)**	**L_c, mm (2)**	**Q, µm/min (4)**
303,2	130	4	54,991	25,858	41,423	17,155
606,3				40,183		29,881
757,9				45,221		34,789
970,1				45,906		39,102
606,3	130	3	47,749	32,534	35,862	21,199
		3,5	51,507	36,317	38,741	25,556
		4,0	54,991	40,183	41,423	29,881
		4,5	58,249	44,294	43,942	33,994
606,3	42	4	54,991	6,131	41,423	5,012
	130			40,183		29,881
	255			87,601		67,105
	395			134,17		102,29
V, m/ min	**F_R, mm/min**	**ΔY, mm**	**Surface rounded along the inner radius R_{DI}=120 mm**			
			L_c, mm (3)	**Q, µm/min (4)**		
303,2	130	4	127,05	38,111		
606,3				65,256		
757,9				76,101		
970,1				82,604		
606,3	130	3	109,7	39,186		
		3,5	118,67	52,349		
		4,0	127,05	65,256		
		4,5	134,96	78,777		
606,3	42	4	127,05	9,115		
	130			65,256		
	255			141,5		
	395			206,98		

Source: Authors, (2025).

Figure 9: Robotic complex based on KUKA KR 210 R2700 EXTRA industrial robot.
Source: Authors, (2025).

Experimental studies were carried out using a robotic complex based on the KUKA KR 210 R2700 EXTRA industrial robot (Figure 9). The process productivity was evaluated by weighing the samples before and after processing using Ohaus Discovery series analytical scales, model DV214C. The workpiece material used was the alloy V95pchT2, which is a typical representative of high-strength aluminum alloys widely used in aerospace engineering.

The processing schemes for surfaces rounded along the outer and inner radii are shown in Figures 10 and 11.

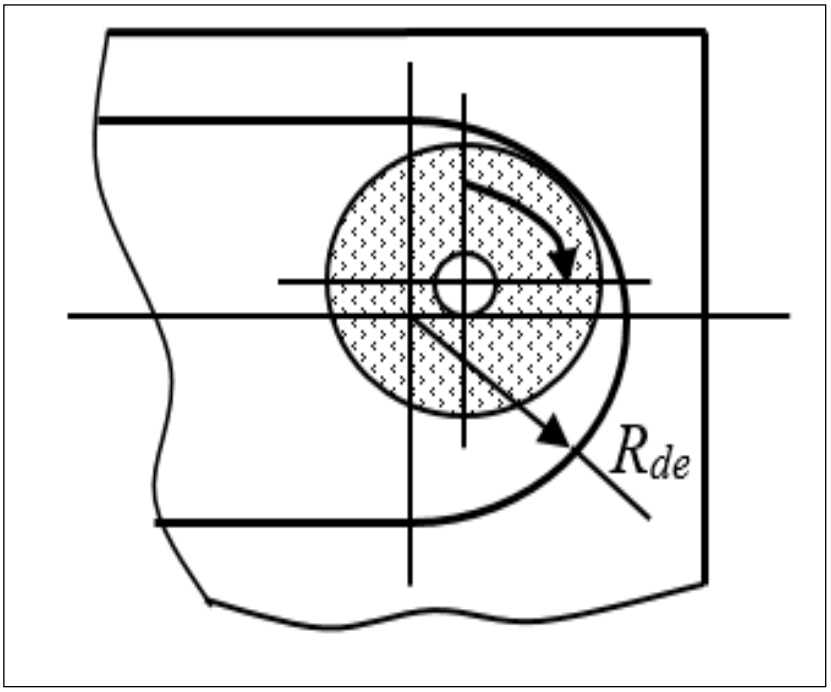

Figure 10: Scheme for processing a surface rounded along the inner radius.
Source: Authors, (2025).

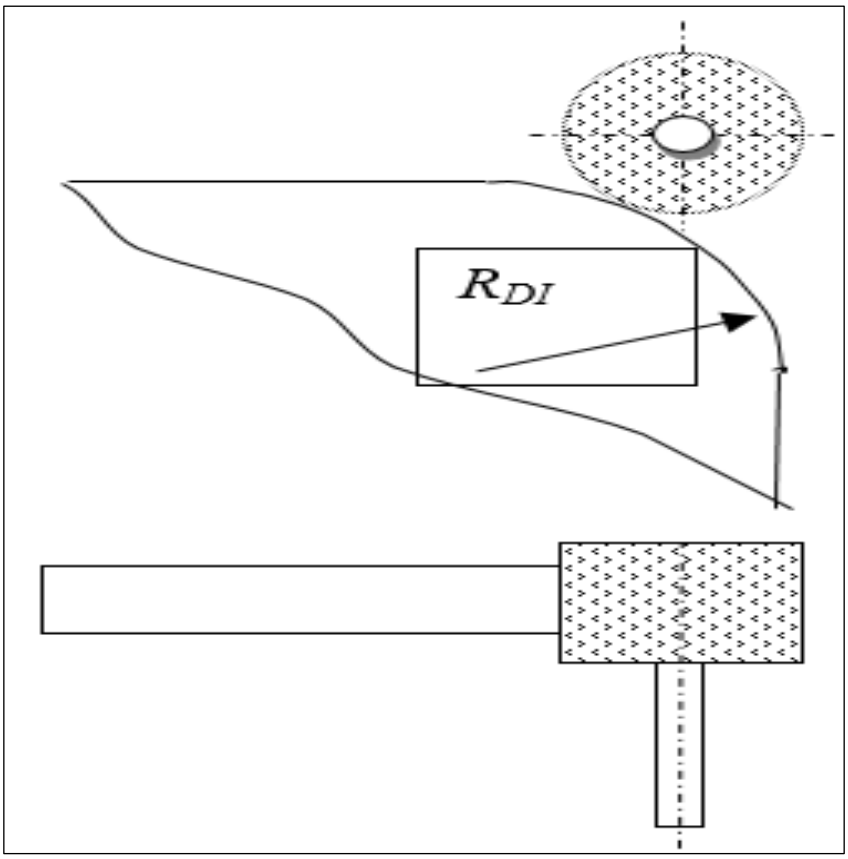

Figure 11: Scheme for processing a surface rounded along the outer radius using an elastic polymer-abrasive wheel.
Source: Authors, (2025).

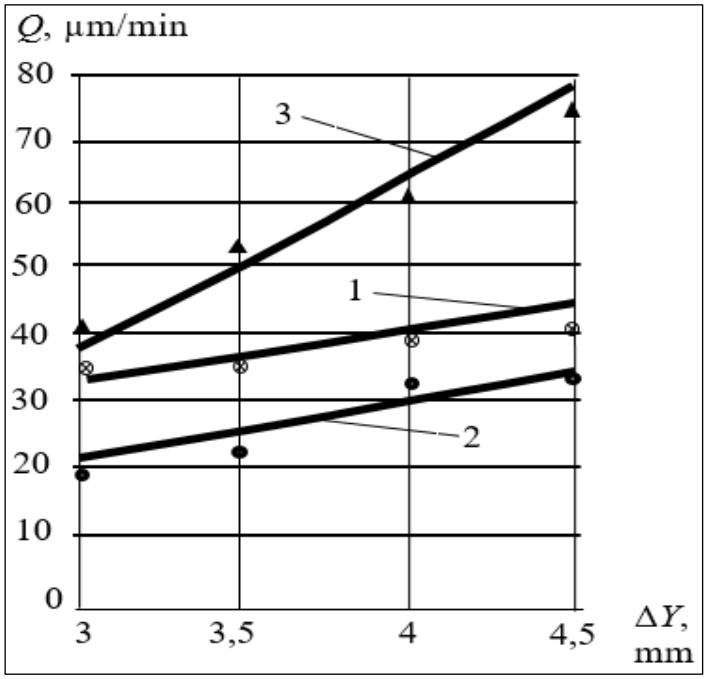

Figure 12: Dependence of the process productivity Q on deformation ΔY (V=606.3 m/min, F_R =130 mm/min) for the CF-FB-0.5 AFIN wheel.
Source: Authors, (2025).

1 – processing of a flat surface;
2 – processing of a surface rounded along the outer radius R_{de}=120 mm;
3 – processing of a surface rounded along the inner radius R_{DI}=120 mm.

As an example, Figures 12 and 13 show the dependences of the process productivity indicator Q on the tool deformation ΔY and the cutting speed V for one of the tools studied. In Figures 12 and 13, dots represent experimental data, while lines represent theoretically calculated data.

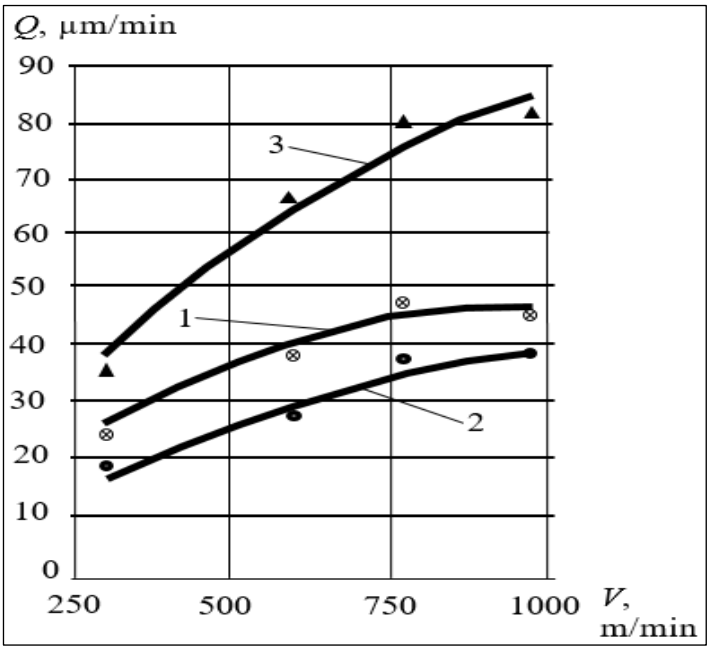

Figure 13: Dependence of the process productivity Q on the cutting speed V (ΔY= mm, F_R =130 mm/min) for the CF-FB-0.5 AFIN wheel.
Source: Authors, (2025).

1 – processing of a flat surface;
2 – processing of a surface rounded along the outer radius R_{de}=120 mm;
3 – processing of a surface rounded along the inner radius R_{DI}=120 mm.

IV. CONCLUSIONS

The flexible polymer-abrasive wheels investigated in this study can be effectively used for processing surfaces of parts made from aluminum alloys used in aerospace engineering. The research has revealed that the geometric features of the processed surfaces have a significant impact on the efficiency of the machining process. For instance, when processing a surface rounded along the outer radius R_{de}=120 mm, the process productivity decreases by 5...40%, whereas when processing a surface rounded along the inner radius R_{DI} =120 mm, the productivity increases by 10...80% depending on the type of flexible polymer-abrasive wheel and the processing conditions. This effect is explained by substantial changes in the contact area and, consequently, the number of active abrasive grains, as well as the cutting forces involved. These findings must be taken into consideration when designing technological operations for finishing parts with flexible polymer-abrasive tools.

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RESEARCH ARTICLE OPEN ACCESS

ENHANCED PERFORMANCE OF MICROSTRIP ANTENNA ARRAYS THROUGH CONCAVE MODIFICATIONS AND CUT-CORNER TECHNIQUES

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ABSTRACT

This paper presents the design and analysis of a high-performance 4×1 linear microstrip-fed antenna array optimized for wireless communication systems operating at 2.45 GHz. A novel concave-shaped modification is introduced on both the horizontal and vertical edges of the rectangular patch elements, significantly enhancing key performance metrics such as gain, impedance matching, and radiation efficiency. In addition, cut-corner techniques are applied to each patch element to minimize return loss and improve bandwidth, effectively addressing common limitations of traditional rectangular patch antennas, such as low gain and narrow bandwidth. Through rigorous simulations and physical prototyping, the proposed antenna array demonstrates a peak gain of 18 dB and a return loss of -33.82 dB at the target frequency. This makes it highly suitable for high-performance wireless applications, including WLAN, mobile communications, and smart transportation systems. The design not only improves antenna efficiency but is also cost-effective and simple to fabricate, making it ideal for mass production in modern communication systems.

I. INTRODUCTION

The manipulation of electromagnetic (EM) waves is critical for advancing modern technologies, such as sensing and biosensing devices [1], energy harvesting [2],[3], and communication systems. Simultaneously, the rapid growth of wireless communication technologies has heightened the demand for efficient, high-gain, and compact antenna systems, capable of supporting a wide range of applications [4],[5], from wireless local area networks (WLAN) to mobile and satellite communications. A key frequency band for these applications is 2.45 GHz, extensively used in Bluetooth, WLAN, and industrial, scientific, and medical (ISM) bands.

It is well-established that the use of substrate materials in radio frequency (RF) and microwave circuits, particularly printed circuit boards (PCBs), presents notable challenges [6]. Among various microstrip patch antenna (MPA) feeding techniques, the microstrip feed line is one of the most commonly employed [7]. The 2.45 GHz band is versatile, supporting applications such as

WLAN, multiple-input and multiple-output (MIMO) systems, Wi-Fi, Bluetooth, and ZigBee [8-10]. In this context, microstrip antennas have gained prominence due to their low profile, lightweight design, ease of fabrication, and compatibility with integrated circuit (IC) technologies. However, despite these advantages, conventional microstrip antennas face limitations, including low gain, narrow bandwidth, and surface wave excitation, which hinder their use in high-performance wireless communication systems.

To address these limitations, research has focused on optimizing microstrip antenna designs, particularly in array configurations, which offer enhanced directivity and gain. Array antennas are especially suitable for applications requiring precise radiation control. Although various geometries—such as circular, triangular, and elliptical-have been explored, the rectangular patch remains the most widely used due to its simplicity and ease of design [11]. Nevertheless, further performance enhancements are essential to meet the increasingly stringent demands of modern communication systems.

Several techniques have been developed to improve the performance of rectangular patch antennas, including careful substrate material selection, optimization of feed networks, and geometric modifications. Among these approaches, the introduction of concave-shaped forms and cut-corner techniques has shown significant promise in addressing the drawbacks of traditional designs. These modifications aim to enhance impedance matching, increase gain, and reduce return loss, ultimately boosting overall system efficiency [12-15].

In this work, we present a novel 4×1 linear microstrip-fed antenna array that incorporates concave-shaped forms on both the horizontal and vertical edges of the rectangular patch elements. This design is further refined by applying cut-corner techniques to the patch elements, which not only reduce return loss but also improve radiation performance. The primary objective of these modifications is to significantly enhance the antenna's gain and minimize return loss, making the array highly suitable for high-performance wireless applications.

The design process involved two key stages. First, the corporate feed network was optimized to ensure uniform power distribution across all patch elements. Then, concave-shaped forms and cut corners were applied to maximize the performance of each patch. Simulations were conducted using the High-Frequency Structure Simulator (HFSS), a widely used tool based on the finite element method (FEM) for antenna design and analysis. Following the simulations, a physical prototype was fabricated and tested in an anechoic chamber to validate the results.

The findings demonstrate that the proposed antenna array significantly outperforms conventional designs in both return loss and gain. The introduction of concave-shaped forms effectively reduced return loss, while the cut-corner technique further improved radiation efficiency and gain. The measured peak gain of 18 dB and return loss reduction to -33.82 dB validate the effectiveness of the proposed design for high-performance wireless systems operating at 2.45 GHz [16].

This paper is organized as follows. Section 2 provides a detailed description of the proposed antenna array design, including feed network optimization and geometric modifications. Section 3 presents the results and findings and their discussion, along with a comprehensive analysis of the antenna's performance in terms of return loss, gain, and radiation patterns. Finally, Section 4 concludes the paper with a summary of findings and future research directions.

II. MATERIALS AND METHODS

II.1 PROPOSED ANTENNA ARRAY DESIGN

This section provides a comprehensive overview of the design process for the proposed 4×1 linear microstrip-fed antenna array. The primary goal of this design was to create a compact yet high-performance antenna array, specifically tailored for wireless communication systems operating at the frequency of 2.45 GHz. To achieve this, the design focused on enhancing critical performance metrics such as gain and optimizing impedance matching. The approach employed several innovative modifications, including concave-shaped alterations to the edges of the rectangular patch elements and the implementation of cut-corner techniques. These modifications were strategically introduced to address the inherent drawbacks of conventional rectangular microstrip patch antennas, which often suffer from limited gain and bandwidth. By incorporating these geometric enhancements, the proposed design aims to improve overall efficiency and meet the demands of modern wireless systems.

II.2 SUBSTRATE AND PATCH DESIGN

The selection of an appropriate substrate is critical to determine the performance of the antenna array. The proposed antenna is designed on a Rogers R04350B substrate, which offers enhanced characteristics for high-frequency applications. This substrate has a relative dielectric constant (εr) of 3.48, a thickness of 1.52 mm, and a low loss tangent (δ = 0.004). These properties help to minimize dielectric losses, contributing to higher radiation efficiency and bandwidth performance [16],[17]. The substrate dimensions are 255mm × 123mm, as shown in Figure 1, which were carefully chosen to accommodate the array elements and provide sufficient surface area for the corporate feed network.

Each element of the array consists of a modified rectangular patch, designed to operate at the center frequency of 2.45 GHz. The dimensions of each patch are determined based on the resonant frequency, calculated using standard microstrip patch antenna design equations, as outlined in references [18-21]. The optimal geometrial design parameters for the antenna array are detailed in Table 1.

Table 1**:** Optimal dimensions of the proposed antenna array.

Parameters	**Values (mm)**	**Parameters**	**Values (mm)**
W	40.91	W_1	1.85
L	32.40	ΔW_0	3.8
g	1.72	ΔW_1	1.68
l	10.46	l_0	15.85
l_f	19.49	l_1	19
h	3.5	d	62
a	3	D	255
W_0	3,44	S	123

Source: Authors, (2025).

II.3 CORPORATE FEED NETWORK

The feed network is a crucial aspect of the antenna array design, as it ensures efficient power distribution among the array elements. The proposed array employs a corporate feed network, which provides equal phase and amplitude excitation to all four patch elements.This network is designed using T-junction power dividers and microstrip transmission lines, ensuring minimal power loss and high efficiency. The characteristic impedance of the main transmission line is Z0=50Ω, while the quarter-wave transformers, used to match the impedance between the transmission line and the

patch elements, have an impedance of Z1=70.7Ω.The feed network utilizes three symmetric T-junction power dividers with triangular notches of dimension ΔW1 = 1.68 mm to reduce unwanted reflections at junctions, which helps maintain impedance matching across the entire structure [22], [23]. The design ensures minimal radiation loss at the right-angled bends by introducing chamfered bends with dimensions ΔW0 = 3.8 mm, which smooths the current flow and prevents sharp turns that could lead to performance degradation [24-28].The corporate feed network is optimized to minimize return loss and achieve high directivity by ensuring that the separation distance between each patch element is approximately λ/2, which corresponds to 62 mm at the operating frequency of 2.45 GHz. This spacing is essential to reduce mutual coupling between the elements and achieve the desired radiation characteristics.

II.3 CONCAVE-SHAPED PATCH MODIFICATION

The proposed patch antenna design introduces concave-shaped geometrical modifications on both the horizontal and vertical edges of each radiating element in the antenna array. These concave features are incorporated with a depth of 3.5 mm, which was determined through parametric studies and simulations. The key objective of these modifications is to enhance the antenna's radiation characteristics, specifically improving its gain and directivity.

The concave shapes, as seen in the image, are implemented on all four sides of each patch element. These structural modifications influence the distribution of surface currents, which is crucial for better impedance matching and reduced surface wave excitation. Additionally, the four corners of each patch are truncated by a distance of 3 mm (denoted as a), a strategic alteration that helps to minimize return loss, further improving the directivity and gain of the antenna (FIgure 1).

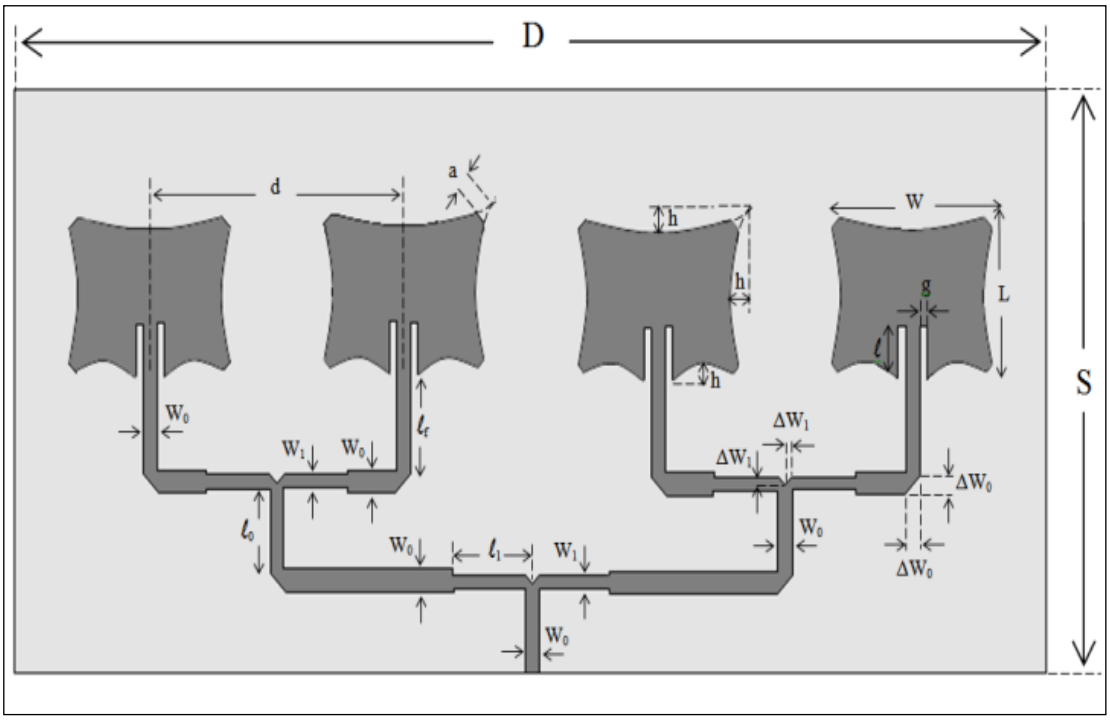

Figure 1: The geometry of the proposed linear microstrip-fed antenna array with four elements.
Source: Authors, (2025).

This concave shaping of the patch not only alters the current paths but also leads to a more focused radiation pattern. The result is a higher radiation efficiency by directing more of the radiated energy in the desired direction. The optimized depth of 3.5 mm was selected based on simulations using HFSS software, which demonstrated that this configuration provided the best balance between return loss and gain, ultimately yielding an antenna design with superior performance in terms of both impedance matching and radiation efficiency [15].

II.4 CUT-CORNER TECHNIQUE

In this configuration, each of the four corners of the rectangular patch elements is truncated by 3 mm. This alteration is aimed at improving impedance matching and reducing return loss, which in turn boosts the overall performance of the antenna.

The cut-corner technique plays a crucial role in increasing the bandwidth and minimizing the reflection coefficient (S11). By cutting the corners, the current distribution on the patch is more evenly spread, reducing unwanted resonances and reflections at the feed point. This leads to greater radiation efficiency and a broader operational bandwidth.

The effectiveness of the cut-corner technique was assessed by simulating three antenna configurations: a basic rectangular patch, a patch with concave-shaped modifications, and a patch incorporating both concave shapes and cut corners. Among these, the combination of concave shapes and cut corners produced the most notable improvement in return loss and impedance matching. Simulations showed a reduction in return loss to -29.90 dB at 2.62 GHz, while measured results indicated a further improved return loss of -33.82 dB at 2.65 GHz, confirming the design's effectiveness.

These dual modifications concave-shaped edges and cut corners work together to enhance impedance matching, increase bandwidth, and reduce the reflection coefficient. This combination results in more efficient radiation and overall better performance for the antenna array.

III. RESULTS AND DISCUSSIONS

III.1 SIMULATED AND MEASURED PERFORMANCE

The performance of the proposed antenna array was first analyzed through comprehensive simulations using Ansoft HFSS, a software based on the finite element method (FEM) as shown in Figure 2. These simulations evaluated critical parameters such as return loss, gain, and the radiation pattern, providing an in-depth understanding of the antenna's behavior and forming the basis for experimental validation.

Following the design optimization, a prototype of the antenna array was fabricated using standard PCB manufacturing techniques. The patch elements and feed network were etched onto a Rogers R04350B substrate, chosen for its superior dielectric properties, ideal for high-frequency applications. To ensure reliable signal transmission, a 50 Ω Sub Miniature version A (SMA) connector was integrated into the design.

The prototype was rigorously tested in an anechoic chamber as shown in Figure 3, which minimizes external interference and reflections. Key performance metrics, including return loss, gain, and radiation pattern, were measured to validate the antenna's real-world performance. Testing was conducted using an Agilent 8722ES vector network analyzer (VNA) to assess the S11 parameter, and the radiation pattern was mapped in the chamber.

The measured results closely aligned with the simulations, confirming the accuracy of the design. The antenna achieved a peak gain of 18 dB and a return loss of -33.82 dB at its operating frequency of 2.45 GHz. Additionally, the radiation pattern exhibited a well-defined main lobe with minimal side lobes, indicating strong directivity and low interference.

These findings demonstrate the effectiveness of the design enhancements, particularly the concave-shaped edges and cut-corner modifications, which significantly improved the antenna's gain, impedance matching, and overall radiation efficiency. The strong correlation between simulated and experimental results highlights the reliability of the design process and its practical applicability.

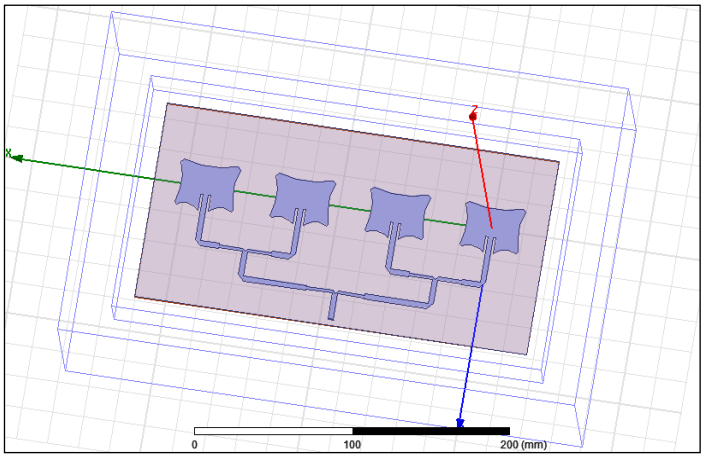

Figure 2: The layout of the proposed (4×1) linear microstrip patch antenna array in HFSS.
Source: Authors, (2025).

The investigated (4×1) linear microstrip patch antenna array was fabricated on thick Rogers R04350B of 1.52mm and permittivity of εr=3.48, with tangent loss of substrate tanδ=0.004. The substrate size is of (255mm×123mm). The return loss characteristic of the manufactured antenna array is measured with an Agilent 8722ES vectorial network analyzer (VNA) as shown in Figure 3a. The radiation pattern of the proposed antenna at the resonant frequency is measured in an anechoic chamber as shown in Figure 3b.

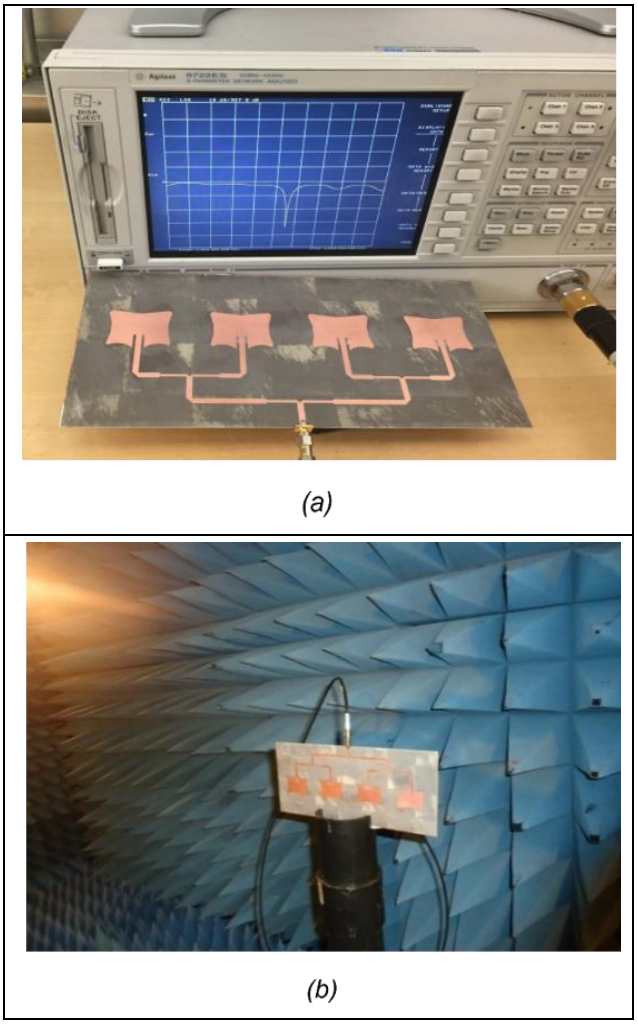

Figure 3: Photograph of the fabricated (4×1) array antenna prototype. (a) S11 parameter measurement protocol with the VNA. (b) Radiation pattern measurement in the anechoic chamber.
Source: Authors, (2025).

Figure 4 presents a comparative study of three different models of a linear (4×1) microstrip patch antenna array. All models are designed using a Rogers R04350B substrate and operate at a frequency of 2.45 GHz. These models explore the effects of geometric modifications on the antenna's performance, specifically return loss, gain, and radiation characteristics.

The first model, shown in Figure 4(a), features the basic structure of the antenna array with standard rectangular patch elements. This configuration serves as the foundational design for subsequent modifications. In Figure 4(b), the second model introduces a concave-shaped form on the patches. This modification, characterized by a depth hhh, is intended to improve the radiation characteristics of the array by altering the current distribution across the patch surface.

Finally, Figure 4(c) depicts the third model, which combines the concave-shaped form with cut corners, where each patch's four corners are truncated by 3 mm. This additional alteration is designed to enhance impedance matching, reduce return loss, and further increase the antenna's gain and directivity.

Each of these models demonstrates the progressive refinement of the antenna design, highlighting the impact of specific geometrical changes on the overall performance.

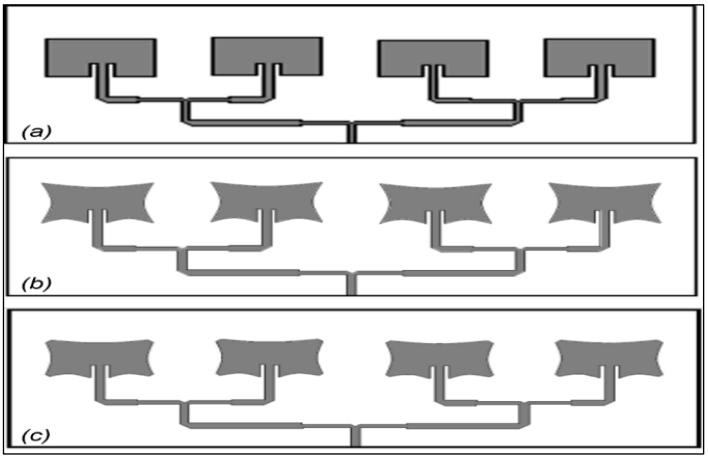

Figure 4: Linear (4×1) microstrip patch antenna array. (a) Basic structure. (b) Basic structure with concave-shaped form. (c) Basic structure with concave-shaped form and cut corners.
Source: Authors, (2025).

Figure 5 illustrates the return loss (S11) for three different microstrip patch antenna array structures presented earlier in Figure 4. The basic model (a) exhibits a simulated return loss of -22.43 dB at the operating frequency of 2.45 GHz. When a concave-shaped form with a depth of h = 3.5 mm is introduced in model (b), the return loss improves, reaching -26.42 dB at 2.56 GHz, reflecting a notable improvement of approximately 2.6 dB compared to the basic structure. Furthermore, the proposed model (c), which incorporates both the concave shape and additional modifications by cutting each corner by a distance of a = 3 mm, results in a significant enhancement of the return loss. The simulated S11 for model (c) achieves -29.90 dB at a frequency of 2.62 GHz.

Notably, the measured return loss for model (c), obtained using an Agilent network analyzer, aligns closely with the simulated results, achieving -33.82 dB at 2.65 GHz. The close agreement between the simulated and measured results for model (c) demonstrates the effectiveness of the concave design combined with corner cuts in further optimizing the antenna's performance. This enhanced return loss in both the simulation and measurement highlights the robustness of the proposed design for practical applications.

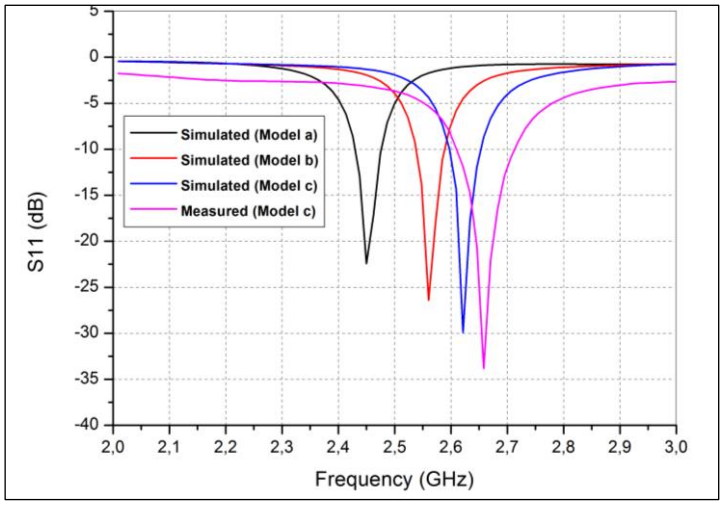

Figure 5: Return loss (S11) for the linear (4×1) microstrip patch antenna array structures. (a) Basic structure. (b) Basic structure with concave-shaped form. (c) Basic structure with concave-shaped form and cut corners.
Source: Authors, (2025).

To geometrically assess the impact of the concave-shaped form's depth (h) on the return loss and radiation pattern, Figure 6 presents the simulated S11 parameters for various values of h, ranging from 0 mm to 3.5 mm. The graph shows how increasing the concave depth progressively improves the antenna's return loss. Initially, with h = 0 mm (black curve), the return loss is -22.43 dB at the operating frequency of 2.45 GHz.

When the depth increases to h = 2.5 mm (red curve), the return loss improves to -23.84 dB. Further enhancements are observed at h = 3 mm (blue curve), where the return loss reaches -25.90 dB at 2.55 GHz. The most significant improvement occurs at h = 3.5 mm (purple curve), achieving a return loss of -26.42 dB at 2.56 GHz. This trend demonstrates that increasing the concave depth leads to a progressive reduction in return loss, improving the impedance matching at the target frequency.

These results emphasize the geometric influence of the concave depth on the antenna's performance, showing that deeper concave shapes lead to better return loss characteristics, which is crucial for optimal radiation pattern and overall antenna efficiency.

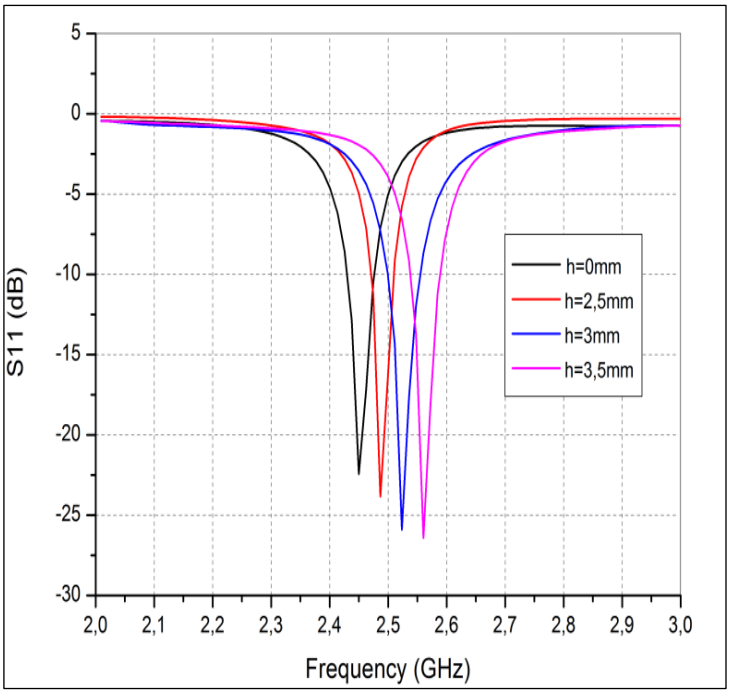

Figure 6: Effect of the concave-shaped form depth on the return loss.
Source: Authors, (2025).

Figure 7 presents the simulation results for the antenna's gain as a function of the angle θ (theta), for various concave-shaped form depths h, specifically 2.5 mm, 3 mm, and 3.5 mm. The plot illustrates a significant improvement in the antenna gain as the concave depth increases.

For a depth of h = 2.5 mm (black curve), the peak gain reaches 11.20 dB. Increasing the depth to h = 3 mm (red curve) enhances the gain to 14.97 dB, while a further increase to h = 3.5 mm (blue curve) results in a peak gain of 16.49 dB.

This trend demonstrates a clear improvement in gain as the concave depth increases, with the deepest concave shape providing the best performance. The graph also shows that the gain pattern becomes more uniform with increasing h, with reduced fluctuations, particularly around 0° and ±90°, leading to better directivity and overall antenna efficiency. These results confirm that optimizing the concave depth not only enhances return loss but also significantly improves the antenna's gain.

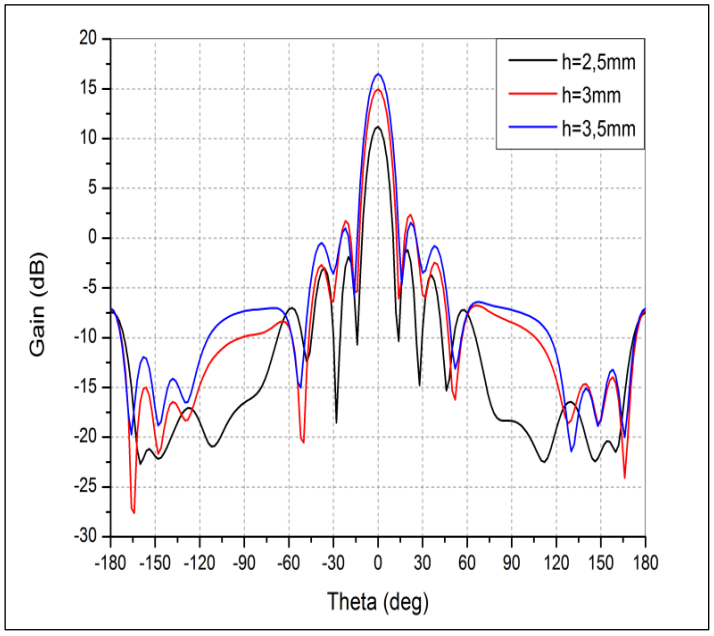

Figure 7: Influence of the concave-shaped form depth on the antenna array gain
Source: Authors, (2025).

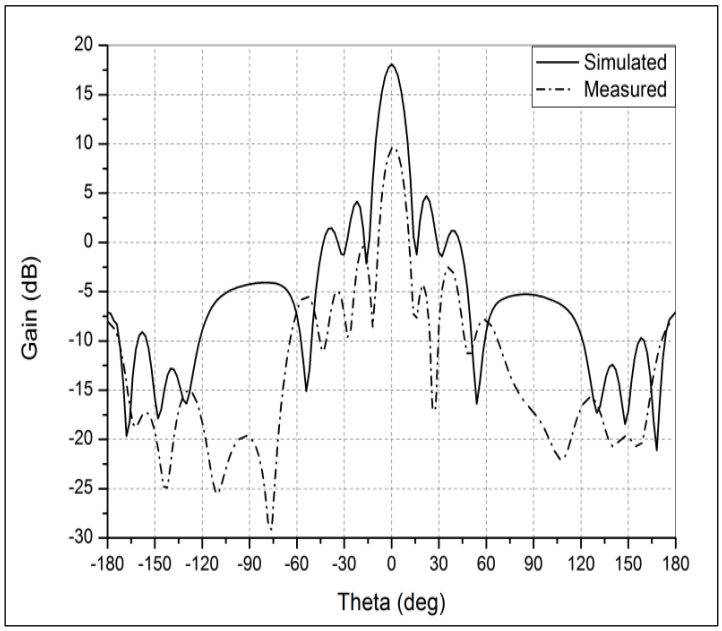

Figure 8: Simulated and measured E-plan gain of the proposed antenna array.
Source: Authors, (2025).

Measured and simulated E-plan gain of the manufactured final structure with the concave-shaped form of a depth h= 3.5mm and cut corners at 2.45 GHz are plotted in Figure 8. It can be noted that the measured gain is lower than that of the simulated model who achieves the best value of gain which is of 18.11dB, whereas for the measured result the E-plan gain is about 9.58dB.

The radiation patterns in E-plane and H-plane at 2.45 GHz of the proposed (4×1) linear patch antenna array for h= 2.5mm, h=3mm and h=3.5mm with cut corners are exhibited in Figure 9. It is observed that good radiation performances are achieved by increasing h from 2.5mm to 3.5mm and it can be noted that the cut of the four corners of each patch can indeed provide an increased gain and give advantages in term of side lobes level and main beam width.

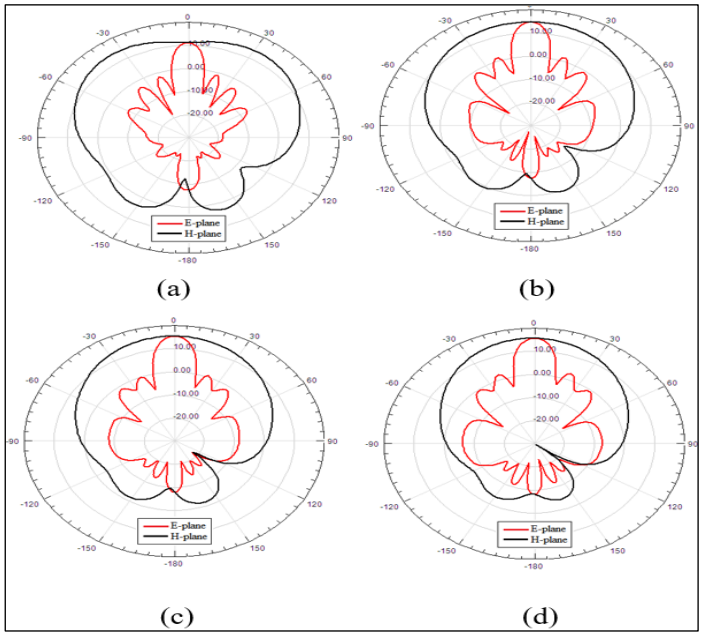

Figure 9: Radiation patterns at 2.45 GHz for the proposed linear patch antenna array. (a) h=2.5mm. (b) h=3mm. (c) h=3.5mm. (d) h=3.5mm and cut corners.
Source: Authors, (2025).

IV. CONCLUSIONS

In this paper, we introduced a novel microstrip-fed linear antenna array design, incorporating concave-shaped forms and cut corners to significantly improve its performance. The proposed design demonstrated substantial enhancements in key antenna characteristics, including return loss, gain, and radiation efficiency. Our approach, leveraging geometric modifications, provides a flexible and highly adaptable solution for optimizing antenna performance at 2.45 GHz, a crucial frequency for wireless communication systems. Both simulated and measured results confirm the effectiveness of the design modifications. The antenna array achieved a peak gain of 18 dB and a return loss of -33.82 dB, outperforming conventional rectangular patch antennas. The concave-shaped forms, in particular, proved effective in optimizing the current distribution, leading to improved gain and impedance matching. Meanwhile, the cut corners contributed to reducing return loss and improving bandwidth, addressing common limitations seen in traditional patch antennas. These design enhancements offer practical benefits for modern communication systems, including WLAN and mobile networks, where high gain and efficient radiation patterns are critical. Moreover, the progressive refinement of the design through simulations, followed by experimental validation, demonstrates the robustness of our methodology. The measured results closely aligned with simulations, showcasing the reliability of the proposed design process. This alignment between theoretical and practical performance reinforces the viability of the antenna for real-world applications.

In conclusion, the proposed microstrip antenna array with concave-shaped forms and cut corners provides a cost-effective, high-performance solution suitable for mass production. The design is simple to fabricate while achieving enhanced antenna characteristics that are crucial for a wide range of wireless applications, including smart transportation systems and mobile communications. Future work can explore further optimizations to extend the bandwidth and apply the design to other frequency ranges, ensuring.

V. AUTHOR'S CONTRIBUTION

Conceptualization: S. B, E.M, A.B, O.B
Methodology: E.M, A.B, O.B, A.R, M.G. A.D, I.T.
Investigation: E.M, A.B, O.B, A.R, M.G. A.D, I.T.
Discussion of results: S. B, E.M, A.B, O.B, A.R, M.G. A.D, I.T
Writing – Original Draft: S. B.
Writing – Review and Editing: E.M, A.B, O.B, A.R, A.D, I.T.
Resources: S. B.
Supervision: S. B, E.M.
Approval of the final text: S. B, E.M, A.B, O.B, A.R.

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RESEARCH ARTICLE OPEN ACCESS

SOLVING NON-BINARY CONSTRAINTS SATISFACTION PROBLEMS USING GHD AND RESTART

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ABSTRACT

The non-binary instances of the Constraint Satisfaction Problem (CSP) could be efficiently solved if their constraint hypergraphs have small generalized hypertree widths. Several algorithms based on Generalized Hypertree Decomposition (GHD) have been proposed in the literature to solve instances of CSPs. One of these algorithms, called Forward Checking based on Generalized Hypertree Decomposition (FC-GHD+NG+DR), combines the advantages of an enumerative search algorithm with those of Generalized Hypertree Decomposition. However, like all structural decomposition methods, FC-GHD+NG+DR depends on the order in which the clusters are processed. In this paper, we propose a new version of the FC-GHD+NG+DR algorithm with a restart technique that allows changing the order of the nodes of GHD to improve performance. The experiments carried out are very promising, particularly on the satisfiable instances where we achieved better results using the restart method in 52.63% of the modified Renault satisfiable benchmarks and an average time resolution of ≈ 0 for the normalized Pret and normalized Dubois benchmarks.

I. INTRODUCTION

Constraint Satisfaction Problems (CSPs) are a fundamental class of problems in artificial intelligence and operations research. They involve a set of variables, each associated with a domain of possible values, and a set of constraints that restrict the simultaneous assignment of these values. Solving CSPs requires finding an assignment that satisfies all constraints. These problems are widely applied in domains such as activity planning and scheduling problems [1] and allocation problem [2]. CSPs also play a pivotal role in computational complexity research, serving as a foundation for classifying the complexity of problems in algebraic and logical frameworks [3], [4].

Despite their importance, CSPs are inherently challenging due to their NP-complete nature, often requiring an exhaustive search of the solution space. The standard method for solving CSPs is backtracking, which systematically explores a search tree to find solutions. While backtracking guarantees correctness, its exponential time complexity in the worst case makes it impractical for large or complex problem instances.

To address these limitations, researchers have developed structural decomposition methods, which aim to divide a CSP into smaller, independent sub-problems. Techniques such as bounded fractional hypertree width [5] and hybrid width parameters [6] have proven effective in reducing computational complexity. Generalized Hypertree Decomposition (GHD)-based algorithms are particularly noteworthy, leveraging problem structure to guide the exploration of solution spaces [7-9]. Among these, the Forward Checking guided by GHD, FC-GHD algorithm has been widely studied. Extensions such as FC-GHD+NG (exploiting structural NoGoods) and FC-GHD+NG+DR (introducing dynamic subtree reordering) have significantly improved its performance [7]. Another promising strategies for enhancing CSP solvers is exploiting data mining techniques for compressing table constraints [10], the use of restart methods, which periodically restart the search process after a certain number of failures. These methods adaptively manage variable and node ordering, as shown in [11], where restart sequences were used to optimize the selection of heuristics.

Inspired by the success of FC-GHD+NG+DR, we propose the Restart-FC-GHD+NG+DR algorithm, which dynamically adjusts cluster orders based on the number of backtracks generated. This approach mitigates excessive backtracking,

reduces unnecessary exploration, and improves solver efficiency, especially for complex and large-scale CSP instances.

Our contribution builds on the theoretical foundations of structural decomposition methods by integrating restart strategies to enhance adaptability and efficiency. The proposed algorithm optimizes the order of clusters dynamically, offering significant improvements in computational performance for diverse applications. Moreover, this work lays the foundation for integrating machine learning techniques into structural decomposition methods, enabling future solvers to predict optimal cluster orders based on problem characteristics, thereby further improving efficiency and adaptability.

The rest of the paper is organized as follows: Section II presents the technical background; Section III introduces the Restart-FC-GHD+NG+DR method; Section IV presents the experimental results; and Section V concludes the paper.

II. BACKGROUND

The notion of Constraint Satisfaction Problem (CSP) has been formally defined by [12]. A CSP instance is defined as a triplet $P = \langle X, D, C \rangle$. Where $X = \{X_i, \ldots, X_n\}$ is a finite set of n variables and $D = \{D_i, \ldots, D_n\}$ is a set of finite domains. Each variable X_i takes its value from its domain D_i. $C = \{C_1, \ldots, C_m\}$ is a set of m constraints. A constraint $C_i \in C$ on an ordered subset of variables, $C_i = (X_{i_1}, \ldots, X_{i_{a_i}})$ (a_i is called the arity of the constraint C_i), is defined by an associated relation $R_i \in$ Ɍ of allowed combinations of values for the variables in C_i. Note that we take the same notation for the constraint C_i and its scope. Binary CSPs are those defined where each constraint involves only two variables, that is $\forall i \in \{1, \ldots, m\}$, $|C_i| = 2$. Constraints of arity greater than 2 are called non binary or n-ary. A CSP with at least one n-ary constraint is called non binary or n-ary CSP. A tuple $t \in R_i$ is a list of values $\left(v_{i_1}, \ldots, v_{i_{a_i}}\right)$ where:

$$a_i = |C_i| : v_{i_j} \in D_{i_j} \; \forall j \in \{1, \ldots, a_i\} \tag{1}$$

A solution to a CSP is an assignment of values to all the variables in X such that for each constraint C_i the assignment restricted to C_i belongs to R_i. The constraint hypergraph associated with a CSP instance $P = \langle X, D, C \rangle$ is the hypergraph Ḥ $= \langle V, E \rangle$ where the set of vertices V is the set of variables X and the set of hyperedges E are the set of constraint scopes in C. For any hyperedge $h \in E$, we denote by $var(h)$ the set of vertices of h and for any subset of hyperedges $K \subseteq E$

$$var(K) = \bigcup_{h \in K} var(h) \tag{2}$$

.

We denote by var(Ḥ) the set of vertices V and by $edges$(Ḥ) the set of $hyperedges\ E$. (We use the term var because the vertices of the hypergraph correspond to the variables of the CSP).

Definition 1: Hypertree

Let Ḥ $= \langle V, E \rangle$ be a hypergraph. A hypertree [13] for Ḥ is a triple $\langle T, \chi, \lambda \rangle$ where $T = (N, F)$ is *a* rooted tree, and χ and λ are labelling functions which associate each vertex $p \in N$ with two sets $\chi(p) \subseteq V$ and $\lambda(p) \subseteq E$. If $T' = (N', F')$ is a subtree of T we define:

$$\chi(T') = \cup_{v \in N'} \chi(v) \tag{3}$$

We denote the set of vertices N of T by $vertices(T)$ and the root of T by $root\ (T)$. T_p denotes the subtree of T rooted at the node p and $Parent(p)$ is the parent node of p in T.

Definition 2: Hypertree Decomposition

A Hypertree Decomposition [14] of a hypergraph Ḥ $= \langle V, E \rangle$ is a hypertree $HD = \langle T, \chi, \lambda \rangle$ which satisfies the following conditions:

i. For each edge $h \in E$, there exists $p \in vertices(T)$ such that:

$$var(h) \subseteq \chi(p) \tag{4}$$

ii. For each vertex $v \in V$, the set

$$\{p \in vertices\ (T) | v \in \chi(p)\} \tag{5}$$

induces a connected subtree of T;

iii. For each vertex

$$p \in vertices(T), \chi(p) \subseteq var\big(\lambda(p)\big) \tag{6}$$

iv. For each

$$p \in vertices(T), var\big(\lambda(p)\big) \cap \chi(Tp) \subseteq \chi(p) \tag{7}$$

The width of a hypertree $HD = \langle T, \chi, \lambda \rangle$ is equal to $max_{\ p \in vertices\ (T)} |\lambda(p)|$.The hypertree-width ($hw$(Ḥ)) of a hypergraph Ḥ is the minimum width over all its hypertree decompositions.

A hyperedge h of a hypergraph Ḥ $= \langle V, E \rangle$ is strongly covered in $HD = \langle T, \chi, \lambda \rangle$ if there exists $p \in vertices(T)$ such that the vertices of h are contained in $\chi(p)$ and $h \in \lambda(p)$.

A hypertree decomposition $HD = \langle T, \chi, \lambda \rangle$ of a hypergraphḤ is complete if every hyperedge h of Ḥ is strongly covered in HD.

A hypertree $HD = \langle T, \chi, \lambda \rangle$ is called a Generalized Hypertree Decomposition (GHD) [15], [16] if the conditions (i), (ii) and (iii) of Definition 2 hold. The width of a Generalized Hypertree Decomposition $HD = \langle T, \chi, \lambda \rangle$ is equal to $max_{\ p \in vertices\ (T)} |\lambda(p)|$. The generalized-hypertree-width (ghw(Ḥ)) of a hypergraph Ḥ is the minimum width over all its generalized hypertree decompositions.

Remark 1. The terms node and vertex will be used interchangeably to refer to a vertex of T.

Example 1. Let $P = \langle X, D, C \rangle$ be a CSP instance defined as follows.

- $X = \{X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}\}$ is the set of variables,
-
  - $D = \{D_1, \ldots, D_{17}\}$ where $D_i = \{0,1\}$ is the domain of the variable $X_i\ \forall i \in \{1, \ldots, 17\}$,
  - $C = \{C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9, C_{10}\}$ is the set of constraints.

Figure 1 is the constraint hypergraph associated with P and Figure 2 is one of its Generalized hypertree decompositions. The width of the decomposition is 3.

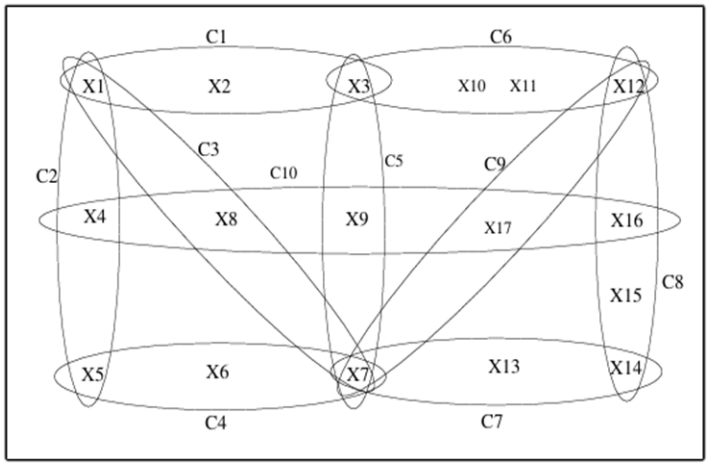

Figure 1: The constraint hypergraph of the CSP instance of Example 1.
Source: Authors, (2025).

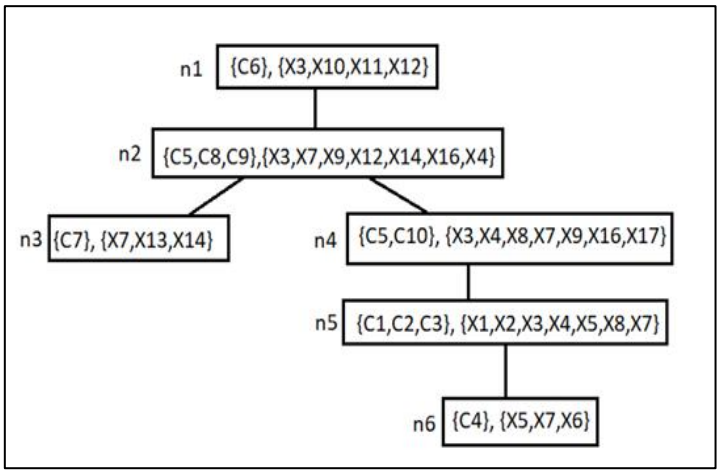

Figure 2: A 3-width generalized hyper tree decomposition of the constraint hyper graph of Example1.
Source: Authors, (2025).,333333

Definition 3: Nogood
A Nogood [17] is an inconsistent partial assignment that cannot be extended to a global solution. A minimal Nogood is any Nogood that is not itself composed of another Nogood.

Definition 4: Subproblem
Let n_i be a node of a GHD. The subproblem [7] associated with n_i is a CSP $< X_{n_i}, D_{n_i}, C_{n_i} >$ where $X_{n_i} = \chi_{n_i}$, D_{n_i} is the set of domains defined in the original CSP for the variables in X_{n_i} and

$$C_{n_i} = \lambda_{n_i} . P_{n_i} \quad (8)$$

Is denotes the subproblem associated with n_i and $sol(P_{n_i})$ denotes the current solution of P_{n_i}.

II.1 THE FC-GHD+NG+DR ALGORITHM

The FC-GHD+NG+DR algorithm [7] searches for a solution for the subproblem associated with the root node and it tries to extend this solution to the other subproblems induced by the nodes of the GHD in a depth-first manner. If a subproblem Pni has no solution, then FC-GHD+NG+DR, reorders the subtrees rooted at children of the current node, backtracks to the subproblem P_{n_j} such that n_j is the parent node of n_i in T, it computes another solution for P_{n_j} and continues from there. FC-GHD+NG+DR is described by (Algorithm 5).

It takes as input a complete $GHD = \langle T, \chi, \lambda \rangle$ associated with a CSP instance $P = \langle X, D, C \rangle$. The nodes of T are organized in a list σ according to the depth-first (preorder) traversal. The subproblems are solved sequentially by the function $Solve\_subpb$ according to σ. If P_{n_i} has a (another) solution then the procedure $Filter - NG$ (Algorithm 4) checks the consistency of the constraints at descendant nodes of n_i. If all these constraints are satisfied and if the current solution is not a Nogood, then all the constraint relations at each child node of n_i are filtered and the subproblem associated with the next node in σ is processed. In the negative case, another solution is computed for P_{n_i} if it exists.

If there is no (other) solution for P_{n_i}, then FC-GHD+NG+DR calls the procedure $BackTrack - DR$ (Algorithm 3) for restoring the tuples removed by the process of filtering, recording a Nogood using the procedure $Record\_nogood$ (Algorithm 1), reordering sub-trees with procedure $Reorder\_hypertree$ (Algorithm 2) such that all nodes of the sub-tree rooted at n_i are inserted between $Parent(n_i)$ and the nodes following n_i in σ noted by $Succ(Parent(n_i))$ and to backtrack to $Parent(n_i)$. FC-GHD+NG+DR stops in two cases:

1. All the subproblems are successfully solved, and then a global solution for the whole CSP instance is computed (line 16).
2. There is no other solution for the subproblem associated with the root node and then the CSP instance is unsatisfiable.

Algorithm 1 *Procedure Record_nogood*

Input n_i : node

1: $S \leftarrow \chi(Parent(n_i)) \cap \chi(n_i)$
2: $nogoods(Parent(n_i)) \longleftarrow nogoods(Parent(n_i)) \cup sol(P_{Parent(n_i)})[S]$

Figure 3: Record_nogood Procedure.
Source: [7].

Algorithm 2 *Procedure Reorder_hypertree*

In n_i : node,
Inout σ : list

1: $cn_1 \longleftarrow Parent(n_i)$
2: $cn_2 \longleftarrow n_i$
3: while $cn_2 \neq \emptyset$ do
4: if $cn_2 \notin nodes(T_{n_i}$ then
5: Break
6: end if
7: $cn_3 \longleftarrow succ(cn_2)$
8: insert cn_2 just after cn_1 in σ
9: $cn_2 \longleftarrow cn_3$
10: $cn_1 \longleftarrow succ(cn_1)$
11: end while

Figure 4: Procedure Reorder_hypertree.
Source: [7].

Algorithm 3 *Procedure Backtrack-DR*

Inout n_i : node,
Inout σ : list

1: *Restore_removed_tuples*(n_i)
2: *Record_nogood*(n_i)
3: *Reorder_hypertree*(n_i)
4: $n_i \longleftarrow Parent(n_i)$

Figure 5: Procedure Backtrack-DR.
Source: [7].

Algorithm 4 *Procedure Filter-NG*

Inout n_i : node

1: if $\neg Nogood(sol(P_{n_i}))$ then
2: if $C_i \in \lambda(T_{n_i}, compatible(sol(P_{n_i})), Rel(C_i))$ then
3: *Filter_child_nodes*(n_i)
4: $n_i \longleftarrow succ(n_i)$
5: end if
6: end if

Figure 6: Procedure Filter-NG.
Source: [7].

Algorithm 5 *FC-GHD+NG+DR*

Input: a complete $\mathcal{GHD} = \langle T, \chi, \lambda \rangle$ associated with a CSP instance P
Output: a solution $\mathcal{A}$ of P if it exists

1: $\sigma \leftarrow (n_1, n_2, \ldots, n_e)$ /* σ is a depth-first (pre-order) traversal of T with n_1 its root */
2: $n_i \longleftarrow n_1$
3: while $n_i \neq \emptyset$ do
4: $sol(P_{n_i}) \leftarrow Solve\_subpb(P_{n_i})$
5: if $sol(P_{n_i}) = \emptyset$ then
6: if $n_i = n_1$ then
7: $\mathcal{A} \leftarrow \emptyset$
8: exit /* P is unsatisfiable */
9: else
10: *Backtrack-DR*(n_i)
11: end if
12: else
13: *Filter-NG*(n_i)
14: end if
15: end while
16: $\mathcal{A} \leftarrow \bowtie_{i=1}^{i=e} sol(P_{n_i})$
17: return $\mathcal{A}$

Figure 7: FC-GHD+NG+DR Algorithm.
Source: [7].

III. RESTART-FC-GHD+NG+DR

In this section, we present $Restart - FC - GHD + NG + DR$ which is a new version of FC-GHD+NG+DR. As all the structural methods, FC-GHD+NG+DR depends in the quality of the decomposition and in the first node (root) considered to process the GHD decomposition. Since finding an appropriate root for processing a GHD is a very hard task [18], we propose to introduce the restart technique in order to consider another root for the hypertree, for this we consider all possible orders (with respect to depth first traversal-pre-order). So, the set of possible order s obtained are represented by $ORDERS$, they are partitioned into many subsets $\sigma_1, \ldots, \sigma_r$ such that $\sigma_1 \cup \ldots \cup \sigma_r = ORDERS$ where r is the number of orders. For the purpose of improving the performances, we introduce the restart techniques to the $FC - GHD + NG + DR$. The main steps of this techniques are:

1. Select the initial order $\sigma_1 \in ORDERS$ and initiate the resolution with $FC - GHD + NG + DR$;

2. At each time the number of backtracks reaches a threshold $limit\_backtracks$ which is updated at each iteration by a constant factor $param$, we apply a restart;

3. Restart allows us to choose another order from the set of $ORDERS$ already defined, and restart the resolution.

III.1 ALGORITHM

$Restart - FC - GHD + NG + DR$ is formally described by Algorithm 6.

Algorithm 6 *Restart-FC-GHD+NG+DR*

Input: a complete GHD $\langle T, \chi, \lambda \rangle$ associated with the CSP instance
Output: a solution $\mathcal{A}$ of P if it exists

1: $\sigma \leftarrow (n_1, n_2, \ldots, n_e)$ /* σ is a depth-first (pre-order) traversal of T with n_1 its root */
2: $n_i \longleftarrow n_1$
3: $nb\_backtracks \leftarrow 0$
4: $restart \leftarrow 1$
5: while $restart = 1$ do
6: while $n_i \neq \emptyset$ do
7: $sol(P_{n_i}) \leftarrow Solve\_subpb(P_{n_i})$
8: if $sol(P_{n_i}) = \emptyset$ then
9: if $n_i = n_1$ then
10: $\mathcal{A} \leftarrow \emptyset$
11: $restart \leftarrow 0$
12: exit /* P is unsatisfiable */
13: else
14: $nb\_backtracks++$
15: if $nb\_backtracks < limit\_backtracks$ then
16: *Backtrack*(n_i)
17: else
18: $restart \leftarrow 0$
19: *Break*
20: end if
21: end if
22: else
23: *Filter-NG*(n_i)
24: end if
25: end while
26: if $rstart = 1$ then
27: $\mathcal{A} \leftarrow \bowtie_{i=1}^{i=e} sol(P_{n_i})$
28: return $\mathcal{A}$
29: else
30: print "P is unsatisfiable"
31: end if
32: end while

Figure 8: Restart-FC-GHD+NG+DR Algorithm.
Source: Authors, (2025).

It takes as input a complete GHD associated with the CSP, and returns a solution of the CSP if it exists. First, (line 1) the algorithm commences by establishing an initial order $\sigma_1 = (n_1, \ldots, n_e)$ where n_1 is the root node. This order is obtained with respect to the depth-first search strategy. At each node n_1 the algorithm tries to solve the associated sub-problem P_{n_i} using the function $Solvesubpb(P_{n_i})$ (line 7). If P_{n_i} has a solution, we use the procedure $Filter - NG$ (line 24) to filter the relations of constraints at the λ label of each child node of n_i, then solves the

next subproblems P_{n_j} associated with the node n_j . In cases where P_{n_i} is inconsistent and n_i is the first node, then the problem P has no solution (line 11). Otherwise, it involves increment the number of backtracks $nb\_backtracks$ and checks the $limit\_backtracks$ (lines 14, 15). If the number of backtracks does not exceed the $limit\_backtracks$, it performs a backtrack (line 16) in order to compute another solution for the subproblem associated with the node $Parent(n_i)$; otherwise, it restarts (line 18), where the algorithm considers an new root for the GHD and adopts with a new order $\sigma_2 = (n_2, \ldots, n_e)$ according to the depth-first strategy.

Example2. Consider the GHD in Figure 2.

Initially the order σ is defined as follows: $\sigma_j = (n_1, n_2, n_3, n_4, n_5, n_6)$ with $n_1$as root of the hypertree. We consider the $limit\_backtracks = 3$.

First, we start the resolution with the first subproblem P_{n_1} associated with the node n_1 which is considered as a root of the hypertree. If P_{n_1} has no solution then we stop the resolution and the problem P has no solution, else we filter all the constraints in the λ label of each child of node n_1 (n_2 and n_3) and then we move to the next node n_2, we look for $sol(P_{n_2})$ which is compatible with $sol\ (P_{n_1})$. If P_{n_2} is consistent, we filter all the constraints in the λ label of each child of the node n_1 (n_2 and n_3). Else, $nb\_backtracks$ is incremented and a backtracking occurs from n_2 to n_1 (if $limit\_backtracks$ is not reached) to calculate another solution forP_{n_1} if it exists. When the solution computed to P_{n_1} is consistent we move to P_{n_2} . If the solution $sol(P_{n_2})$ is inconsistent, $nb\_backtracks$ is incremented to 2 and a backtracking occurs from n_2 to n_1 , then it generates another solution to P_{n_1} if it exists. If the solution $sol(P_{n_2})$ is consistent then move to the next subproblem.

At this stage, if P_{n_3} or another P_{n_i} is inconsistent, the $nb\_backtracks$ is incremented and if $limit\_Backtracks$, it restarts from the new root n_2 of the order $\sigma_2 = (n_2, n_3, n_4, n_5, n_6, n_1)$ (see Figure 9).

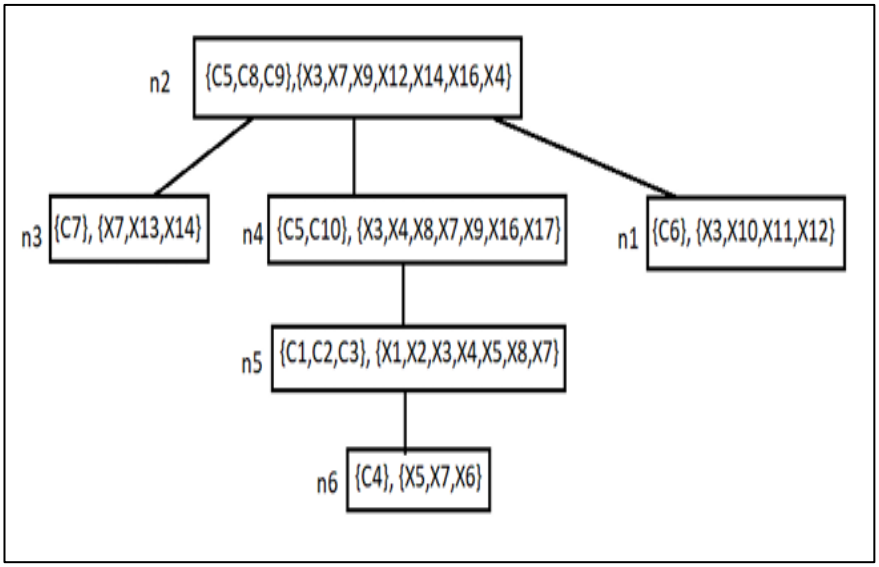

Figure 9: The GHD of Example 1 after reordering nodes.
Source: Authors, (2025).

IV. EXPERIMENTS

This section presents the experiments carried out in order to evaluate the performances of the $RestartFC - GHD + NG + DR$ method. $Restart - FC - FGD + NG + DR$ has been implemented in MPI C++ and run on a Core (TM) 2 Duo CPU T5670 @ 1.80 GHZ with 2GB of RAM under Linux Debian. The tests have been executed on benchmarks selected for the CSP Solver international Competitions CPAI'08 and CPAI'09.1.

For each instance, the time out (TO) is fixed to 1,800 seconds. The Memory Out (MO) is fixed to 2GB.

For computing the GHD Decomposition we used the Bucket Elimination (BE) algorithm [19] which is one of the best algorithms giving nearly optimal generalized hypertree decompositions within a reasonable CPU time [19][2]

In all the following tables of results, $|X|$ is the number of variables, $|C|$ is the number of constraints, w is the width of the GHD decomposition returned by BE and $time$ is the CPU run time needed to solve the instance of the considered series. The results in bold are the lowest (best) of each row. All CPU times are given in seconds.

They include the time for computing a GHD using BE (unless otherwise stated), in addition to the time for completing the GHD and solving the problem. In all the tables, the symbol '/' indicates unknown values.Note that the reported times for each instance are average runtime sover 5 executions because of the random nature of the BE algorithm, giving possible different GHD decompositions for one given instance. For this study, we have used the following benchmarks: Renault series, Renault Modified series, Pret series, Dubois series and VarDimacs which are described in Subsection 4.1.

IV.1 DESCRIPTION OF BENCHMARKS

Structured Instances: Both the Renault series and the Renault-mod series consist of multiples instances related to the Renault Megane configuration problem. These instances are represented in different forms:

- Renault Series: contains 2 structured instances coming from the original Renault Megane configuration problem appearing under two forms: normalized and simple form. Both instances involve large constraint relations of high arity and the largest relation contains 48,721 tuples.
- Renault-mod Series: this class (Modified Renault) contains 50 structured instances involving domains with up to 42 possible values. The largest constraint relation contains 48,721 tuples.

Quasi random instances (random plus a small structure):

- Boolean instances (each variable domain is {0,1}):

  - Pret series: contains 8 instances encoding 2-coloring problems forced to be unsatisfiable with either 60 or 150 variables. The maximum arity of the constraints is 3 (3-SAT) and each constraint relation contains 4 tuples.
  - Dubois series: contains 13 randomly generated unsatisfiable 3-SAT instances. For each instance, each constraint relation contains 4 tuples.
  - VarDimacs series: comes from the original Sat formalization of Circuit fault analysis: Bridge Fault (BF): 4 unsatisfiable instances, and from the well-known Pigeon-hole problem: 5 unsatisfiable instances. The maximum arity of the constraints is greater than 2 and the largest constraint relation contains 1,023 tuples (normalized-hole-10_ext).

IV.2 COMPARING $Restart - FC - GHD + NG + DR$ WITH $FC - GHD + NG + DR$

This subsection gives the comparative results of Restart-FC-GHD+NG+DR and FC-GHD+NG+DR on all the considered series.

IV.2.1 on normalized renault

Table 1 presents the comparison results of FC-GHD+NG+DR and Restart-FC GHD+NG+DR on the two instances of Renault series. The two algorithms have almost similar performances with little advantage to Restart-FC-GHD+NG+DR. The two instances of Renault series are very structured and come from real applications. This explains the good time results of the two methods.

Table 1: Comparison between FC-GHD+NG+DR and Restart-FC-GHD+NG+DR: Renault series.

Problems normalized	Size			W	FC − GHD + NG + DR	Restart − FC − GHD + NG + DR
	$\|X\|$	$\|C\|$	r		Time	Time
renault ext	101	134	48,721	3	0.83	**0.6**
renault-mgd ext	101	113	48,721	2	0.96	**0.7**

Source: Authors, (2025).

IV.2.2 On Modified Renault.

Table 2 presents the comparison results of the two algorithms on the Renault-mod series. It shows that $Restart - FC - GHD + NG + DR$ clearly improves $FC - GHD + NG + DR$ in terms of CPU time for both consistent and inconsistent instances. We can observe that the $FC - GHD + NG + DR$ is better than the $Restart$ one on few instances. This is due to the restart technique which needs more deeper study in order to fix the $limit\_backtaracks$.

Table 2: Comparison between FC-GHD+NG+DR and Restart-FC-GHD+NG+DR on Renault-mod series.

Problems normalized Renault-mod	Size			W	$FC - GHD + NG + DR$	$Restart - FC - GHD + NG + DR$	Consistency
	$\|X\|$	$\|C\|$	r		Time	Time	
-0_ext	111	154	48,721	4	1.32	**0.86**	Consistent
-1_ext	111	154	48,721	3	7.73	18.87	Inconsistent
-2_ext	111	154	48,721	5	1.59	**1.21**	Consistent
-3_ext	111	154	48,721	3	6.02	**5.98**	Inconsistent
-4_ext	111	154	48,721	4	1.49	**1.11**	Consistent
-5_ext	111	154	48,721	3	13.97	40.72	Inconsistent
-6_ext	111	154	48,721	3	0.85	**0.83**	Inconsistent
-7_ext	111	154	48,721	4	1.93	3.07	Consistent
-8_ext	111	154	48,721	3	0.83	**0.80**	Inconsistent
-9_ext	111	154	48,721	3	1.09	**1.08**	Consistent
-10_ext	111	154	48,721	3	7.57	**7.22**	Inconsistent
-11_ext	111	154	48,721	3	1.28	**1.25**	Consistent
-12_ext	111	154	48,721	3	32.04	107.73	Inconsistent
-13_ext	111	154	48,721	3	1.03	**1.00**	Consistent
-14_ext	111	154	48,721	3	6.91	18.04	Inconsistent
-15_ext	111	154	48,721	3	4.36	12.60	Inconsistent
-16_ext	111	154	48,721	3	11.58	**11.19**	Inconsistent
-17_ext	111	154	48,721	3	2.11	**1.84**	Inconsistent
-18_ext	111	154	48,721	3	206.13	**1.69**	Inconsistent
-19_ext	111	154	48,721	3	1.06	**0.95**	Inconsistent
-20_ext	111	154	48,721	3	9.71	9.74	Inconsistent
-21_ext	111	154	48,721	3	52.02	421.08	Inconsistent
-22_ext	111	154	48,721	3	26.45	28.05	Inconsistent
-23_ext	111	154	48,721	4	2.21	**1.82**	Inconsistent
-24_ext	111	154	48,721	4	3.37	**3.29**	Inconsistent
-25_ext	111	154	48,721	3	40.01	107.94	Inconsistent
-26_ext	111	154	48,721	3	MO	MO	Inconsistent
-27_ext	111	154	48,721	3	2.14	**1.96**	Inconsistent
-28_ext	111	154	48,721	3	74.04	76.61	Inconsistent
-29_ext	111	154	48,721	4	14.18	**13.82**	Inconsistent
-30_ext	111	154	48,721	3	4.78	10.45	Inconsistent
-31_ext	111	154	48,721	3	1.65	**1.63**	Consistent
-32_ext	111	154	48,721	4	5.09	14.41	Consistent
-33_ext	111	154	48,721	5	12.40	12.41	Inconsistent
-34_ext	111	154	48,721	4	6.13	9.76	Consistent
-35_ext	111	154	48,721	3	19.72	50.41	Inconsistent
-36_ext	111	154	48,721	4	21.08	45.90	Consistent
-37_ext	111	154	48,721	4	11.02	27.67	Inconsistent
-38_ext	111	154	48,721	4	1.70	2.58	Consistent
-39_ext	111	154	48,721	4	51.71	638.17	Inconsistent
-40_ext	108	149	48,721	3	553.60	1560.17	Inconsistent
-41_ext	108	149	48,721	4	7.59	18.18	Consistent
-42_ext	108	149	48,721	3	1.17	**1.10**	Inconsistent
-43_ext	108	149	48,721	3	1.85	**1.45**	Consistent
-44_ext	108	149	48,721	4	1.03	**0.93**	Consistent
-45_ext	108	149	48,721	4	19.89	44.54	Consistent
-46_ext	108	149	48,721	4	5.86	**5.44**	Consistent
-47_ext	108	149	48,721	4	1.19	**0.74**	Inconsistent
-48_ext	108	149	48,721	4	47.01	84.04	Consistent
-49_ext	108	149	48,721	4	24.38	85.57	Consistent

Source: Authors, (2025).

IV.2.3 On Pret Series and Dubois Series

Tables 3 and 4 show the comparison results of the two algorithms on the Boolean Pret and Dubois series. On these series, $Restart - FC - GHD + NG + DR$ and $FC\ GHD + NG + DR$ solve all instances in short time. On Pret series, the average runtimes of the two algorithms $FC - GHD + NG + DR$ and $Restart - FC - GHD + NG + DR$ are 0.007 and $\approx 0\ seconds$ respectively. On Dubois series, their average runtimes are 0.0035 and $\approx\ 0\ seconds$ respectively.

Table 3: Comparison between FC-GHD+NG+DR and Restart-FC-GHD+NG+DR on Pret series.

Problems normalized pret	Size			W	$FC - GHD + NG + DR$	$Restart - FC - GHD + NG + DR$	Consistency
	$\|X\|$	$\|C\|$	r		Time	Time	
-60-25_ext	60	40	4	5	0.36	**≃0**	Inconsistent
-60-40_ext	60	40	4	5	0.008	**≃0**	Inconsistent
-60-60_ext	60	40	4	5	0.01	**≃0**	Inconsistent
-60-75_ext	60	40	4	5	0.01	**≃0**	Inconsistent
-150-25_ext	150	100	4	5	0.05	**≃0**	Inconsistent
-150-40_ext	150	100	4	5	0.17	**≃0**	Inconsistent
-150-60_ext	150	100	4	5	0.37	**≃0**	Inconsistent
-150-75_ext	150	100	4	5	0.023	**≃0**	Inconsistent

Source: Authors, (2025).

Table 4: Comparison between FC-GHD+NG+DR and Restart-FC-GHD+NG+DR on Duboi.

Problems normalized Dubois	Size		W		$FC - GHD + NG + DR$	$Restart - FC - GHD + NG + DR$	Consistency
	$\|X\|$	$\|C\|$	r		Time	Time	
-20_ext	60	40	4	2	0.043	**≃0**	Inconsistent
-21_ext	63	42	4	2	0.005	**≃0**	Inconsistent
-22_ext	66	44	4	2	0.004	**≃0**	Inconsistent
-23_ext	69	46	4	2	0.005	**≃0**	Inconsistent
-24_ext	72	48	4	2	0.005	**≃0**	Inconsistent
-25_ext	75	50	4	2	0.005	**≃0**	Inconsistent
-26_ext	78	52	4	2	0.006	**≃0**	Inconsistent
-27_ext	81	54	4	2	0.006	**≃0**	Inconsistent
-28_ext	84	56	4	2	0.006	**≃0**	Inconsistent
-29_ext	87	58	4	2	0.007	**≃0**	Inconsistent
-30_ext	90	60	4	2	0.006	**≃0**	Inconsistent
-50_ext	150	100	4	2	0.011	**≃0**	Inconsistent
100_ext	300	200	4	2	0.049	**≃0**	Inconsistent

Source: Authors, (2025).

IV.2.4 On VarDimacs Series

Finally, Table 5 presents the behavior of the two algorithms on VarDimacs series. $FC\ GHD + NG + DR$ and $Restart - FC - GHD + NG + DR$ succeed to solve four instances. The average runtime of the two algorithms is 4.01 and 130,75 seconds respectively. But we have better results with $Restart - FC - GHD + NG + DR$ except for the instance normalized bf-0432-007_ext.

Table 5: Comparison between FC-GHD+NG+DR and Restart-FC-GHD+NG+DR on Pret series.

Problems normalized	Size			W	$FC - GHD + NG + DR$	$Restart - FC - GHD + NG + DR$	Consistency
	$\|X\|$	$\|C\|$	r		Time	Time	
-bf-0432-007_ext	970	1,943	31	29	35.15	129.87	Consistent
-bf-1355-075_ext	1,818	2,049	5	5	9.74	**0.81**	Consistent
-bf-1355-638_ext	532	339	31	2	0.18	≃0	Consistent
-bf-2670-001_ext	1,244	1,354	31	7	0.31	**0.29**	Inconsistent

Source: Authors, (2025).

V. CONCLUSIONS

In this work, we have presented a new method called Restart-FC-GHD+NG+DR, which combines the FC-GHD+NG+DR algorithm, exploiting GHD, with a restart strategy to solve non-binary CSPs. Our experiments on benchmark of literature have demonstrated the efficiency of the proposed algorithm, particularly on consistent instances. The results show significant improvements over the FC-GHD+NG+DR algorithm, with a 52.62% better performance on modified Renault consistent instances and near-zero execution time for the Normalized Dubois and Normalized Pret series. This confirms the algorithm's potential in enhancing CSP-solving strategies. This approach offers significant contributions, the method advances CSP-solving by addressing limitations of traditional algorithms, introducing a dynamic, restart-based approach that adapts to various problem structures. It opens new research avenues by integrating machine learning for adaptive reordering, encouraging cross-disciplinary applications in fields like artificial intelligence, operations research, and network optimization. However, some limitations remain, such as managing the limit_backtaracks more effectively, as excessive backtracking can still increase execution time. Additionally, enhancing the algorithm's handling of inconsistent problem instances is necessary to avoid exploring all possible orders, which would further improve computational efficiency. For future work, we plan to integrate machine learning and deep learning techniques to dynamically reorder the nodes of the GHD decomposition.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Fatima Ait Hatrit, Kamal Amroun
Methodology: Fatima Ait Hatrit, Kamal Amroun
Investigation: Fatima Ait Hatrit, Kamal Amroun
Discussion of results: Fatima Ait Hatrit, Kamal Amroun
Writing – Original Draft: Fatima Ait Hatrit, Kamal Amroun
Writing – Review and Editing: Fatima Ait Hatrit, Kamal Amroun **Resources:** Fatima Ait Hatrit, Kamal Amroun
Supervision: Fatima Ait Hatrit, Kamal Amroun
Approval of the final text: Fatima Ait Hatrit, Kamal Amroun

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RESEARCH ARTICLE OPEN ACCESS

IOT BASED LOCATION ALERT AND CONTROLLING SYSTEM FOR ANIMAL BELTS VIA MOBILE DEVICES

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ABSTRACT

Traditional pet containment methods often lack efficiency and ease of use, posing significant challenges to maintaining pets within designated boundaries. This study presents the Animal Belt, an innovative geofencing-enabled pet management system designed to monitor and control pets' movements. The system utilizes GPS technology to establish virtual boundaries, triggering vibratory feedback and pre-recorded voice commands when the pet breaches the defined geofence. Additionally, owners receive real-time alerts via a mobile application, including a Google Maps link for precise pet location tracking. Experimental evaluations validated the system's performance within a 300-meter geofence radius, demonstrating consistent activation of feedback mechanisms upon boundary violations. The results underscore the system's ability to enforce geofence limits effectively, leveraging feedback mechanisms to prompt pets' return. Key features include customizable operational settings and a user-friendly interface, offering a modern alternative to traditional leashing methods. The proposed system enhances pet safety, minimizes owner intervention, and provides a reliable solution for outdoor pet management.

I. INTRODUCTION

Over the past 15 years, heightened environmental degradation has emphasized the critical need for enhanced wildlife monitoring and protection. Animal tracking systems play a crucial role in studying behavior, migration patterns, and ecosystem dynamics, as each species uniquely contributes to its environment, underscoring the importance of safeguarding biodiversity.

However, escalating challenges such as accidents, injuries, and disease outbreaks significantly threaten animal populations, particularly in vast and remote wilderness areas where pinpointing injured animals is challenging [1].

Additionally, animals face risks like theft, especially at night when vigilance is reduced, necessitating advanced monitoring solutions [2]. Current animal tracking systems incorporate technologies such as GPS, GPRS, RFID, and sensors. Studies by Khor TM reveal low awareness and high costs as significant barriers to adoption in Malaysia. Technologies like microchips and tattoos, while beneficial for pet recovery, lack real-time tracking capabilities. GPS, widely integrated into smartphones, uses geofencing to create virtual boundaries for pet monitoring [3]. Research by S.-H. Kim et al. explored the use of GPS and RFID in zoological gardens, proposing an intelligent monitoring service with sensor nodes and web interfaces but noted limitations due to reliance on outdated technology platforms, potentially hindering scalability and compatibility with modern systems. Nonetheless, the prototype offers benefits such as remote access via web-based open APIs [4].

Similarly, M. Gor et al. developed the GATA system, integrating Wireless Sensor Networks (WSN) and GPS for wildlife monitoring with an emphasis on real-time tracking. While GATA provides straightforward real-time animal monitoring compared to traditional methods like radio tracking and picture identification, it faces challenges related to labor and high monitoring costs due to insufficient research on power-efficient microcontroller-based monitoring modules [5].

V. R. Jain et al. investigated wildlife monitoring using an automated WSN system, improving energy efficiency and positional accuracy with enhanced collar designs. Despite their promise, these studies encounter obstacles such as high costs, significant energy consumption, and dependence on outdated technology platforms [6]. Despite advancements, there is a scarcity of research and services employing GPS, RFID, and sensors in

zoological settings. Existing systems are hindered by high costs, energy consumption, and the need for more efficient power management, highlighting a gap in developing cost-effective, energy-efficient, and scalable animal tracking solutions compatible with contemporary technology platforms. The objective of this study is to develop a comprehensive and cost-effective real-time animal tracking and monitoring system leveraging geofencing and mobile device integration to enhance animal safety and security, addressing the limitations of current methods.

This study addresses critical gaps in existing animal tracking systems by integrating modern technologies for real-time monitoring, improving energy efficiency, and reducing costs. The proposed system aims to provide a scalable solution compatible with contemporary technology platforms.

The contributions of this study include the development of a cost-effective, real-time animal tracking and monitoring system leveraging geofencing and mobile devices; enhanced energy efficiency and positional accuracy through improved design and technology integration; provision of real-time information to users via web interfaces, ensuring remote access and monitoring; and improved safety and security for animals, addressing risks such as theft and injury through advanced tracking and monitoring techniques.

II. THEORETICAL REFERENCE

This section discusses the application of IoT technologies to revolutionize animal safety and improve monitoring systems. The discussion is structured into communication methods, geofencing, GPS/GSM systems, and vibrational feedback, focusing on their roles, methodologies, advantages, and limitations.

II.1 WIRELESS COMMUNICATION

Wireless communication forms the backbone of modern animal monitoring systems by enabling seamless data transmission between sensor nodes, controllers, and user interfaces. The Animal Belt system, for instance, employs NodeMCU, a cost-effective microcontroller with built-in Wi-Fi, as the primary communication hub. NodeMCU interfaces with GPS modules to continuously track pet movements within predefined geofence boundaries.

Ateeq Ur Rehman et al. [7] present a smart dairy monitoring system designed to enhance livestock management in developing regions. Traditional monitoring methods fail to meet modern industry demands, necessitating real-time, automated solutions. Their system uses wireless sensor nodes, IoT, and NodeMCU to integrate features such as cow collars equipped with temperature, GPS, and heart rate sensors, as well as an environmental parameter regulation unit. Data from these sensors is transmitted wirelessly to an IoT-based interface for analysis. While the system offers scalability and automation, challenges include dependency on reliable connectivity and precise sensor calibration.

Similarly, Jahangir Arshad et al. [8] propose a cost-effective dairy monitoring solution addressing inefficiencies in the livestock industry. Their system integrates NodeMCU and wireless sensor nodes for real-time monitoring of environmental conditions, animal health, and geospatial data.

The inclusion of automation significantly reduces labour costs, enhances animal well-being, and boosts dairy production. Despite these benefits, the system's reliance on stable wireless communication and potential sensor accuracy issues pose challenges.

II.2 GPS AND GSM

The Global Positioning System (GPS) and Global System for Mobile Communication (GSM) technologies are critical in tracking and communication applications, particularly in livestock and wildlife monitoring systems. GPS provides accurate real-time location data, while GSM facilitates remote data transmission, enabling enhanced tracking capabilities. The Animal Belt system incorporates the Neo-6M GPS module, known for its high accuracy and low power consumption, making it suitable for wearable devices. This module continuously tracks the animal's location by receiving satellite signals to determine latitude and longitude, enabling geofence monitoring.

G. Ramesh et al. [9] details a GPS- and IoT-based animal tracking system using ESP8266-12E. The system addresses challenges in locating livestock on large farms by offering precise location tracking via GPS and real-time data transmission through GSM. While this approach improves animal safety and monitoring, its effectiveness is limited by GPS and GSM signal availability in remote areas.

For wildlife conservation, Gayatri Mohanta et al. [10] present an advanced tracking system (ATS) combining GSM and GPS. The system continuously monitors wildlife behaviour and health parameters, including heart rate, body temperature, and rumination, alongside environmental metrics like temperature and humidity. This solution enhances conservation efforts by providing real-time, accurate data for informed decision-making. However, signal coverage and energy consumption remain notable limitations for long-term monitoring in remote areas.

II.3 GEOFENCE TECHNOLOGY

Geofencing establishes virtual perimeters around predefined geographic areas, allowing real-time monitoring of animal movements. It is a key feature in modern tracking systems, enabling notifications when animals breach specified boundaries.

Deni Setiawan et al. [11] propose a geofencing-based pet tracking system employing the U-Blox Neo 6M GPS module for location tracking and SIM800L GSM module for data transmission using GPRS. An Arduino Pro Mini microcontroller manages the system's input and output processes, while an Android application notifies owners of geofence breaches. This system enhances pet recovery efforts with real-time tracking and automated alerts but relies heavily on strong GPS and GSM signals, which can limit its performance in remote areas.

Agung Pangestu et al. [12] further advance geofencing technology with a GPS-based tracking system using the ESP32 microcontroller and NEO7M GPS module. Their Android application provides real-time location tracking and distance calculations from a designated home base. The system demonstrates 92% accuracy in open areas, though its performance is reduced in indoor environments due to signal obstruction. Additionally, delays of over three minutes in signal processing and challenges with battery optimization highlight areas for improvement.

II.4 VIBRATIONAL FEEDBACK

The Vibrational feedback provides a non-invasive method of alerting animals through tactile stimuli, ensuring minimal distress. The Animal Belt incorporates a pancake vibration module, which delivers subtle cues when animals breach geofence limits.

This feedback mechanism effectively captures the animal's attention, prompting it to return to the designated area.

Amruta Helwatkar et al. [13] explore the use of vibration sensors in automating animal health monitoring within dairy farming. By detecting behavioural changes linked to common diseases, vibration sensors facilitate the early identification of health issues, improving overall herd management. These sensors, integrated into a cost-effective monitoring system, enhance productivity and reduce labour costs. However, the system's scalability is limited by sensor calibration and integration challenges in large-scale farms.

Amelie Bonde et al. [14] take a novel approach to livestock behaviour monitoring by employing structural vibration sensors. These sensors track pig activities, particularly piglet nursing, by detecting unique vibration patterns caused by animal movement. The system is robust to harsh farm conditions, achieving up to 90% accuracy in monitoring activities like sow lying and piglet growth. Despite its effectiveness, the system faces challenges from unpredictable environmental noise and potential sensor damage.

III. MATERIALS AND METHODS

This section provides a comprehensive explanation of the system, detailing the components utilized and fuction's operational flow. It is divided into two subsections, as illustrated in Fig. 1, which highlights the features of the belt.

III.1 SYSTEM OVERVIEW

This section includes overview of 2 systems. One system is for a geofence alert system, integrating a pancake vibration sensor, Neo 6M GPS, APR33A3, and SIM800L GSM modules with an Arduino Uno. This system provides automated auditory commands and vibration feedback through a belt mechanism when a pet breaches a predefined geofenced area [15]. And another system shows the integration of the APR33A3 module and pancake vibration module with a Node-MCU, utilizing IoT technology to induce belt vibrations and deliver audible commands to a pet. The system is controlled via the Blynk app on mobile devices [16].

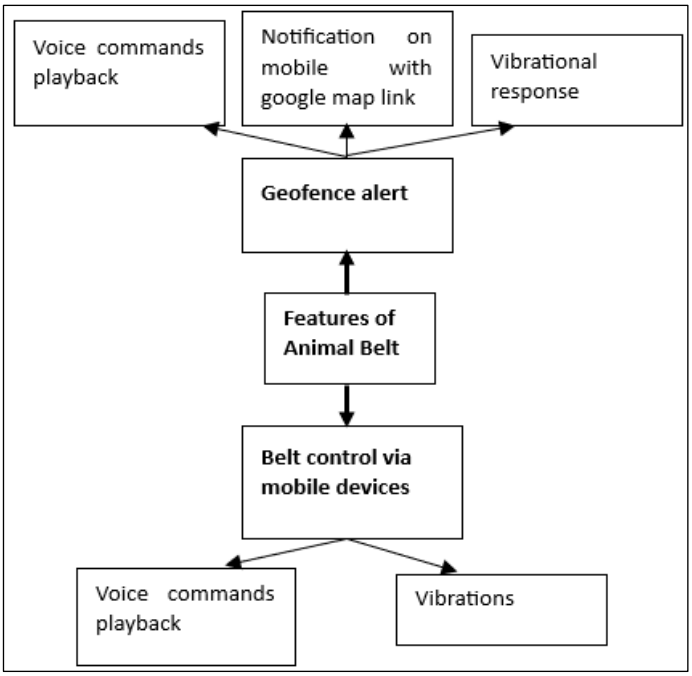
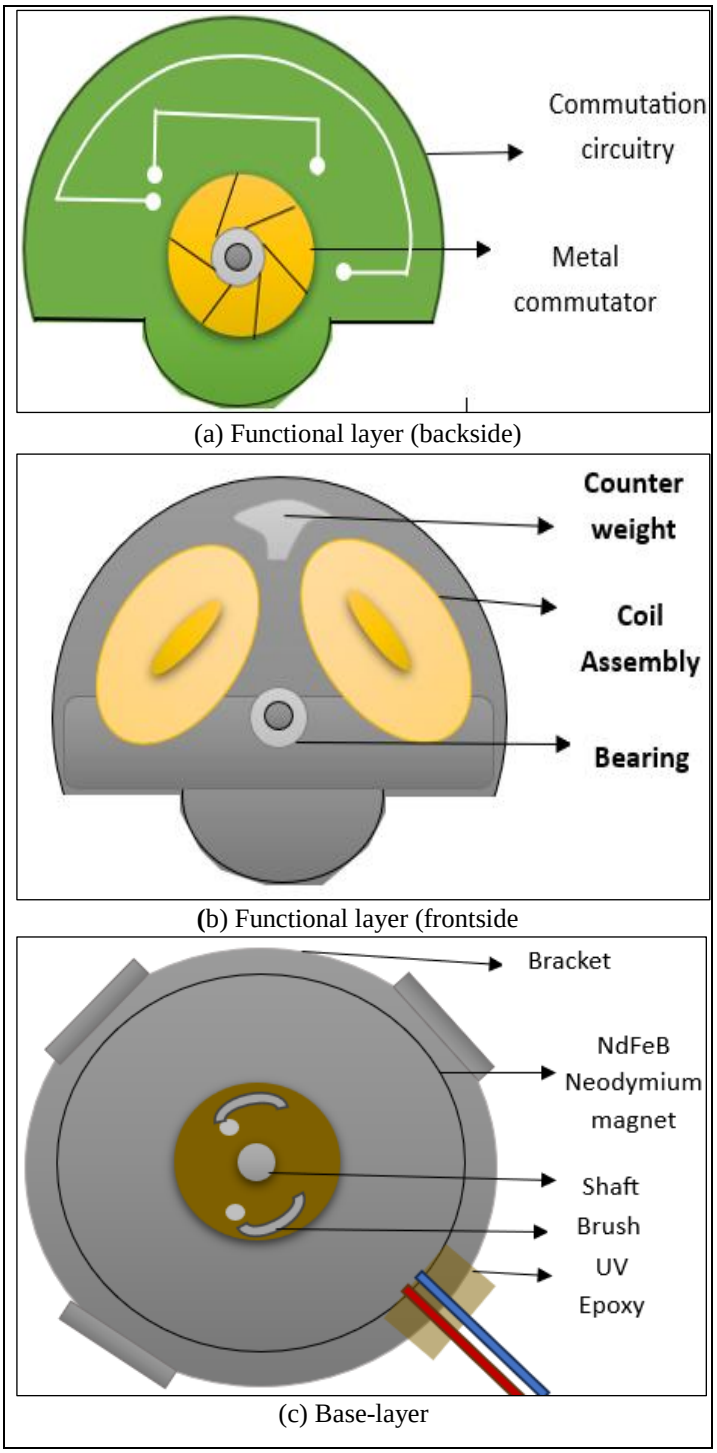


Figure 1: Features of animal belt.
Source: Authors, (2025).

III.2 HARDWARE

The section presents the description of the following components used in system.

1. Pancake vibration module



(a) Functional layer (backside)

(b) Functional layer (frontside

(c) Base-layer

Figure 2: Pancake vibration module (internal structure).
Source: Authors, (2025).

A coin vibration motor, commonly used in smartwatches and fitness trackers, employs Eccentric Rotating Mass (ERM) technology. This involves a flat PCB with a 3-pole commutation circuit around an internal shaft as shown in Fig. 2(a). The motor rotor, consisting of two voice coils and a lightweight mass on a plastic disc, is attached to the shaft via a central bearing as shown

in Figure. 2(b). Electrical power is supplied through brushes contacting the PCB commutation pads. Upon activation, the voice coils generate a magnetic field, interacting with a disc magnet in the motor chassis as shown in Figure. 2(c).

The commutation circuit reverses the magnetic field in the voice coils, engaging with the neodymium magnet's poles, causing the off-centered mass to rotate and induce vibration. The commutator, with six segments linked to two coils, allows for six distinct magnetic orientations, configuring the motor as a six-pole machine. Brush resistance varies throughout the rotation cycle [17],[18].

Neo 6M GPS module

The Neo-6M GPS module is a highly efficient GPS receiver with an integrated 25 x 25 x 4mm ceramic antenna for robust satellite acquisition. It synchronizes with signals from a constellation of 24 satellites to determine precise location coordinates (latitude, longitude, and altitude) using trilateration. Analyzing the travel time of microwave signals from at least three satellites, the module calculates its position [19],[20].

The Neo-6M features an LED indicator for 'Position Fix' status:

- No blinking: Searching for satellites.
- Blinking every 1 second: Position Fix is found (sufficient satellites detected).

2. Sim800l GSM module

The SIM800L is a compact cellular module operating on the 900 MHz and 1800 MHz bands, supporting GPRS, SMS, voice calls, internet connectivity, and FM reception. It communicates with microcontrollers via UART and responds to AT commands for tasks like signal strength checks, SIM card details, network status, battery monitoring, text handling, and call management. Operating at 3.4V to 4.4V, it's suitable for direct LiPo battery use and requires an external antenna soldered to its PCB [21], [22]. The module features an LED indicator:

- Blink every 1 second: Module running, awaiting network connection.
- Blink every 2 seconds: Active GPRS data connection established.
- Blink every 3 seconds: Connected to a cellular network for voice calls and SMS.

3. Power supply

Li-Po batteries have a voltage range of 3.7V to 4.2V – perfect for a SIM800L module. Any Li-Po battery with a capacity of 1200 mAh or higher should work, as these batteries can withstand current spikes up to 2 A while maintaining usable voltage [23]. The 9V battery is a rectangular dry cell classified by its 48.5mm x 26.5mm x 17.5mm dimensions and one-sided clasp terminals. They hold mid-range capacities upwards of 1,200mAh [24].

5 Arduino uno

Arduino Uno is a microcontroller board based on the Atmga328P. It was 14 digital input/output pins (of which 6 can be used as PWM output), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button.

6 APR33A3 voice module

APR33A3 Voice Recorder and Playback Module is designed for easy recording and playback of audio files. It features a built-in microphone, supports various audio formats, and includes a 3.5mm headphone jack for direct audio output. Key functionalities are enabled by the APR33A series IC, integrating advanced audio processing, ADC, and DAC capabilities [25-26].

The module operates in modes for recording, playback, resetting, messaging, PWM (Pulse Width Modulation), erasing, and voice input. In 7-message mode, recording starts when the /REC pin is low (VIL) and a tact switch (M0 to M6) is pressed. Playback begins in the VIH state, triggered by pressing a tact switch. PWM mode drives a speaker via VOUT1 and VOUT2, and standby mode reduces power until initialization via the RSTB pin. Erasing data is initiated by setting the M7 pin low, confirmed by LED. Modifications are made by holding M7 low and pressing the M pin, indicated by LED. The APR33A3 module provides reliable voice recording, playback, PWM output, and erasing capabilities for various applications.

7. Node MCU

Node MCU is an open-source IoT (Internet of Things) platform based on the ESP8266 Wi-Fi module. It is used to control various electronic devices and make them communicate with each other over a network.

III.3 SOFTWARE

1. Blynk app:

Blynk app is an IoT platform for iOS and Android smartphones, enabling remote control and monitoring of Arduino, Raspberry Pi, and Node MCU devices over the internet. It allows users to create GUIs using widgets like buttons and sliders [27-28].

Key components:

- Blynk App: Mobile app for designing and configuring interfaces.
- Blynk Server: Manages communication between smartphones and devices, can be cloud-based or local.
- Blynk Libraries: Facilitate integration with hardware, ensuring smooth data exchange and command synchronization.

Blynk supports IoT applications in the monitoring, control, and prototyping stages of projects.

2. ThingSpeak IoT platform

Thing-Speak is an IoT analytics platform that enables data collection, storage, analysis, and visualization from IoT devices. It supports real-time data streaming and integrates with MATLAB for

advanced data processing, making it ideal for monitoring, analytics, and actionable insights in various IoT applications.

III.4 OPERATIONAL FLOW

This section provides comprehensive details on the features, divided into two sub-features as shown in Figure 1. Each sub-feature is further divided into three parts: technology used, steps for setting up the devices, and operational flow.

1. Geofence alert

Geo-fencing technology uses GPS and/or Wi-Fi to create virtual perimeters, called "geofences," around specific geographic areas on digital maps. When a location-tracking device crosses these boundaries, predefined actions or notifications are triggered via the GSM module. In this implementation, GPS signals determine the location and boundaries, using a circular geofence defined by the latitude and longitude of the area's center. This method is straightforward, involving inputting the coordinates into the microcontroller [29].
The Haversine formula is given by:

$$d = 2r \arcsin\left(\sqrt{sin^2\left(\frac{\emptyset_2-\emptyset_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)}\right) \quad (1)$$

Equation 1 presents the calculation of the distance 'd' between two points on the Earth's surface using the haversine formula.

This formula, represented in (1), utilizes differences in latitude (Δφ) and longitude (Δλ) to compute haversine values, with 'R' denoting the Earth's radius (6371 km). The resulting distance 'd' is expressed in kilometers, matching the Earth's radius units [30].

Unlike the Euclidean distance formula applicable to flat surfaces, the haversine formula is ideal for spherical Earth calculations due to its accurate handling of spherical geometry. It is derived from the spherical law of cosines, optimized for precision in determining distances over large areas.

Below are the steps for configuring the animal belt device for a desired location:
1. Use Google Maps to locate and mark the desired area for the geofence (as shown in Fig. 3).

2. Select the specific region on the map to define the boundaries of the geofence (illustrated in Fig. 4).

3. Plot the point within the chosen area and obtain latitude and longitude coordinates from a popup message. Determine the radius (r) of the circular geofence, as demonstrated in Fig. 5 and 6, and input these details into the microcontroller.

Here, coordinates 48.06706010314518, 11.305574622256353 are extracted while testing.

The accompanying figures visually demonstrate the step-by-step procedure using Google Maps.

Figure 3: Location finding on Google map.
Source: Authors, (2025).

Figure 4: Selecting region for Geofencing.
Source: Authors, (2025).

Figure 5: Plotting a point on selected region.
Source: Authors, (2025).

Figure 6: Setting the radius of Geofence circle.
Source: Authors, (2025).

Figure. 7 illustrates the operational workflow of the entire system following the establishment of connections between modules and the development board.

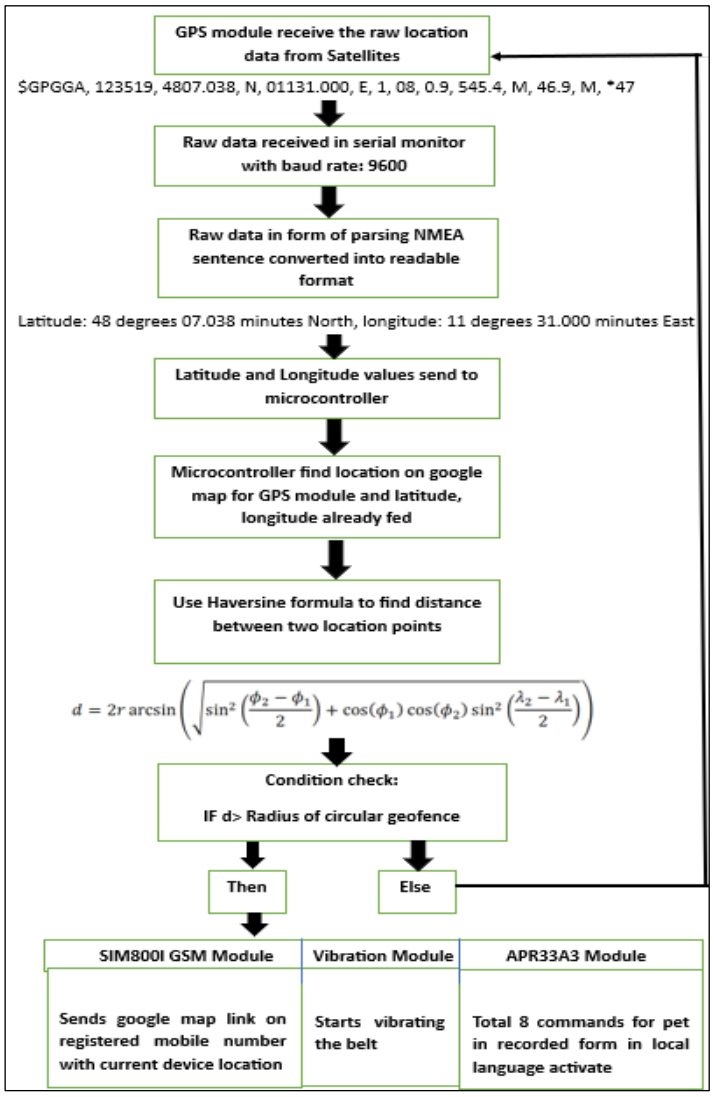


Figure 7: Workflow of Geofence alert system.
Source: Authors, (2025).

Initially, the Neo6M GPS module receives raw GPS data and communicates serially using Software Serial. This data is transmitted in the NMEA standard language to the serial monitor. In microcontroller applications, parsing NMEA sentences is essential to extract relevant data segments and transform them into a user-friendly format [31].

An obtained NMEA sentence is: "$GPGGA, 123519, 4807.038, N, 01131.000, E, 1, 08, 0.9, 545.4, M, 46.9, M, *47." The structure of this NMEA sentence is analyzed and detailed in table 1.

Table 1: NMEA message structure.

Field value	Description
$	Starting of NMEA sentence.
GPGGA	Global Positioning System Fix Data
123519	Current time in UTC – 12:35:19
4807.038, N	Latitude 48 degrees 07.038′ N
01131.000, E	Longitude 11 degrees 31.000′ E
1	GPS fix
08	Number of satellites being tracked
0.9	Horizontal dilution of position
545.4, M	Altitude in Meters (above mean sea level)
46.9, M	Height of geoid (mean sea level)
(empty field)	Time in seconds since last DGPS update
(empty field)	DGPS station ID number
*47	The checksum data always begins with *

Source: Authors, (2025).

From table 1, the device's location is identified as latitude 48 degrees 07.038 minutes North and longitude 11 degrees 31.000 minutes East.

To find the distance using the haversine formula, need to compute the values for Δφ and Δλ:

Let,
Latitude1 as lat1: 48.070380
Latitude2 as lat2: 48.073023604601474
Longitude1 as long1: 11.310000
Longitude2 as long2: 11.31542538591539

For Δφ:
Δφ = (lat2 * π/180) - (lat1 * π/180)
Δφ = (48.073023604601474 * π/180) - (48.070380 * π/180)
Δφ ≈ 0.00005 radians

For Δλ:
Δλ= (long2 * π/180) - (long1 * π/180)
Δλ= (11.31542538591539 * π/180) - (11.310000 * π/180)
Δλ ≈ 0.00009 radians

Now, plug these values in (1):

$\sin^2(\Delta\varphi/2) \approx \sin^2(0.000025)$
≈ 0.000000000625
$\cos(\varphi 2) \approx \cos(0.83944)$
≈ 0.670
$\cos(\varphi 1) \approx \cos(0.83939)$
≈ 0.671
$\sin^2(\Delta\lambda/2) \approx \sin^2(0.000045)$
≈ 0.000000002025

$a = \sin^2(\Delta\varphi/2) + \cos(\varphi1) * \cos(\varphi2) * \sin^2(\Delta\lambda/2)$

$a \approx 000000000625 + (0.671 * 0.670 * 0.000000002025)$
≈ 0.000000001545
Now, compute the distance:

$distance = 2 * 6371 * \arcsin(\sqrt{a})$
$\approx 6371 * 2 * \arcsin(0.000038)$
$\approx 6371 * 0.000076$
≈ 0.484196 km

So, the approximate distance between the two points is about 484 meters.

Upon evaluation of (1), which calculates the distance (d) between the device and the geofence center, two conditions emerge:

Condition 1: If d < r, indicating that the device is within the geofence region.
Condition 2: If d > r, indicating that the device is outside the geofence region.

When condition 2 is met:

- The system activates the Sim800l GSM module to send SMS messages and make calls, transmitting the device's location via a Google Maps link.
-
- The APR33A3 voice module plays recorded instructions to the pet in the owner's voice, typically in the local language.
- Vibrations generate in the belt continuously.

2. Vibration and voice commands controlled via mobile devices

The system utilizes a Node-MCU, Blynk application, and various hardware components to enable remote control of a pet belt. Commands issued via the Blynk mobile app are sent to the Blynk Cloud server and then transmitted to the Node-MCU for processing [32].

For device setup, the Node-MCU is configured to interface with vibration modules and the APR33A3 voice module, ensuring it can control these components based on received commands [33]. Operationally, commands from the Blynk app are relayed through the Blynk Cloud server to the Node-MCU [34].

The Node-MCU processes these commands, activating or deactivating the vibration modules and playing voice instructions via the APR33A3 module, facilitating remote pet training and communication [16].

IV. BELT PROTOTYPE AND APPLICATION

This section details the prototypes, practical applications of the pet belt, and specialty. Fig. 8 presents the prototype belt featuring three key components in separate enclosures: the central box houses the geofencing system, optimized for GPS signal transmission, while the other two boxes contain the vibration feedback and recording playback modules. Fig. 9 illustrates the proper placement of the elastic belt on the pet, which is worn from the rear by lifting the hind legs due to the absence of hooks or buttons.

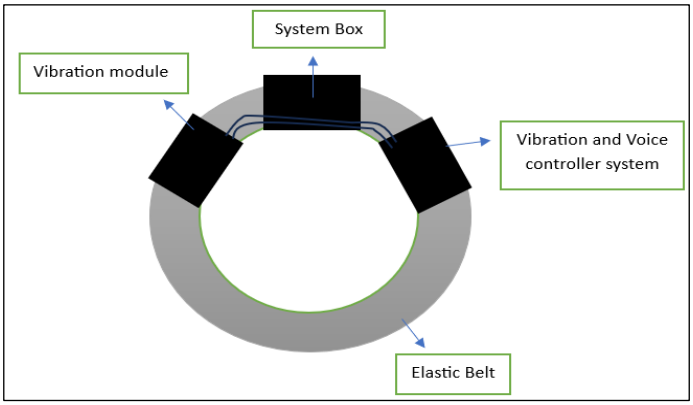


Figure 8: Prototype of Animal belt.
Source: Authors, (2025).

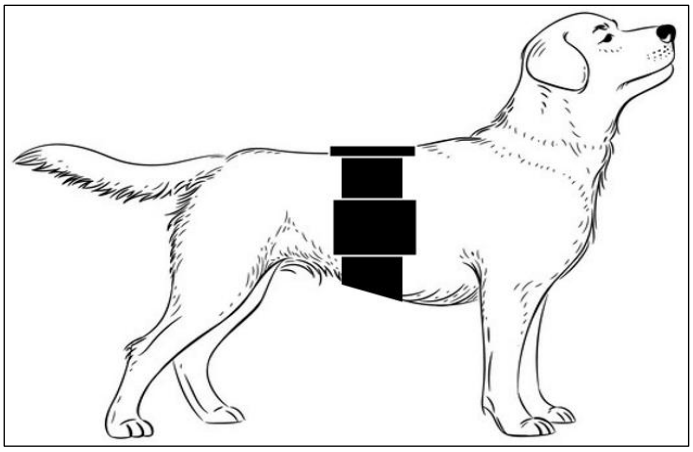


Figure 9: Application of belt.
Source: Authors, (2025).

The belt includes a feature to assist in case of pet loss. If the pet strays beyond 1 kilometer from the geofence center and exceeds a set speed threshold, specific voice commands are activated to aid in rescue during potential kidnapping scenarios. These commands are:

1. "This animal is under military-trained surveillance."
2. "This pet is subject to real-time GPS location tracking."
3. "Law enforcement authorities have accessed the pet's current location and are actively pursuing it."

The elastic belt's design, lacking hooks or buttons, makes removal difficult for kidnappers. It is secured tightly and must be worn by passing it through the pet's back legs. The belt also emits vibrations every 10 seconds to hinder quick removal. Users can customize these voice commands to suit regional languages, ensuring clear communication across diverse linguistic backgrounds.

V. RESULTS

The testing phase produced notable results regarding the system's performance, particularly during geofence assessment. With the geofence radius set at 300 meters, the system consistently demonstrated reliable operation. Table 2 summarizes the empirical analysis, confirming the system's effectiveness in accurately defining and enforcing spatial boundaries for pet mobility.

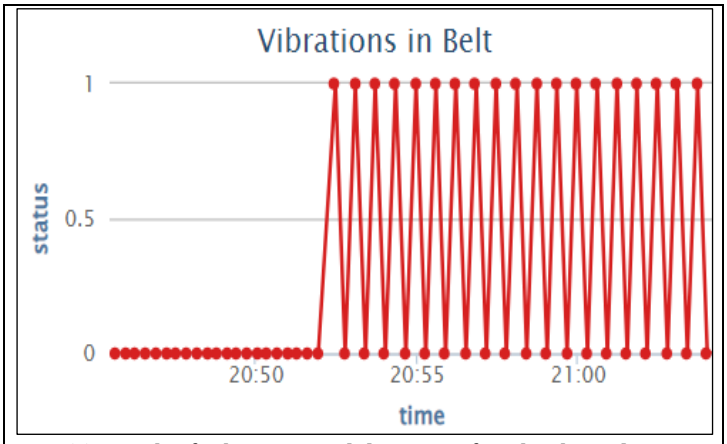
Table 2: Geofence alert system performance.

No. of Attempts	Pet distance from Geofence center in meters(m)	System status (vibration and audible commands)
1.	440m	ON
2.	210m	OFF
3.	755m	ON
4.	179m	OFF
5.	620m	ON
6.	2207m	ON
7.	1405m	ON

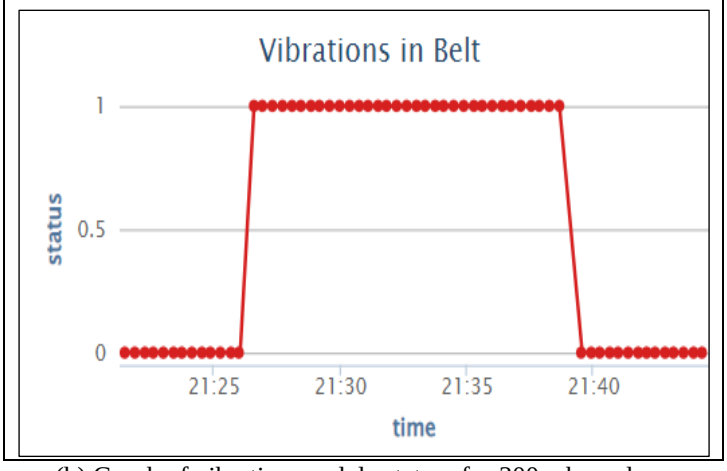
Source: Authors, (2025).

The data illustrates that the system remained inactive when the pet was within the 300-meter radius, as seen in attempts 2, and 4. Conversely, the system activated when the pet exceeded the geofence boundary, as evidenced in attempts 1, 3, 5, 6, and 7.

The following graphs illustrate the system's performance fig.10(a) depicted the operational status of the vibration module before and after breaching the geofence boundary and subsequently moving 1 km from the center. The module activated a vibration every 10 seconds once the predefined condition is met. Fig.10(b) demonstrated the vibration behavior when the pet is within the designated region, initiates continuous vibration upon exiting the region, and ceases vibrating once the pet returns to the owner inside the geofence boundary.



(a) Graph of vibration module status- for 1km boundary



(b) Graph of vibration module status- for 300m boundary

Figure 10: Vibration status in belt.

Source: Authors, (2025).

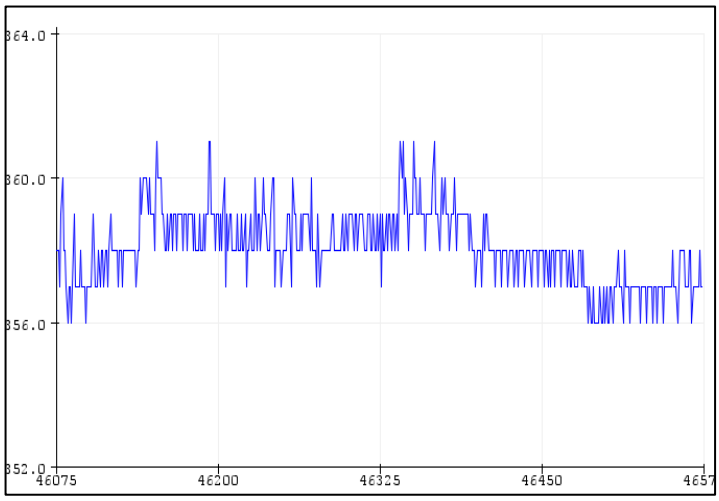


Figure 11: Vibration signal waveform.

Source: Authors, (2025).

Fig. 11 displays the vibration signal graph obtained during testing. The x-axis shows time (46075-46575), and the y-axis shows the vibration intensity as ADC values (352-364). This graph illustrates the belt's vibration intensity over a 5 seconds interval. Each data point is recorded every 10 millisecond. A prominent spike is observed in the graph, reaching an ADC value of 360 and above. This indicates a sudden increase in vibration intensity, caused by an external impact or force acting on the belt at that moment.

VI. DISCUSSIONS

The development of the pet belt system, incorporating advanced geo-fencing technology and mobile app management, signifies a substantial leap in pet safety and control. Utilizing vibration feedback for guiding pets within predefined boundaries, the system exhibited high reliability within a 300-meter radius during testing. Customizable settings enhance training efficacy and boundary enforcement, catering to diverse pet behaviors and temperaments, thus providing a tailored and humane management approach.

The integrated location tracking feature enhances safety during outings, mitigating concerns regarding pet loss and kidnapping. However, the system faces challenges, primarily due to the high power consumption associated with GPS technology, necessitating frequent recharging. Additionally, the initial cost may exceed that of traditional solutions, potentially limiting accessibility.

Dependence on mobile app management could also present usability challenges for non-tech-savvy individuals or those without compatible smartphones. When compared to other pet tracking studies, the GPS integration in the pet belt system is noteworthy for its superior accuracy and unlimited range, unlike RFID and Wi-Fi technologies, which are less effective outdoors. The design judiciously balances the advantages of GPS for outdoor tracking with the challenges of power consumption. The implications of this study are significant.

The pet belt system offers a modern, tech-driven solution for pet safety, establishing a new standard for training and management. Future enhancements, such as solar-powered components and real-time health monitoring, could further optimize performance and sustainability, potentially inspiring similar innovations in animal monitoring.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Harshal Ambadas Durge.
Methodology: Harshal Ambadas Durge.
Investigation: Harshal Ambadas Durge.
Discussion of results: Harshal Ambadas Durge, Vijay Mahadev Mane.
Writing – Original Draft: Harshal Ambadas Durge.
Writing – Review and Editing: Harshal Ambadas Durge, Vijay Mahadev Mane.
Resources: Vijay Mahadev Mane.
Supervision: Vijay Mahadev Mane.
Approval of the final text: Harshal Ambadas Durge, Vijay Mahadev Mane.

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IX. CONCLUSION

The innovative pet belt system, utilizing advanced geo-fencing technology and a user-friendly mobile app interface, represents a substantial advancement in pet management solutions. By automating boundary control and eliminating the necessity for traditional leashes, the system significantly enhances pet safety and owner convenience. The integration of customizable vibration feedback and voice command playback through the app further augments control and communication between pet owners and their animals. This system offers distinct advantages over traditional rope belts and existing monitoring solutions, including precise boundary control and reduced human effort. Potential applications extend beyond pet management to wildlife conservation and elderly care, demonstrating its versatility and broad impact. These extensions could help mitigate human-wildlife conflicts, ensure the safety of cognitively impaired individuals, and provide advanced safety solutions.Future research should focus on improving the accuracy of geo-fencing technology and enhancing the responsiveness of the vibration feedback mechanism. Current studies are exploring AI-driven behavioral analysis and the integration of biometric sensors, aiming to adapt the system to individual pets' habits and monitor their health in real-time. These advancements will enhance the system's functionality and reliability, unlocking new possibilities for automated boundary control applications across various fields.

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RESEARCH ARTICLE OPEN ACCESS

FAULT DIAGNOSIS AND FAULT TOLERANT CONTROL STRATEGY FOR INTERLEAVED BOOST DC/DC CONVERTER DEDICATED TO PEM FUEL CELL APPLICATIONS

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ABSTRACT

This paper proposes an improved fault diagnosis and fault tolerant control (FTC) strategy for interleaved boost DC/DC converter that is suitable for fuel-cell applications. This paper investigates a two-phase interleaved boost DC-DC converter. This design offers several advantages, including: Low ripple current, by splitting the load current between two phases, the ripple current at the input and output is significantly reduced compared to a single-phase converter. Reduced semiconductor stress, Each phase handles only a fraction (1/N) of the total current, which reduces stress on individual components and promotes higher reliability and operating margins. Furthermore, the paper proposes and evaluates an H-infinity controller for the converter. This advanced control strategy ensures robust performance despite variations in reference voltage and load conditions. The power converter suffers from failure switching due to various factors. To address these drawbacks and achieve both accurate reference tracking with desired dynamic response and rapid fault detection, an algorithm based on current-slopes are proposed. Minimizing current ripples is crucial to ensure the longevity of PEMFCs, so the interleaved boost converter structure is dedicated to the PEMFCs in order to reduces the ripple of the generated current. The overall system has been simulated using MATLAB/Simulink software under different conditions such as reference voltage variation, load variation, and Short Circuit default; the obtained results in different phase demonstrate the higher performance, of the proposed systems in terms of dynamic performance, fast fault detection and fault tolerant action to restore the health stat.

I. INTRODUCTION

PEMFCs offer a compelling future for environmentally friendly sustainable power generation, particularly in aviation, automobiles, and shipping. Their appeal lies in several key advantages: minimal environmental pollutants, quiet operation, low operating temperatures, and high efficiency. [1-2].

The PEMFC system exhibits a non-linear relationship between voltage and current (V-I) [3]. The voltage and current are directly proportional to the generated power level.

Undoubtedly, fluctuations in current have been demonstrated to negatively impact the operational lifespan of Polymer Electrolyte Membrane Fuel Cells (PEMFCs). To address this, integrating a power interface necessarily required. This interface serves two key purposes: stabilizing the output voltage and mitigating current ripples by employing a DC-DC converter, we can effectively regulate the FC output voltage, eliminating inconsistencies and protecting the PEMFCs, ultimately extending their lifespan [4].A DC–DC converter can be used to adjust the output voltage value of the renewable energy sources (PEMFC) [5] It's essential to minimize the ripple current in the PEM fuel cell. [6]

Furthermore, several control strategies have been employed for interleaved converters, each with its own advantages and limitations. PI control based on the average model is a simple and popular approach, but it can be less effective at handling nonlinearities and varying operating conditions [1]. In [7-9] a linear quadratic mode controller is designed this method offers improved robustness against disturbances.

Semiconductors are much more likely to fail than in other application areas, with over 30% of switch failures. These failures can be broadly grouped into two types: short circuit faults (SCF) and open circuit faults (OCF). Because of this, early fault diagnosis is crucial for finding and fixing switch failures. [10]

In [11] deals with open switch faults detection and localization in shunt active three-phase filter based on two level voltage source inverter [11].

In [12] focus on the diagnosis of short-circuited turns fault in BLDC motors. The proposed approach is based on residual generation using a first order sliding mode observer which has been widely used for BLDC sensorless control.

In [13] focuses on define the fault classification and then give an example of modeling and introduce a fault detection method to detect the assumed faults.

A switch fault diagnosis technique based on a Luenberger observer is presented in [14] for the dc-dc interleaved boost converter for fuel cell (FC) application.

Shahbazi. et al. [15] has investigated FD in non-isolated dc-dc converters using FPGA. The sign of the input current slope and switch gate edge type are used to detect the fault.

Firstly, this paper present a comparative study between a simple PI controller and H∞ robust controller of an interleaved boost converter in order to Current ripple reduction from the PEM Fuel cell and to Tight output voltage regulation at the required value without failure mode.

Secondly, this paper proposed a new algorithm fault detection in dc-dc boost converter based on input current slope for Short Circuit power switch failure mode and fault tolerant actions to restore healthy state.

This paper is organized into three section areas: Section 2 Introduces the Proton Exchange Membrane Fuel Cell (PEMFC). In section 3, Explores the DC-DC boost converter, delving into its presentation and modeling. In section 4, Focuses on the interleaved boost DC-DC converter, providing details and its presentation. In section 5 focuses on the development of an algorithm for the diagnosis of switch failures. The proposed algorithm aims to enhance converter resilience and availability through early detection of switch malfunctions.

Presents and discusses the simulation results obtained for the proposed the control for interleaved boost converter ‹The discussion covers both healthy and failed operational conditions, providing valuable insights into its performance and robustness in section 6.

Finally, Key findings and insights are summarized and the paper's most significant contribution in the concluding section 7.

II. PEMFC PRESENTATION

In this section, the mathematical model is derived for a fuel cell stack

We'll unravel the key chemical reactions at the anode, cathode, and within the entire process, laying the foundation for understanding the precise equations that govern this technology.

Anode:

$$H{=}2H^{+} + 2e^{-} \qquad (1)$$

Cathode:

$$\frac{1}{2}O_2 + 2H^{+} + 2e^{-} = H_2O \qquad (2)$$

Global reaction:

$$H_2 + \frac{1}{2}O_2 = H_2O \qquad (3)$$

Figure 1 presents the single cell's static V-I polarization curve, The significant voltage drop in Fig. 1 is stack voltage stems from three primary losses, Notably, at low current levels, ohmic loss becomes negligible and the voltage rise primarily results from slower chemical reactions. This region is aptly named "activation polarization." At very high current density the voltage plummets considerably due to diminished gas exchange efficiency.[9-16],[17]

$$V_{FC} = E - V_{ac} - V_{ohm} - V_{con} \qquad (4)$$

Where:

VFC : Open-circuit voltage of PEMFC
E : thermodynamic voltage
Vac : activation losses
Vohm : ohmic losses
Vcon : concentration losses

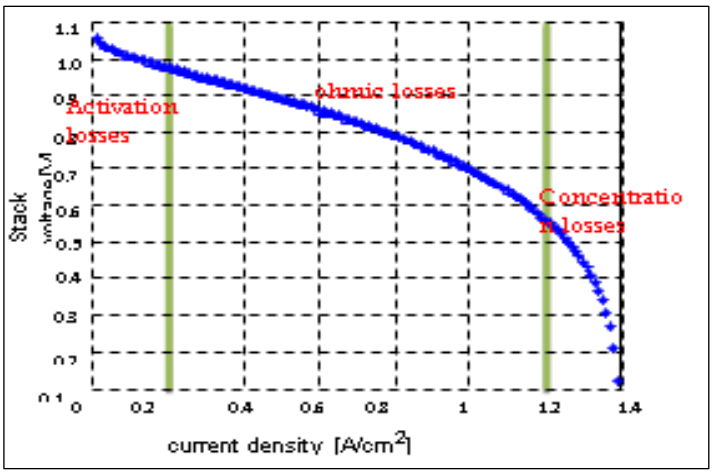

Figure 1: V-I characteristic of a PEM fuel cell.
Source: Authors, (2025).

The distributed nature of phase interleaving allows the converter to manage higher currents, making it ideal for high-power applications thanks to its unique structural advantages [18].

III. MODELING AND CONTROL OF DC-DC BOOST CONVERTER

III.1 MODELING OF BOOST CONVERTER

In the realm of power electronics, the DC-DC boost Converter plays a crucial role by takeing a lower DC voltage to a higher, desired level. As illustrated in Figure 2 the converter is showed.

The DC-DC boost converter comprises several key components: an inductor, a MOSFET switch, a rectifier diode, and an output capacitor. The inductor acts as an energy reservoir, storing energy during the switch's ON-time and releasing it when the switch is OFF. The switch control the converter ON or OFF; the diode element enforces unidirectional energy flow, and the output capacitor stores to deliver stabilized power to the load [19].

The duty cycle of the boost converter is generally controlled via pulse width modulation (PWM).[20].

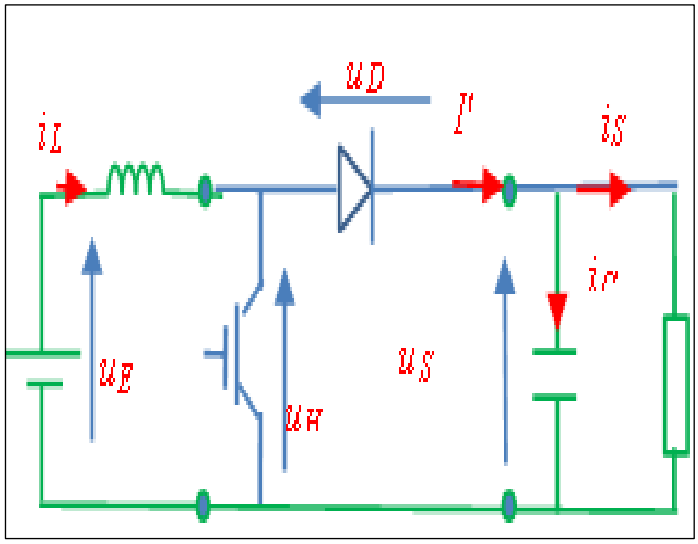

Figure 2: fundamental schematic of a DC-DC boost converter.
Source: Authors, (2025).

Let's analyze the DC-DC converter's governing equation. Specifically, let's identify the model.

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(U_E - U_H) \\ \frac{du_S}{dt} = -\frac{1}{RC}u_S + \frac{1}{C}I' \end{cases} \quad (5)$$

We calculate the mean values of the voltages and currents:

$$\begin{cases} U_H = \frac{1}{T}\int_{\alpha T}^{T} U_S\, dt = \frac{U_S}{T}(T - \alpha T) = u_s(1-\alpha) \\ I' = \frac{1}{T}\int_{\alpha T}^{T} i_L\, dt = \frac{i_L}{T}(T - \alpha T) = i_L(1-\alpha) \end{cases} \quad (6)$$

By replacing UH, I' in Eq. (5),
The model is:

$$\begin{cases} \frac{di_L}{dt} = -\frac{1-\alpha}{L}u_s + \frac{U_E}{L} \\ \frac{du_s}{dt} = \frac{1-\alpha}{C}i_L - \frac{1}{CR}u_s \end{cases} \quad (7)$$

We can linearize the behavior of the model with the equilibrium point:

$$\begin{cases} u_{s0} = \frac{U_E}{1-\alpha_0} \\ i_{L0} = \frac{U_E/R}{(1-\alpha_0)^2} \end{cases} \quad (8)$$

Applying the Laplace transform to the model in in Eq. (7), we obtain the following representation :

$$\frac{\Delta u_S}{\Delta \alpha} = -\frac{U_E\left[\frac{S}{RC(1-\alpha_0)^2} - \frac{1}{LC}\right]}{\left[S^2 + \frac{S}{RC} + \frac{1}{LC}(1-\alpha_0)^2\right]} \quad (9)$$

III.2 PI CONTROL

The controller employs a proportional gain (Kp) to enhance system dynamics and an integral term with gain (Ki) to ensure accurate steady-state tracking. The PIDTOOL instruction within the direct closed-loop system facilitates the synthesis of these optimal Kp and Ki values. [1] [21]

III.3 H∞ MIXED SENSITIVITY CONTROL DESIGN

A H∞ regulator ensures precise regulation the output voltage of the DC-DC converter as presented in Figure 3.

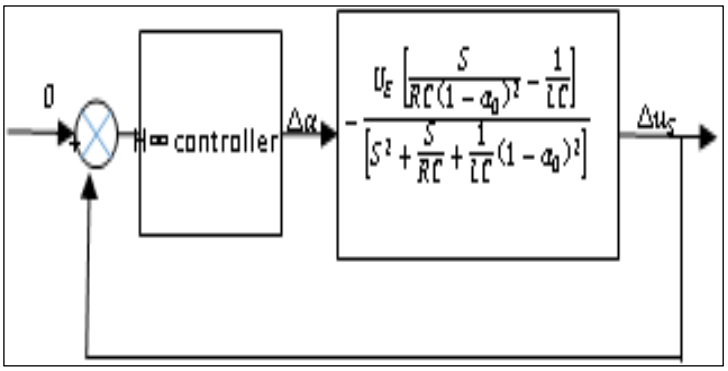

Figure 3: voltage controller.
Source: Authors, (2025).

To impose some dynamical performances in a H∞ control , it is necessary to include some weighting filters. In the proposed design, two weighting filters W1(s) and W2(s) are included in the Plant [22]

The parameters of the H∞ controller are designed using the transfer function given by Eq. (9) as follows:
the weighting function ws(s) is chosen as:

$$Ws(s) = \frac{0.6667*s+495.9}{s+0.002.48}$$

The weighting function Wu2 is defined as:
$Wu(s) = 1$

The "hinfsyn" tools is used to performed the design of the H∞ mixed sensitivity controller K(s).

The H∞ mixed sensitivity current loop controller is described as:

$$K_{\infty Voltage}(s) = \frac{6436*s^2+2.575e06*s+6.436e09}{s^3+7.421e04*s^2+2.733e09*s+8.2e06}$$

IV. INTERLEAVED BOOST CONVERTER PRESENTATION

In a two-phase interleaved converter, the parallel converters switch ON and OFF at staggered times, separated by half the switching period (T/2). Both branches operate with identical duty cycles.

The average model of the IBC is the same as the conventional boost DC-DC converter the IBC's distinct characteristic is the presence of two current inductors.

Interleaved boost converters (IBCs) enable high current flow while significantly reducing input current ripple. Figure 4 illustrates the IBC topology.

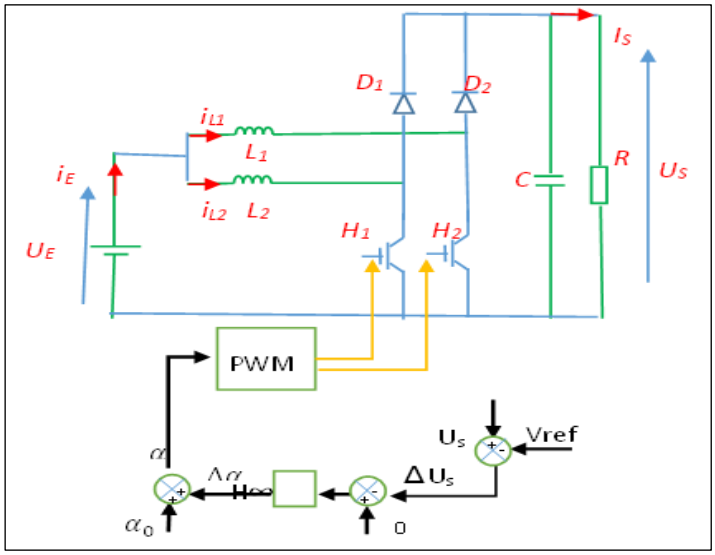

Figure 4: DC-DC Interleaved boost converter.
Source: Authors, (2025).

V. FAULT DIAGNOSIS

We propose a new general fault detection method for the conversion DC to interleaved DC, based on an algorithm to detect any type fault open-circuit (OCF) or short-circuit (SCF) occurring at the switch orderable. The algorithm is based on observing the waveform of the current flowing through the inductor. We mention right now that this algorithm is very fast and is robust and effectively detects all types of faults in all conditions.

Fault detection is a two-step process involving fault time logging and fault alarm generation. Subsequent to these steps, automatic restoration mechanisms are employed to enable the process to recover its secure operational state. [23]

This method characterized by:

- high robustness
-very fast for Detection
-low Implementation Effort
- low cost
- Do not depend on load

This algorithm is based on the following principle (see Figure **5**):

Normal operation, when the SW controllable switch is closed, the current at through the inductance (iL) then increases that when the same switch is opened, the Current iL decreases. the current slope sign iL changes simultaneously with the command order of the SW switch. In practice, in particular because of the effects of switching and SW driver downtime, there is a Td delay between the order change of control of the SW switch and its effective change of state.

We would like to point out here that it is not useful to know the exact value of diL/dt, but only its sign. So, we can use a simple and effective method so that the fault detection process is not too complex and does not require too much processing time, to the detriment of the temporal performance of the detection method.

Since our method is intended to be implemented digitally, we propose estimate the length of time that the err signal is equal to '1' (under normal operation, this duration is denoted Ts in Figure 6). We then built the detection offered on a signal called Trig. This signal consists of a series of pulses of short duration (equal to Ts), equal to '1' and generated at the beginning of each operation, when switching to '1' of the signal. After each pulse of the Trig signal, the current in the inductance must then increase, and then decrease. If this current iL is always increasing or decreasing between the two pulses of the Trig signal, it can be concluded that a fault has occurred. A counter, shown on the Figure 6 shows this duration, quantified in terms of the number of periods sampling Ts" and denoted nc. When the err signal is equal to '1', the nc output of The counter increments with each clock rising edge (active edge). The value of nc is reset after each descending edge of the err signal. The resulting nc signal is a "Sawtooth" type signal. The maximum value achieved is directly related to two quantities: the time during which the err signal is equal to '1' (duration Td, Figure 6) and the value of Ts (Td = nc *Ts).

Next, the nc signal is compared with its N-rated threshold value. This threshold must be greater than the maximum nc value during normal operation of the converter.

The absolute value of the error $|err|$ signal is "constantly monitored": this means that The fault must be executed in parallel with the control algorithm of the converter. If this err signal remains in the '1' state for a longer period of time than NTc, we concludes that there is a failure. In Figure 6, we can visualize the Schematic representation of fault detection by the FD algorithm. This block has an output (FD), three nc, $|err|$ and SdiL inputs, one clock input and one Reset (Rst) input for reset. [24]

From these two sampled values of the current iL ,the SdiL1 function is compare the current slope to zero:

If the dIL1 is positive, the SdiL1 is 1
Else the SdiL1 is equal 0, We can So write:

$$\begin{cases} S\,\frac{di1}{dt} = 1 \; t\epsilon[0, DT_s] \\ S\,\frac{di1}{dt} = 0 \; t\epsilon[DT_s, T_s] \end{cases} \quad (9)$$

The difference between SdiL1 and State Switch K1, gives us the absolute value of the error $|err|$:

$$|err| = \text{State Switch K1 - SdiL1} \quad (11)$$

In normal operation, without failure, we must have:

$$Td < nc * Ts \quad (12)$$

After the fault detection, and its isolation, the proposed control reconfiguration methodology implements corrective actions, enabling the DC-DC Interleaved Boost Converter to resume pre-fault operation. Simulations in MATLAB/Simulink validate the approach's effectiveness. Notably, the suggested algorithm is simple, and easy configurability.

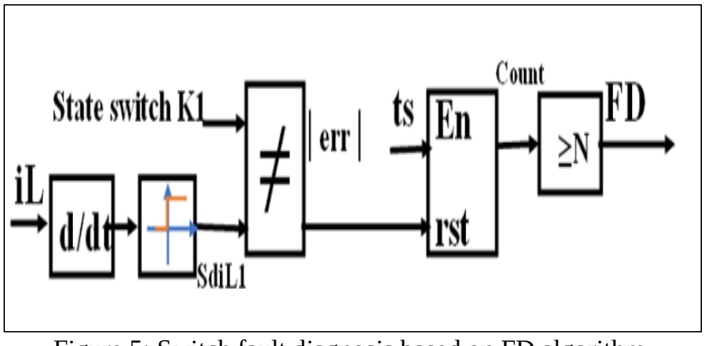

Figure 5: Switch fault diagnosis based on FD algorithm.
Source: Authors, (2025).

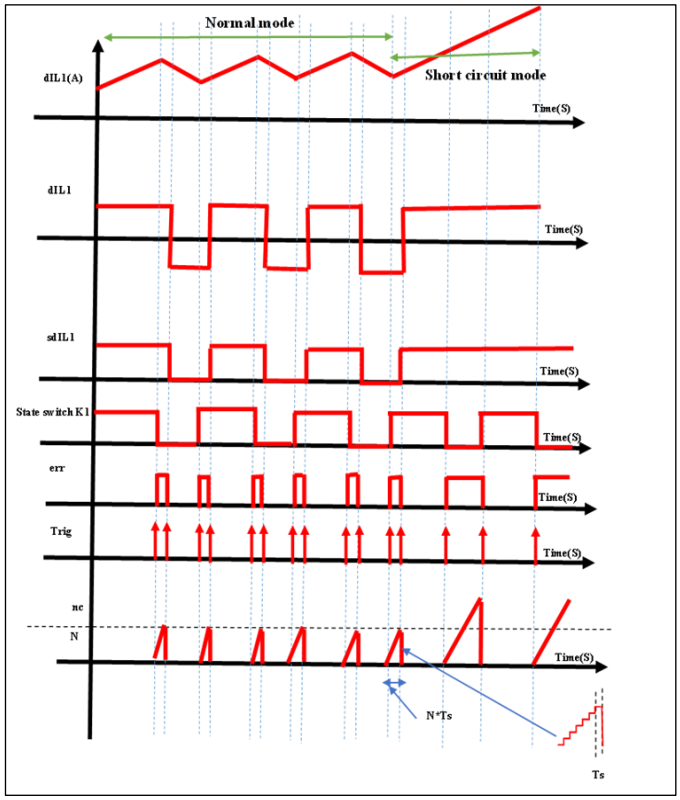

Figure 6: Main signals of the DF algorithm during a under short circuit fault.
Source: Authors, (2025).

VI. RESULTS AND DISCUSSIONS

The Table I below outlines the parameters of a DC-DC interleaved boost converter, The following subsections evaluate and compare the performance of each controller.

Table 1: DC-DC interleaved boost converter parameters.

PARAMETERS	E	L1	L2	C	F	R
VALUE	40 V	5MH	5MH	50 μ F	20 KHZ	50 OHMS

Source: Authors, (2025).

The Values of the parameters of the H∞ and PI controllers are given in Table II

Table 2: parameters of the controllers.

SWITCHING FREQUENCY	20 KHZ
KP	0.00037088
KI	0.4619
WS(S)	(0.4*S+180)/(S+0.003)
WU(S)	1

Source: Authors, (2025).

VI.1 VARIABLE REFERENCE OUTPUT VOLTAGE

The H∞ controller effectively regulates the system for both transient and steady-state conditions, as demonstrated in Figure 7, Increasing the reference output voltage, also shown in Figure 7, results in a proportional increase in IBC currents iL1, iL2, and iL depicted in Figure 8 and Figure 9 respectively.

The interleaved boost structure effectively reduces the absorbed current ripple. The IBC design ensures consistently low current ripple across different output voltage phases, regardless of fluctuations in the output reference voltage (as demonstrated in in Figure 9). Notably, Figure 10 illustrates the corresponding duty cycle behavior, where higher reference voltages translate to increased duty cycle values.

The state commutation of switch K1 is clearly 20 kHz, as illustrated in Figure 11.

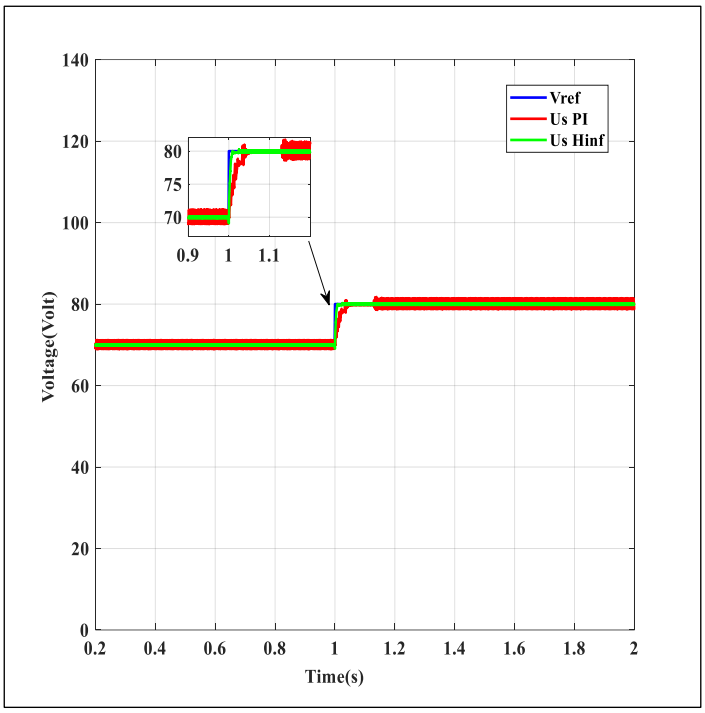

Figure 7: output voltage of the DC-DC converter under voltage variation.
Source: Authors, (2025).

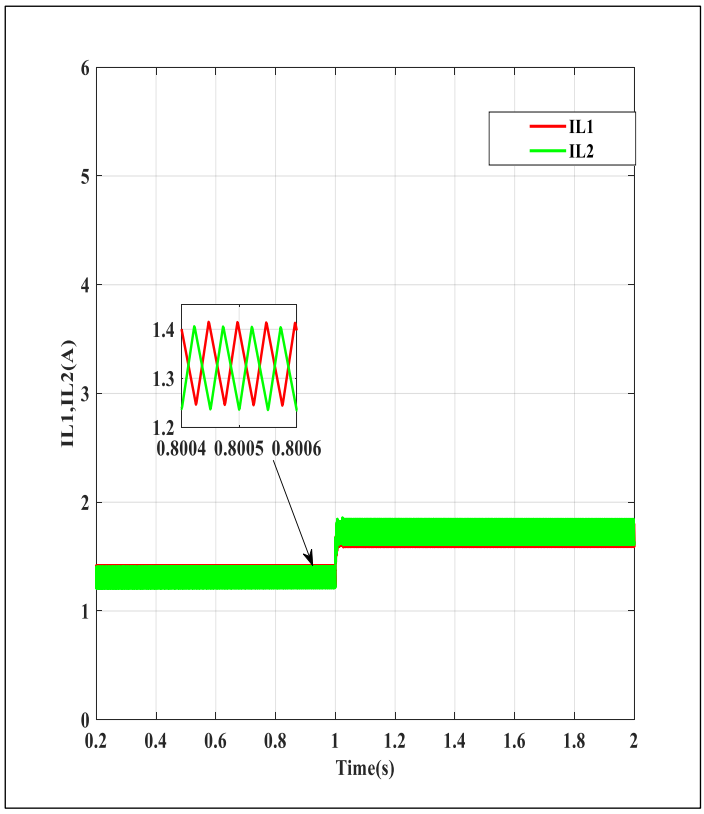

Figure 8: Waveform of branch currents iL1, Il2 under voltage variation.
Source: Authors, (2025).

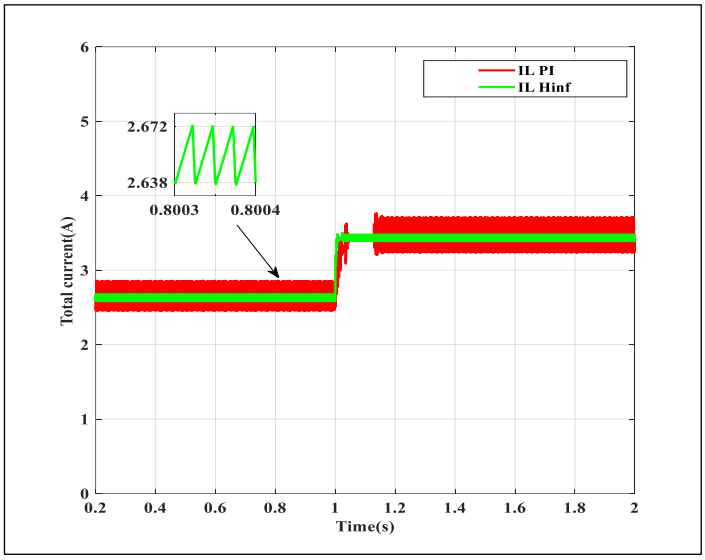

Figure 9: Waveform of total current under voltage variation.
Source: Authors, (2025).

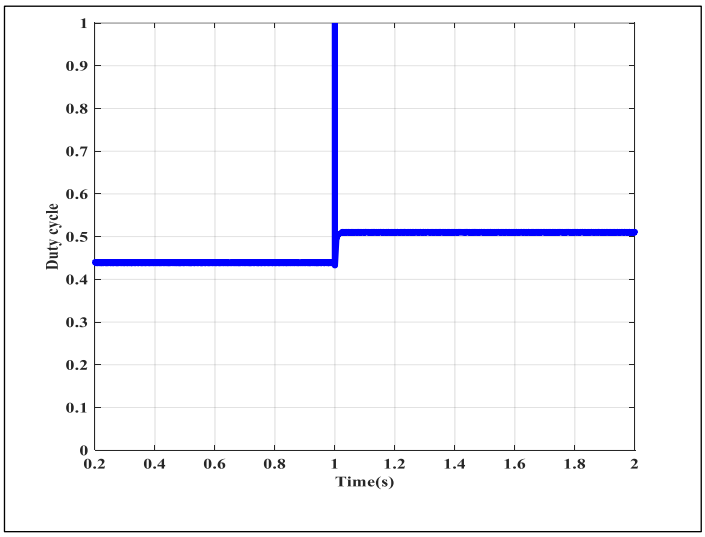

Figure 10: Duty cycle evolution under voltage variation.
Source: Authors, (2025).

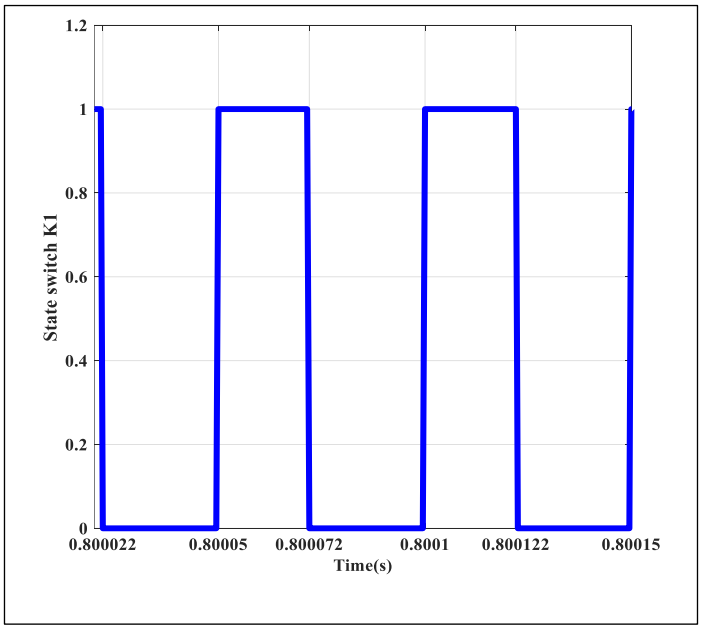

Figure 11: State Switch commutation.
Source: Authors, (2025).

VI.2 FAULT DETECTION METHOD

This section outlines the different steps involved in the proposed fault detection method implemented using MATLAB/Simulink.

Firstly, a Short-Circuit Fault (SCF) is simulated on the first power switch of a two-stage interleaved boost converter. This is achieved by connecting a normally- off ideal switch in parallel with the first switch, which switch-on at tfault =7ms, effectively short-circuiting the switch Figure 12 depicts the system's response under the simulated SCF scenario.

It is obvious that the converter structure is fault tolerant. We can only note a minor degradation in performance.

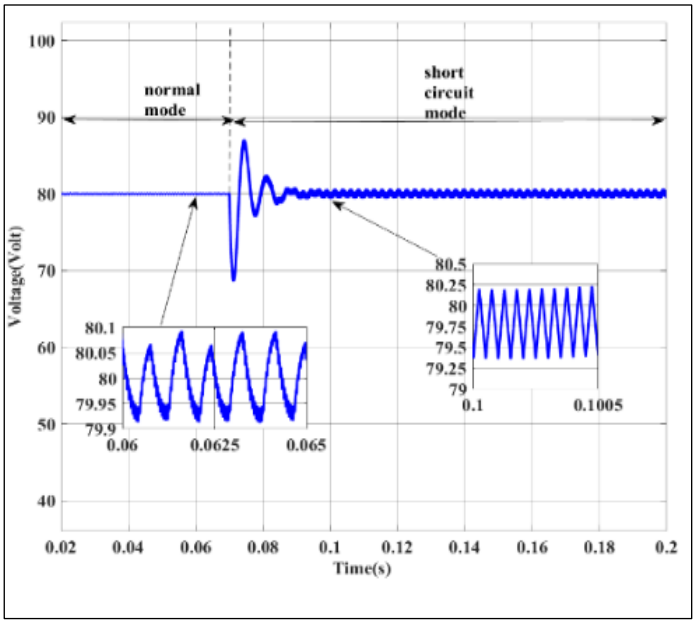

Figure 12: output voltage of the DC-DC converter under short circuit fault.
Source: Authors, (2025).

Figure 13 shows the evolution of currents iL1 , iL2 and iL , before and after the fault.

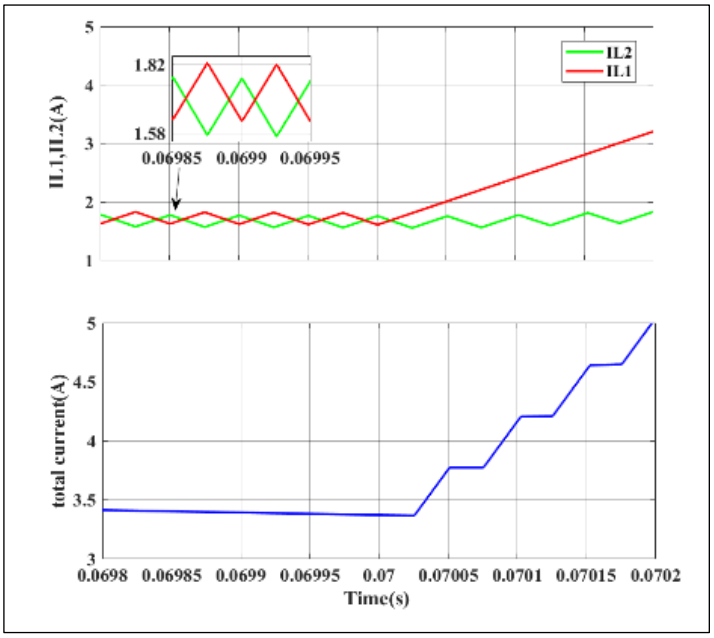

Figure 13: Waveform of IL1, Il2 and IL under short circuit fault.
Source: Authors, (2025).

The process of fault detection using the proposed method is described in detail in the following simulation results.

Figure 14 shows the control signal. the difference between the diL1 current derivation signal and the switch 1 control signal represents the time required for the switch to be opened or to be closed. see Figure 14 (healthy mode).

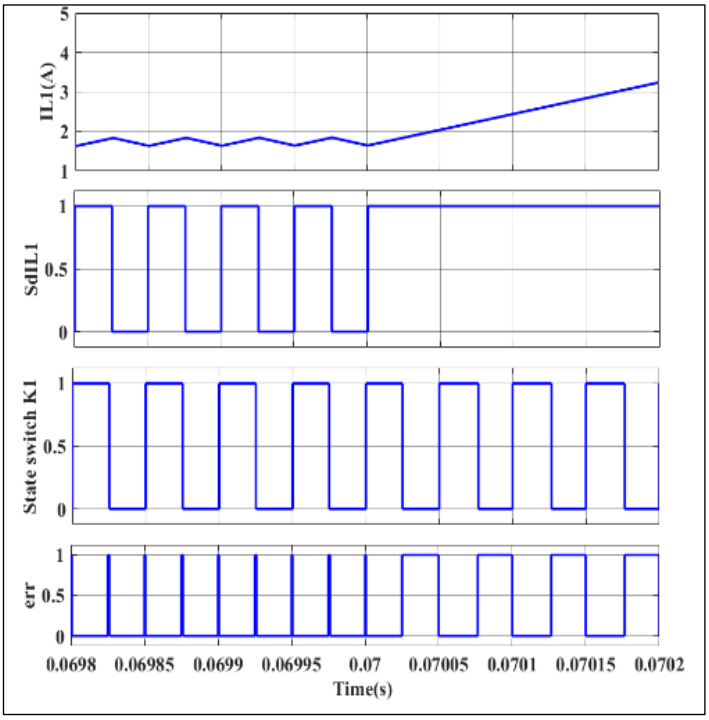

Figure 14: Waveform of IL1, sdIL1,state switch K1 and err under short circuit fault.
Source: Authors, (2025).

A counter is used to convert the time required to open or close the power switch into N*Ts (see Figure 15).
This N*Ts must not exceed 20 microseconds (normative delay). if this time is exceeded, the fault is detected as shown in Figure 16.

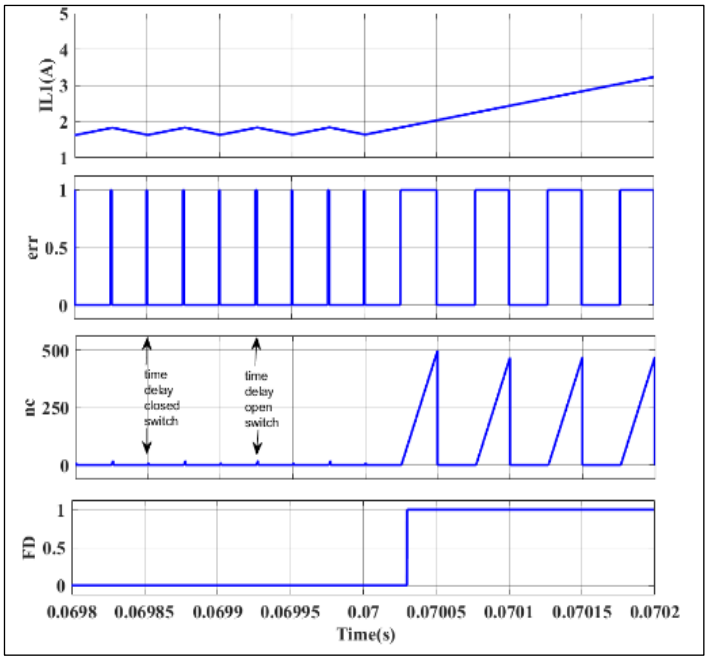

Figure 15: Waveform of IL1, err, nc and FD under short circuit fault.
Source: Authors, (2025).

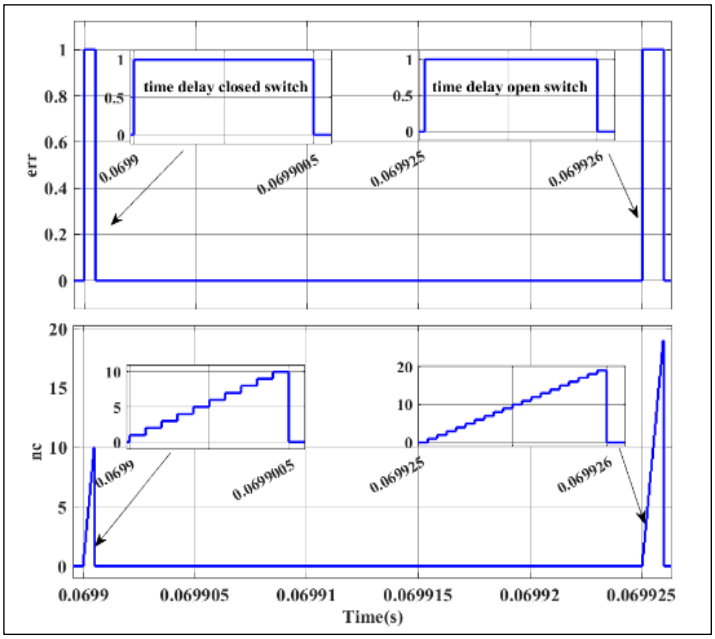

Figure 16: Waveform of the time required to open or close the power switch.
Source: Authors, (2025).

Normal operation, we note that (the time delay closed circuit is deferent for the time delay open circuit (Td_closed=5e-7s, Td_open=1e-6s)

VI.3 FTC FOLLOWING A DCC DETECTED BY DF ALGORITHM (R= 50)

A fault tolerant control is used in the event of a fault being detected, which consists of isolating the faulty converter stage. Figure 17 shows the evolution of currents iL1 and iL2. In the event of a fault on power switch 1, stage 1 is isolated (iL1 becomes zero as shown in Figure 17).
we note only a minor degradation in performance.

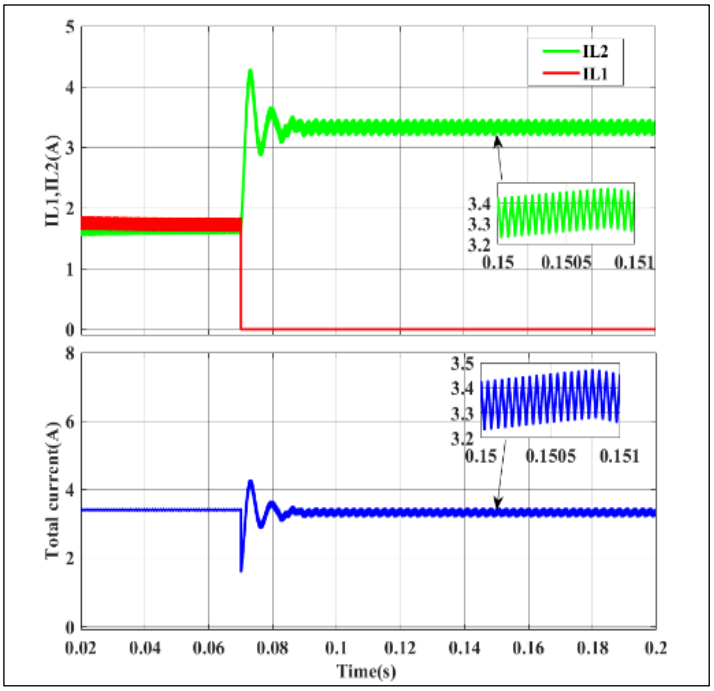

Figure 17: Waveform of IL1, IL2 and IL under fault tolerant control.
Source: Authors, (2025).

V. CONCLUSIONS

In this paper a fault diagnosis and fault tolerant control (FTC) strategy for interleaved boost DC/DC converter is discussed. The structure proposed allows the reduction of the undulation of the current delivered by the PEMFC, and the reduction of the stresses on the semiconductors.

Also, this paper introduces a technique based on H∞ controller used to regulate the output voltage of the interleaved boost DC/DC converter operating in continuous conduction mode. After converter modeling and H∞ controller design, MATLAB/Simulink simulations were conducted to evaluate controller performance under varying desired output voltages and load conditions.

Also, this paper proposes a new general fault detection method based on an algorithm to detect any type fault open-circuit (OCF) or short-circuit (SCF).

The algorithm is based on observing the waveform of the current flowing through the inductor.

As a final conclusion, that the proposed system offers good performances under different conditions such as reference voltage variation and Short Circuit default. The obtained results in different phase demonstrate the higher performance, of the proposed systems in terms of dynamic performance, fast fault detection and fault tolerant action to restore the health stat.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Belkheir Abdesselam, Amar Benaissa, Ouahid Bouchhida, Samir Meradi , Mohamed Fouad Benkhoris .
Methodology: Belkheir Abdesselam, Amar Benaissa, Ouahid Bouchhida, Samir Meradi , Mohamed Fouad Benkhoris .
Investigation: Belkheir Abdesselam, Amar Benaissa, Ouahid Bouchhida, Samir Meradi , Mohamed Fouad Benkhoris .
Discussion Of Results: Belkheir Abdesselam, Amar Benaissa, Ouahid Bouchhida, Samir Meradi , Mohamed Fouad Benkhoris .
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Resources: Belkheir Abdesselam, Amar Benaissa, Ouahid Bouchhida, Samir Meradi , Mohamed Fouad Benkhoris .
Supervision: Belkheir Abdesselam, Amar Benaissa, Ouahid Bouchhida, Samir Meradi , Mohamed Fouad Benkhoris .
Approval Of The Final Text: Belkheir Abdesselam, Amar Benaissa, Ouahid Bouchhida, Samir Meradi , Mohamed Fouad Benkhoris.

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RESEARCH ARTICLE OPEN ACCESS

TRANSFORMER-BASED OPTIMIZATION FOR TEXT-TO-GLOSS IN LOW-RESOURCE NEURAL MACHINE TRANSLATION

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ABSTRACT

Sign Language is the primary means of communication for the Deaf and Hard of Hearing community. These gesture-based languages combine hand signs with face and body gestures for effective communication. However, despite the recent advancements in Signal Processing and Neural Machine Translation, more studies overlook speech-to-sign language translation in favor of sign language recognition and sign language to text translation. This study addresses this critical research gap by presenting a novel transformer-based Neural Machine Translation model specifically tailored for real-time text-to-GLOSS translation. First, we conduct trials to determine the best optimizer for our task. The trials involve optimizing a minimal model, and our complex model with different optimizers; The findings from these trials show that both Adaptive Gradient (AdaGrad) and Adaptive Momentum (Adam) offer significantly better performance than Stochastic Gradient Descent (SGD) and Adaptive Delta (AdaDelta) in the minimal model scenario, however, Adam offers significantly better performance in the complex model optimization task. To optimize our transformer-based model and obtain the optimal hyper-parameter set, we propose a consecutive hyper-parameter exploration technique. With a 55.18 Recall-Oriented Understudy for Gisting Evaluation (ROUGE) score, and a 63.6 BiLingual Evaluation Understudy 1 (BLEU1) score, our proposed model not only outperforms state-of-the-art models on the Phoenix14T dataset but also outperforms some of the best alternative architectures, specifically Convolutional Neural Network (CNN), Long Short Term Memory (LSTM), and Gated Recurrent Unit (GRU). Additionally, we benchmark our model with real-time inference tests on both CPU and GPU, providing insights into its practical efficiency and deployment feasibility.

I. INTRODUCTION

Sign languages, as visual-gestural forms of communication, are integral components of the linguistic landscape for the Deaf and Hard of Hearing (DHH) community. Unlike spoken languages, sign languages rely on visual and gestural elements, incorporating manual signs, body movements, and facial expressions to convey meaning. This unique modality enables individuals within the DHH community to express themselves with depth and nuance, offering a rich and diverse means of communication. The significance of visual-gestural languages becomes particularly evident when considering the limitations of traditional spoken languages in meeting the communication needs of the DHH community. Spoken languages heavily rely on auditory cues, making them less accessible for those with hearing impairments. In contrast, sign languages provide an inclusive and versatile medium that allows individuals to communicate effectively without dependence on auditory stimuli. Visual-gestural languages play a crucial role in facilitating social interactions, education, and professional engagement within the DHH community. The use of manual signs allows for the expression of abstract concepts, emotions, and complex ideas. Additionally, facial expressions and body language contribute to the linguistic richness of sign languages, enhancing the overall communicative experience. However, the broader societal landscape predominantly relies on spoken languages. This linguistic dissonance results in a noticeable

communication gap that Speech-to-Sign Language translation tools endeavor to address. However, for truly seamless interaction, real-time translation is crucial. Consider a classroom environment where a lecture is being translated, a delay can disrupt the flow of information and hinder understanding. The imperative development and implementation of these tools, particularly those with real-time capabilities, play a crucial role in facilitating effective and inclusive communication between individuals who use spoken languages and those who depend on visual-gestural languages, as these tools play a pivotal role in harmonizing interactions, promoting accessibility across linguistic and cultural boundaries, ensuring equal access to information, opportunities, and social interactions.

The evolution of machine translation has been a dynamic journey, progressing through various phases of development. It began with the early attempts of rule-based systems, as presented in [1], which explored the collaborative role of human translators and machines, emphasizing the synergy required for effective language translation in the early phases. These rule-based systems, however, faced challenges in capturing the complexities and nuances of language due to their reliance on predetermined linguistic rules. The subsequent transition to statistical methods marked a pivotal moment in machine translation's evolution. Brown et al.'s groundbreaking work [2] introduced probabilistic models that significantly enhanced translation accuracy by addressing linguistic variations. This departure from rigid rules allowed the model to learn patterns and relationships from data, enabling more nuanced and context-aware translations. The paradigm shift continued with the advent of neural networks. Ref [3] presented a transformative neural machine translation model with attention mechanisms. Unlike traditional models, this approach allowed the model to selectively focus on distinct sections of the input sequence amid translation. This attention mechanism proved crucial in handling long sentences and capturing contextual information, leading to substantial improvements in translation quality. Building upon this, [4] introduced the transformer architecture, which further refined the attention mechanism. The transformer architecture replaced recurrent layers with self-attention mechanisms, enabling the model to consider dependencies across the entire input sequence simultaneously. This innovation significantly improved the efficiency of training and the model's capacity to represent long-range dependencies, setting new standards in machine translation performance.

Sign language translation has followed a parallel evolution, incorporating diverse approaches to bridge the communication gap between spoken languages and visual-gestural languages. Early contributions include the work of According to [5], who presented a rule-based system for speech-to-sign language translation. Their focus on National Identification Document (NID) and Passport-related content demonstrates the practical application of translation systems. Transitioning to an alternative approach, the Arabic context highlights a significant achievement. An interdisciplinary team, collaborating closely with deaf native signers and an Arabic Sign Language (ArSL) interpreter, developed an example-based machine translation (EBMT) system [6]. This system adeptly translates Arabic text into ArSL, aligning with the unique linguistic nuances and cultural context of the Arabic deaf and hearing-impaired community. The choice of EBMT ensures adaptability to the intricate grammar, structure, and idioms inherent in ArSL.

In contrast to traditional rule-based approaches, recent advancements delve into the integration of Neural Machine Translation (NMT), showcasing the evolving landscape of sign language translation. According to [7] present an innovative synthesis by seamlessly integrating NMT and Generative Adversarial Networks to produce sign language video sequences from spoken language sentences. This approach not only showcases the capabilities of text-to-gloss translation but also underscores the potential for video generation in sign language translation offering a fresh perspective independent of avatars and motion-capture-based methods. In a different vein, [8] focus on the bidirectional translation of sign language, proposing a deep learning approach based on GRU and Long Short-Term Memory (LSTM) models with attention mechanisms. Their work stands out by demonstrating superior performance on ASLG-PC12 and Phoenix-14T corpora, particularly with the GRU model using Bahdanau attention [3]. This highlights the effectiveness of their approach in capturing the linguistic structure and context of natural sign language sentences. For Sign Language Production (SLP), Saunders et al. [9] provide a progressive Transformers architecture that performs end-to-end translation of spoken language sentences into continuous 3D sign pose sequences. Their method addresses the need for architectures more appropriate for continuous sign sequence generation by applying a counter-decoding methodology. By providing benchmarks on the complex PHOENIX14T dataset and establishing a baseline for subsequent studies, Saunders et al. emphasize the importance of continuous sequence synthesis and lay the groundwork for further exploration in the field.

These modern translation methods showcase a notable advancement over earlier techniques. However, several studies shed light on the critical role of hyper-parameter tuning in improving Transformer performance in low-resource neural machine translation (NMT) scenarios. In [10] Araabi and Monz run several experiments on subsets of the IWSLT14 training corpus, they highlight the influence of hyper-parameters on the performance of Transformer models under low-resource scenarios. This study underscores the importance of proper configuration, showing that optimizing Transformer hyper-parameters can lead to an improvement of up to 7.3 BLEU points in translation quality compared to using default settings. Additionally, [11] focus on deep Transformer optimization for translation tasks in low-resource conditions, specifically for Chinese-Thai machine translation. Their exploration of various experiment settings, including the embedding size, dropout probability, and number of BPE merge operations, highlights the significance of choosing optimal configurations, even when dealing with low-resource scenarios. This research reinforces the notion that hyper-parameter optimization is critical to enhancing the performance of Transformer models across different language pairs and data conditions.

Expanding on the existing body of research, and building on our previous work [12], our study investigates the intricacies of optimizing transformers for the real-time text-to-GLOSS translation task, marking the first comprehensive study in this domain. The exploration is initiated by crafting a minimal model for thorough optimizer screening, specifically Adaptive Delta (AdaDelta) [13], Stochastic Gradient Descent (SGD) [14], and Adaptive Moment Estimation (Adam) [15], Adaptive Gradient (AdaGrad) [16]. Subsequently, harnessing the potential of the best optimizers, we employ an innovative hyper-parameter exploration technique tailored for Transformers. This methodology enables us to discern the optimal architecture for sign language translation, thereby making a significant contribution to the field of NMT for sign language processing.

Within this scope, the key contributions of this study are:

- We propose a novel hyper-parameter exploration technique for Transformer-based architectures on low-resource tasks, and use it to create a real-time text-to-GLOSS sequence-to-sequence translation model.
- We investigate the performance of AdaDelta, SGD, AdaGrad, and Adam optimizers on low-resource sequence-to-sequence tasks and evaluate their performance on Transformer models.
- We evaluate the proposed model's performance on the PHOENIX-14T corpus, demonstrating superior performance using the Bi-Lingual Evaluation Understudy (BLEU), and the Recall-Oriented Understudy for Gisting Evaluation (ROUGE) metrics.
- We compare our model's performance with other sequence-to-sequence architectures like GRU, CNN, and LSTM.

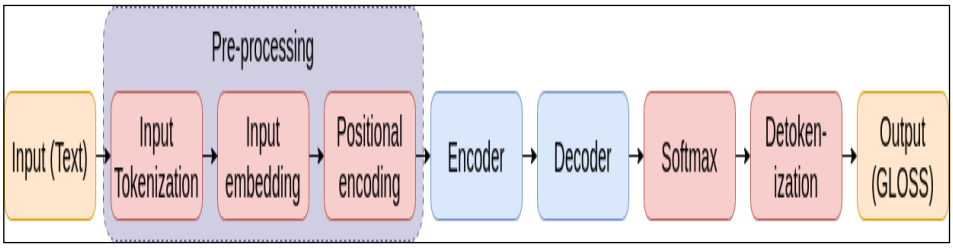

Figure 1: Proposed pipeline for Text-to-GLOSS Neural Translation
Source: Authors, (2025).

I.1. PROPOSED METHODOLOGY

In this section, we will present the resources necessary to understand our methodology approach and provide an overview of each of these elements. First, we will introduce our pipeline and describe each of the steps used to process the input text and generate the GLOSS output, then we will address the transformer architecture as it is a critical component of our architecture, then we will present the used optimizers in detail as they are a key element in producing a high fidelity translation model, then we are going to discuss the used performance metrics as it is extremely challenging to compare each model and optimizer's performance without an adequate performance metric.

II. REAL-TIME TEXT-TO-SIGN LANGUAGE GLOSS TRANSLATION PIPELINE USING TRANSFORMERS.

Our real-time text-to-sign language GLOSS translation pipeline encompasses a series of essential steps to enable a seamless conversion of textual input into a sign language GLOSS representation. As can be seen in Figure 1, the process begins with input tokenization, which divides the source text into discrete units for processing. Subsequently, input embedding encodes these tokens into vector representations, while positional encoding introduces spatial information to maintain word order.

The heart of the pipeline features the transformer architecture, consisting of an encoder that captures context and dependencies within the input text and a decoder that generates the corresponding sign language gloss. The SoftMax layer assigns probabilities to different gloss elements. Finally, detokenization reconstructs the output into a coherent GLOSS that represents the signed expression of the original text.

Each of the pipeline steps involves the following:

- **Input Tokenization:** The input text is divided into smaller units called tokens, which can be individual words or subwords. Tokenization is essential for representing text data in a format that the Transformer model can process.
- **Input Embedding:** Each input token is mapped to a high-dimensional vector representation called an embedding. The embedding layer helps the model to capture the semantic meaning of the tokens and their relationships within the input sequence.
- **Positional Encoding:** Since the Transformer architecture does not have built-in mechanisms to handle the sequential order of the input tokens, Positional encoding serves to provide information about the token's position in the sequence. By appending positional encoding to the input embeddings, the model is better able to comprehend the input data's sequential structure.
- **Encoder:** A series of transformer layers is used to process the input token embeddings with positional encodings. The input sequence is processed by the encoder, generating a sequence of continuous representations that capture the learned information for each token.
- **Decoder:** A set of transformer layers is applied to the encoder's output. The decoder's role is to generate the output sequence, which in this case is the gloss.

Softmax: The output of the decoder is subjected to an activation function to obtain a probability distribution over the possible glosses. The equation of the softmax function is:

$$\text{softmax}(z_i) = \frac{e^{z_i}}{\sum_{j=1}^{K} e^{z_j}} \quad (1)$$

with z_i the i^{th} element of the input vector, and K the number of elements in the input vector.

Detokenization: Convert the predicted gloss back into text form. This is the reverse process of tokenization.

II.1 TRANSFORMER-BASED MODEL ARCHITECTURE.

Our text-to-GLOSS translation model, based on transformers, is inspired by the well-established encoder-decoder architecture commonly found in neural models for sequence transduction [17],[18]. This structural choice is vital for preserving the task's sequential aspect, allowing the production of GLOSS outputs that are both coherent and contextually accurate.

Incorporating a sophisticated attention mechanism, the two primary components of our model's architecture are an encoder and a decoder. The encoder maps a sequence of input symbol representations $(x_1, \ldots, x_n)$ to an output sequence $(z_1, \ldots, z_n)$, while the output sequence $(y_1, \ldots, y_n)$ is generated by the decoder in an autoregressive manner. This sequential generation preserves the integral temporal dependencies within the translation process,

ensuring that each output element is generated based on the symbols produced previously.

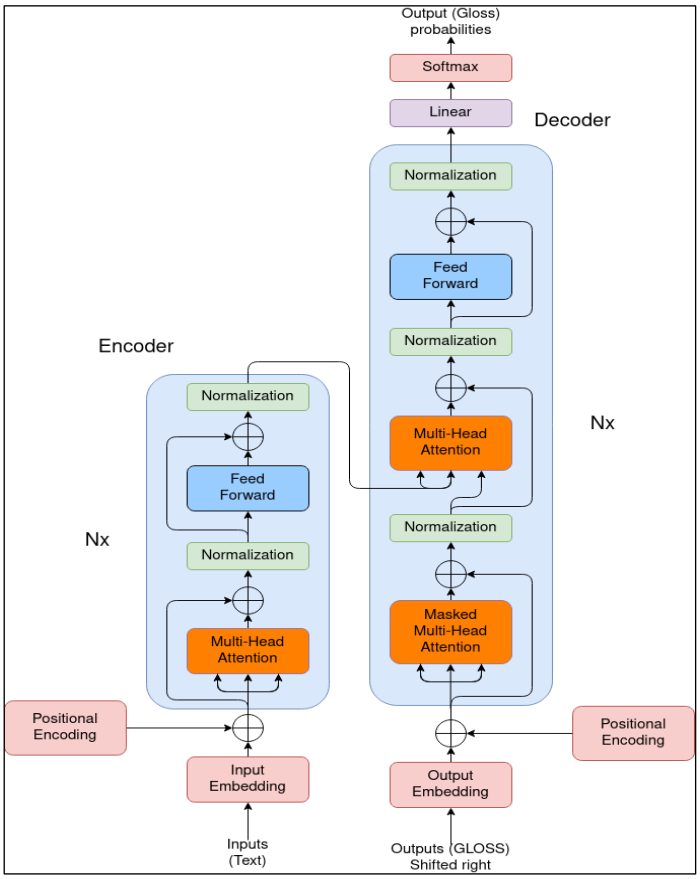

Figure 2**:** Proposed transformer-based model architecture for text-to-GLOSS translation.
Source: Authors, (2025).

Figure 2 shows the Transformer architecture, which is well-known for its effectiveness in processing sequential data via a combination of layered self-attention and dense layers, providing a visual representation of both the encoder and decoder components. Consisting of *N* identical layers, each comprising two sub-layers, the encoder integrates a multi-head self-attention mechanism into its first sub-layer. The second sub-layer employs a position-wise fully connected feed-forward network. Each sub-layer is surrounded by a residual connection [19], and to ensure smooth information flow, layer normalization [20] is applied after the residual connection. Notably, an output dimension *d* is maintained across all sub-layers, aligning with the dimension of the embedding layer. Similarly, the decoder is structured with a stack of *N* identical layers, augmented by a multi-head attention sub-layer designed to handle the output of the encoder stack. This is followed by a residual connection and a normalization layer. Thus, the output of each sub-layer in the model can be expressed as:

$$LayerNorm(x) = \left(x + Sublayer(x)\right) \quad (2)$$

where *Sublayer* represents the function applied by the sub-layer and *LayerNorm* denotes layer normalization.

To maintain the autoregressive nature of the decoder, information flow from subsequent positions is prevented by masking the self-attention sub-layer. To achieve this, the output embeddings are shifted one position and masked to ensure only known outputs from preceding positions are used to predict the output at position *i*.

The attention mechanism has become an integral part of sequence-to-sequence and transduction models. Attention allows modeling dependencies regardless of their distance in the input and output sequences. In our model, we use a combination of scaled dot-product and multi-head attention. The scaled dot-product attention computes the dot products of the query and keys, divides each by the square root of the dimension of the keys, and applies a SoftMax function to obtain the weights on the values. It is computed as follows:

$$\text{Attention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V \quad (3)$$

where the values, keys, and queries are packed together into the V, K, and Q matrices accordingly. And d_k is the dimension of the input keys (and queries).

The multi-head attention mechanism on the other hand uses several parallel attention layers, with each attention layer (head) having its own set of queries, keys, and values. This is expressed by the equation:

$$MultiHead(Q, K, V) = \text{Concat}(\text{head}_1, \dots, \text{head}_h)W^O \quad (4)$$

with $\text{head}_i = \text{Attention}\left(QW_i^Q, KW_i^K, VW_i^V\right)$. Where Q, K, and V are the query, key, and value matrices respectively, h is the number of attention heads, W_i^Q, W_i^K, and W_i^V projections are the parameter matrices for the i-th attention head, and W^O is the output projection matrix.

II.2 MODEL OPTIMIZATION

Optimizers are essential for training deep learning models, as they determine how the model's parameters are updated based on the gradients of the loss function. A good optimizer can significantly improve the convergence speed and final performance of the model. In the context of transformers, which are complex and computationally intensive models, choosing the right optimizer is essential for efficient training and inference.

- **Stochastic Gradient Descent(SGD)** [14]: is a widely used optimizer in deep learning. It updates the model's parameters by taking small steps in the direction of the loss function's negative gradient. The learning rate, which determines the step size, is a critical hyper-parameter that requires precise adjustment. The SGD algorithm utilizes the following equation to update the model's parameters:

$$\theta_{t+1} = \theta_t - \eta \frac{1}{n} \sum_{i=1}^{n} \nabla_\theta L(f(x_i; \theta_t), y_i) \quad (5)$$

where θ_t represents the model parameters at iteration t, η the learning rate, which indicates the step size in the parameter update, $\nabla_\theta L(f(x_i; \theta_t), y_i)$ the gradient of the loss function with respect to the model parameters at iteration t (evaluated on a batch of training examples (x_i, y_i))

- **Adaptive Gradient (AdaGrad)** [16]: is an optimizer that adapts the learning rate for each parameter based on its past gradients. It performs smaller updates for parameters that are frequently updated and larger updates for infrequently updated parameters. The AdaGrad algorithm updates the parameters according to the following equations:
  - The first step is to compute the gradient g_t of the loss function with respect to the parameters θ.

- Update the squared sum of the gradients: $G_t = G_{t-1} + g_t^2$
- Update the parameters: $\theta_t = \theta_{t-1} - \frac{\eta}{\sqrt{G_t+\epsilon}} \cdot g_t$

where G_t is the sum of the square gradients up to the iteration t, η is the learning rate that controls the step size in the parameter update, and ϵ is a small constant added for numerical stability.

- **Adaptive Delta (AdaDelta)** [13]**:** is a stochastic gradient descent method that extends AdaGrad and seeks to address its limitations. Like AdaGrad, AdaDelta maintains a per-parameter learning rate, but it also introduces a decay term that helps to prevent the learning rate from becoming too small. This decay term allows AdaDelta to adapt to changing data and model parameters. The AdaDelta algorithm functions as follows: First the accumulation variables $E[g^2)$ and $E[\Delta x^2)$ are initialized to zero; then to update each parameter x at time t:

- Compute the gradient g_t
- perform a gradient accumulations step: $E[g^2)_t = \rho E[g^2)_{t-1} + (1-\rho)g_t^2$
- Computes the parameter update: $\Delta x_t = -\frac{RMS[\Delta x)_{t-1}}{RMS[g)_t} g_t$
- Accumulates updates: $E[\Delta x^2)_t = \rho E[\Delta x^2)_{t-1} + (1-\rho)\Delta x_t^2$
- Apply the updates: $x_{t+1} = x_t + \Delta x_t$

where x_t is the current value of the model's parameters, ρ is the decay rate, g_t is the gradient of the loss function in relation to the model parameters at time step t, Δx_t is the update to the parameter, and $RMS[\cdot)$ is the root mean square of the values.

- **Adaptive Moment Estimation (Adam)** [15]: combines the advantages of two popular optimizers: AdaGrad, which is advantageous in sparse gradient situations, and RMSProp, which excels in online and non-stationary settings. It uses the first and second moments of the gradients to adapt the learning rate for each parameter. The update rule for Adam is given by:

- Compute the gradient g_t.
- Update the first momentum estimate: $m_t = \beta_1 m_{t-1} + (1-\beta_1)g_t$
- Update the second momentum estimate: $v_t = \beta_2 v_{t-1} + (1-\beta_2)g_t^2$
- Correct the bias of the first moment estimate: $\hat{m}_t = \frac{m_t}{1-\beta_1^t}$
- Correct the bias of the second moment estimate: $\hat{v}_t = \frac{v_t}{1-\beta_2^t}$
- Update the parameters: $\theta_{t+1} = \theta_t - \frac{\alpha}{\sqrt{\hat{v}_t+\epsilon}} \hat{m}_t$

where m_t and v_t are the first and second moments of the gradients, respectively, $\hat{m}_t$ and $\hat{v}_t$ are the bias-corrected estimates of the moments, θ_t is the current value of the model's parameters, g_t is the gradient of the loss function with respect to the parameters at time step t, α is the learning rate, β_1 and β_2 are the exponential decay rates for the moment estimates and ϵ is a small constant added for numerical stability.

II.3 MODEL EVALUATION

In the evaluation of the text-to-gloss transformer pipeline, we employed several metrics to assess the performance of the generated glosses. Each metric serves a specific purpose and provides valuable insights into different aspects of the generated text. The following metrics were used:

Perplexity: is a commonly used metric to measure the quality of language models. It measures the accuracy with which a model predicts a sample of text. More precisely, it measures how well a model predicts the following word in a series based on the preceding word sequence. Models demonstrating higher predictive capabilities over a text sample are characterized by a lower perplexity score.

Bi-Lingual Evaluation Understudy(BLEU) [21]: is a metric that measures the similarity between a generated text and one or more reference texts. It is often used in machine translation tasks but can also be applied to other text generation tasks such as text summarization, and image caption generation. BLEU scores range from 0 to 1 with a higher score indicating a better translation quality. The BLEU score also incorporates a brevity penalty to penalize translations that are shorter than the reference text. The driving factor behind the use of this penalty is that shorter translations in addition to being easier to generate are more likely to have a higher n-gram precision.

Recall Oriented Understudy for Gisting Evaluation (ROUGE) [22]: is a set of metrics used for evaluating automatic summarization of texts as well as machine translations. It evaluates the quality of summaries or translations by comparing them to a set of reference summaries. It measures the overlap between the generated summary and the reference summaries in terms of n-gram matches and word sequences. ROUGE scores range from 0 to 1, with higher scores indicating better performance. Out of the ROUGE score variations, we specifically use the ROUGE-L which uses the Longest Common Subsequence.

II.4 REAL-TIME INFERENCE

For seamless communication in real-time scenarios, achieving fast and efficient translation is crucial. We leverage CTranslate2 [23], a custom C++ Transformer-specific inference engine, to enable real-time deployment of our text-to-gloss translation model. CTranslate2 offers a significant advantage by having no runtime dependencies on TensorFlow or PyTorch. This eliminates potential compatibility issues and streamlines deployment. Additionally, CTranslate2 demonstrates optimized inference capabilities, including CPU and GPU support, leading to up to 4 times faster translation speeds compared to PyTorch [23]. This focus on real-time performance allows our model to be used in applications like live captioning and educational settings, providing greater inclusivity for the Deaf and hard-of-hearing community.

III. EXPERIMENTAL RESULTS

In this section, we present the results of our experiments, which demonstrate the effectiveness of the transformer in text-to-gloss translation tasks and provide valuable insights into the performance of this model in this specific task. The results are organized as follows: In the first subsection we introduce the experimental setup used to run our experiments, then the dataset subsection will provide more details about the dataset used for training and benchmarking our models, and finally, a results subsection that presents our consecutive hyper-parameter exploration, followed by a model optimization section, before finally presenting the performance results we share the obtained optimal parameters of our final model.

III.1 EXPERIMENTAL SETUP

Our text-to-GLOSS transformer model was built using the open source OpenNMT toolkit [24] with a pytorch backend [25]. The experiments were performed on a PC with an Intel Core I5

Central Processing Unit, an Nvidia RTX 3060 Graphics Processing Unit, 16GB of Random-Access Memory, and an Ubuntu Operating System.

Table 1: Text-to-Gloss Examples from the PHOENIX14T Dataset.

Text	GLOSS
AM SAMSTAG IST ES WIEDER UNBESTÄNDIG	SAMSTAG WECHSELHAFT
AUCH AM SAMSTAG TEILWEISE FREUNDLICH .	SAMSTAG AUCH FREUNDLICH
SONST SCHEINT VERBREITET DIE SONNE .	SONST REGION SONNE
IM SÜEDOSTEN REGNET ES TEILWEISE LÄNGER .	SUEDOST DURCH REGEN

Source: Authors, (2025).

Consistency in scoring methodologies is essential for establishing reliable benchmarks and facilitating meaningful comparisons between different models and research studies. The use of standardized scoring scripts helps to mitigate discrepancies in evaluation and ensures that the reported results are directly comparable. For this purpose, we specifically selected the Moses multi-bleu-detok.perl script for BLEU scoring, as it's used extensively used to report BLEU scores in research. To ensure a uniform ROUGE scoring and an accurate ROUGE comparison with other studies, we used HuggingFace's rouge scoring script which is a wrapper of Google Research's native Python implementation of ROUGE scoring.

III.2 DATASET

The PHOENIX-14T parallel text-to-GLOSS corpus [26] was employed to assess the performance of our proposed model. It is developed at RWTH Aachen University in Germany by the Human Language Technology & Pattern Recognition Group as part of the RWTH-PHOENIX-Weather 2014 corpus [27].

Table 2: PHOENIX14T Dataset Distribution.

	GLOSS			TEXT		
	Train	**Dev**	**Test**	**Train**	**Dev**	**Test**
Sentences	7 096	519	642	7 096	519	642
Words	67 781	3 745	4 257	99 081	6 820	7 816
Vocabulary	1 066	393	411	2 887	951	1 001

Source: Authors, (2025).

The dataset encompasses German sign language interpretation in the form of high-quality video recordings sourced from daily weather forecasts and news from 2009 to 2011. Additionally, the original German speech has been transcribed using a combination of speech recognition and manual cleaning. Manual GLOSS notation for German Sign Language (DGS) is available for 386 editions of weather forecasts. Some examples of the parallel text GLOSS dataset are provided in Table 1, and detailed statistics of the dataset's sentence, word, and vocabulary count are provided in Table 2.

The PHOENIX14T dataset proves to be a valuable asset for our research for several compelling reasons. Firstly, it is a non-synthetic dataset, offering accurate interpretations in German Sign Language (DGS) from professional interpreters. This authenticity is important for developing a high-performing system that can deliver accurate translations in uncontrolled environments. Additionally, the dataset is widely utilized in the sign language recognition and translation field, indicating its relevance and reliability for training text-to-GLOSS translation systems. Furthermore, its adoption facilitates the establishment of a standardized evaluation for our proposed architecture through a comparative analysis of our findings with state-of-the-art models. Despite its relatively small size, the dataset is comprehensive, offering a diverse range of linguistic and visual data for robust model training and evaluation. This further solidifies its suitability for the development of the text-to-GLOSS neural translation system.

III.3 RESULTS

III.3.1 Hyper-parameter Exploration

In this subsection, we introduce a novel transformer-based text-to-GLOSS translation architecture, considering the challenges posed by the limited resource conditions of the task. Thanks to their ability to capture contextual information and model long-range dependencies, Transformers have demonstrated remarkable success in various natural language processing tasks, especially in NMT. However, while having considerable accomplishments in NMT, their optimal utilization in the text-to-GLOSS translation endeavor remains to be comprehensively explored. Achieving this potential requires thorough hyper-parameter optimization, a vital operation for achieving optimal performance in low-resource scenarios.

Identifying the optimal Transformer architecture using grid search for a comprehensive exploration of hyper-parameters can be prohibitively expensive. Consequently, researchers resort to one of two techniques: a random hyper-parameter exploration [28] or an individual hyper-parameter grid search. While random search may yield superior hyper-parameter combinations, it typically incurs a greater time expense for a comprehensive exploration. Alternatively, grid search, for a single hyper-parameter at a time, only identifies the best value for the current hyper-parameter set, which is unaltered even after adjusting other hyper-parameters. This prompted us to adopt a consecutive hyper-parameter exploration approach. This method remedies the aforementioned downfalls by consecutively refining the model's hyper-parameters and not only relying on one round of optimization. The hyper-parameter range outlined in Table 3 is used to carry out this exploration.

Table 3: Explored hyper-parameter space.

Hyper-parameter	Values
Warmup steps	100 200 300 400 500 600
Batch-size	256 512 1024 2048 4096
Attention heads	1 2 4 8
Number of layers	1 2 3 4 5 6 7
Embedding dimension	32 64 128
Feed-forward dimension	128 256 512
Dropout	0.1 0.2 0.3 0.4 0.5
Label smoothing	0.1 0.2 0.3 0.4 0.5 0.6

Source: Authors, (2025).

During the iterative process of consecutive hyper-parameter exploration, a methodological approach is applied to refine the transformer-based architecture. The methodology involves the careful selection of an initial set of hyper-parameters, followed by sequential optimization of each parameter. Each hyper-parameter is individually addressed while keeping the others constant, and the model's performance on the selected dataset is assessed. The results of the first optimization cycle are used to modify the hyper-parameter values. Iteratively fine-tuning the model for each hyper-parameter separately until there are no more gains in improvement

to the model's output. By using this strategy of exploring hyper-parameters sequentially, it is possible to have a thorough grasp of how each hyper-parameter affects the performance of the model. This iterative approach enables the development of an optimal architecture, maximizing translation accuracy through the application of the most effective hyper-parameter set.

III.3.2 Minimal Transformer Model Tuning

To identify the most effective optimizer for our hyper-parameter exploration, we compared four commonly used optimizers on an arbitrary minimal model. This model comprises a single layer, a feed-forward dimension of 256, an embedding dimension of 32, one attention head, a label smoothing of 0.6, and a dropout rate of 0.3. All optimizers were configured with the same learning rate of 1.

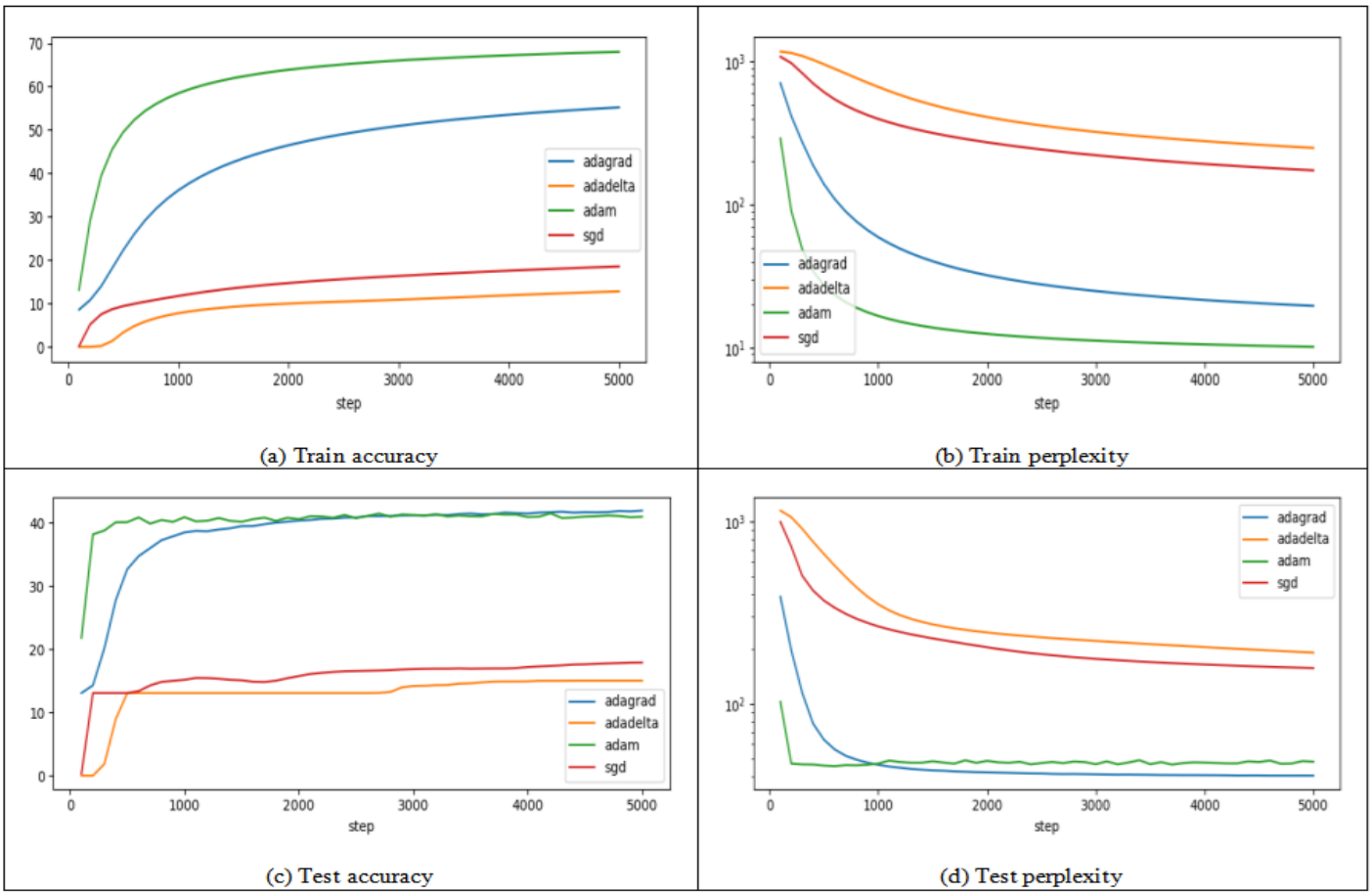

Figure 3: Comparative performance of stochastic optimizers on train and test sets for the minimal transformer model.
Source: Authors, (2025).

As can be observed in Figure 3, SGD and AdaDelta had the worst performance, as they had the lowest train and test accuracy, and the highest train and test perplexity. A logarithmic scale is used on the perplexity plots to facilitate the visualization of their progress, which was particularly necessary due to their significantly poorer performance. Adam and AdaGrad had the best results with Adam taking the lead with a higher train accuracy and a lower train perplexity. And AdaGrad had a marginally higher test accuracy and lower test perplexity.

Table 4: Comparison of ROUGE and BLEU scores for different optimizers on the minimal transformer model.

OPTIMIZER	ROUGE	BLEU			
		BLEU-1	BLEU-2	BLEU-3	BLEU-4
ADADELTA	1.75	16.5	0.0	0.0	0.0
SGD	12.08	22.7	4.8	3.3	0.0
ADAGRAD	48.14	**55.6**	**23.3**	**11.5**	**6.3**
ADAM	**48.78**	54.2	22.5	11.0	5.5

Source: Authors, (2025).

We report the best ROUGE and best BLEU-1 score accompanied by the corresponding BLEU-2, BLEU-3, and BLEU-4 scores of the resulting model's performances for each optimizer in Table 4. SGD and AdaDelta have the poorest performance with AdaDelta having a BLEU-2, BLEU-3, and BLEU-4 score of 0, and SGD having a BLEU-4 of 0.

This indicates that the model trained with the SGD optimizer struggles to generate 4-gram sequences that match a 4-gram sequence existing in the testing corpus, while the same can be said about the model trained using the AdaDelta optimizer, but in addition to 4-grams, the AdaDelta model fails to get matching 3-gram and 2-gram sequences too.

AdaGrad takes the lead when it comes to BLEU scores with BLEU-1, BLEU-2, BLEU-3, and BLEU-4 of 55.6, 23.3, 11.5, and 6.3 respectively, but Adam has an apparent advantage in terms of ROUGE scores with a 48.74 score. Stemming from these results, we decided to adopt the Adam optimizer for training our models and performing our hyper-parameters optimization.

Table 5: Dropout hyper-parameter exploration metrics.

METRICS	DROPOUT				
	0.1	0.2	0.3	0.4	0.5
BLEU-1	61.2	62.6	63.6	63.1	62.9
STEP	700	700	1000	7600	1000
ACCURACY	45.76	47.17	47.35	47.9	45.6
ROUGE	54.41	53.79	55.18	52.78	55.55

Source: Authors, (2025).

Table 6: Attention heads hyper-parameter exploration metrics.

METRICS	ATTENTION HEADS			
	1	2	4	8
BLEU-1	62.5	63.6	63.1	61.4
STEP	800	1000	1500	2900
ACCURACY	47.53	47.35	47.72	47.88
ROUGE	54.22	55.18	54.56	53.96

Source: Authors, (2025).

III.3.3 Fine-tuning Our Proposed Transformer Model

With the optimal optimizer identified in the first experiment, we shifted our focus to constructing our Transformer-based text-to-GLOSS model, in this subsection, we shed light on the consecutive hyper-parameter exploration to then unveil our final architecture. Our consecutive hyper-parameter exploration was performed manually and using the BLEU-1 metric for scoring the models and picking the best hyper-parameter in each run. Table 5 presents the dropout BLEU-1 score of our last hyper-parameter exploration run, in addition to the best BLEU-1 score of each dropout, the table also shows the step at which the score was obtained as well as the accuracy and the ROUGE score at that step. The table reveals that despite having a slightly lower accuracy on the test set, the dropout value of 0.3 yields the best BLEU-1 score of 63.6, and reaches its optimal performance in the 1000th step. The results for the attention tuning run are also provided in Table 6, a similar trend can be observed in the attention heads tuning run where despite not having the best accuracy, the model with 2 attention heads still yields a better BLEU-1 score of 63.6 taking the lead in the attention tuning run, it's best performance was achieved at the 1000th step, with an accuracy of 47.35.

The hyper-parameter optimization process took place until the model's parameters settled at the same value. The final hyper-parameter set is depicted in Table 7. The final model reached a training accuracy of 77.21, which translates to 47.35 test accuracy. It also reached BLEU scores of 63.6, 28.5, 15.2, and 9.0 in BLEU-1, BLEU-2, BLEU-3, and BLEU-4 respectively, and a ROUGE score of 55.18. The best BLEU-1 score was obtained at the 1000th training step, while the best ROUGE score was obtained at the 4900th step

Once our best-performing parameters were reached, the final parameter set was used to perform an optimizer comparison. Figure 4 illustrates the achieved performance metrics of the final model using the four optimizers: Adam, AdaGrad, AdaDelta, and SGD. The optimizers had the same parameters as the first optimizers trial in conjunction with the model's parameter set in Table 7. When it comes to the train set performance, Adam is clearly ahead of AdaGrad in both accuracy and perplexity. Furthermore, even with AdaGrad having a closer performance to Adam on the test set, Adam still takes the lead with a higher test accuracy, and a lower test perplexity. Both SGD and AdaDelta have significantly worse performance compared to Adam and AdaGrad over both the train and the test set.

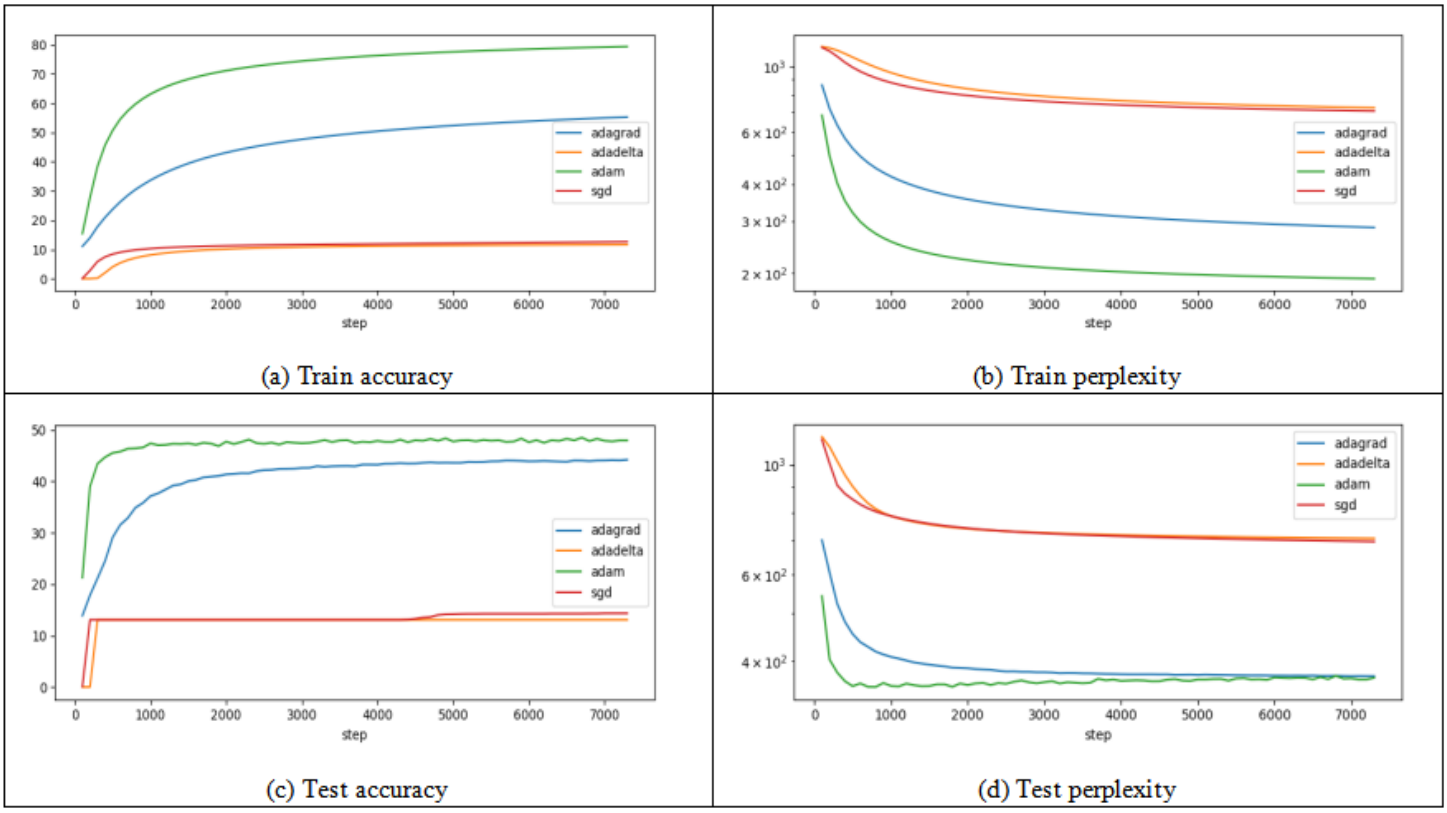

Figure 4: Comparative performance of stochastic optimizers on train and test sets for our proposed transformer model.
Source: Authors, (2025).

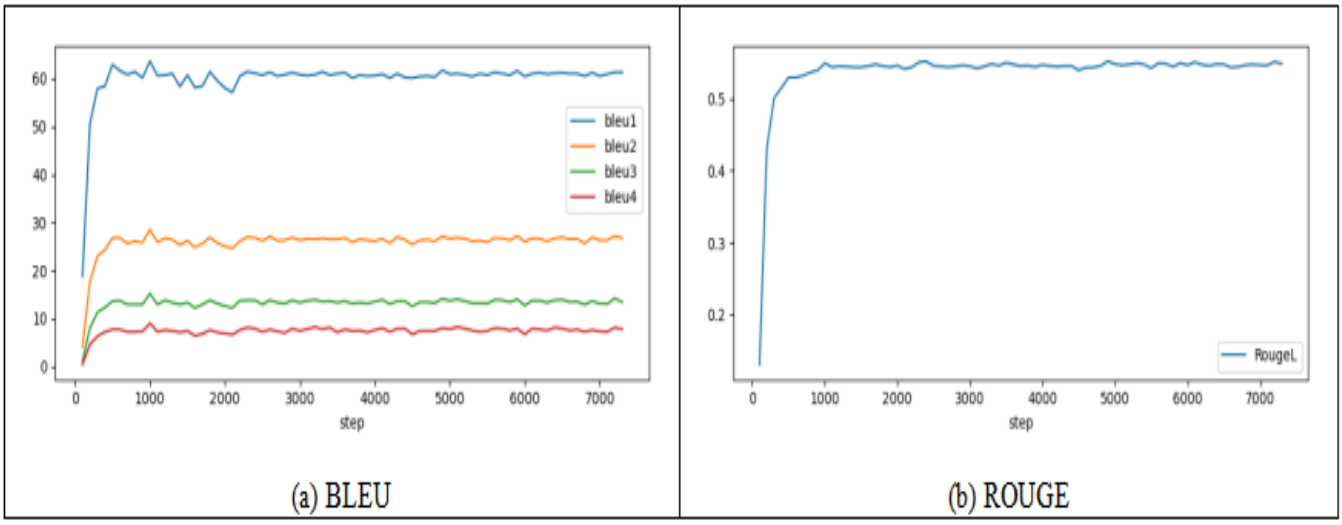

Figure 5: Performance metrics evolution of our proposed transformer-based model for text-to-GLOSS translation during training.
Source: Authors, (2025).

Table 7: Optimal hyper-parameters for our proposed transformer model.

Hyper-parameter	Value
Warmup steps	300
Batch-size	4096
Attention heads	2
Number of layers	5
Embedding dimension	64
Feed-forward dimension	256
Dropout	0.3
Label smoothing	0.6

Source: Authors, (2025).

Table 8 presents the best ROUGE scores obtained from the experiment and the best BLEU-1 score with the corresponding BLEU-2 to 4 scores. From the results presented in the table, we can observe that the AdaDelta optimizer has the worst scores, with 0.09 ROUGE and 0.0 in all BLEU scores. The SGD optimizer has slightly better scores with 4.10 ROUGE, 13.5 BLEU-1, and 0.0 BLEU-2, BLEU-3, and BLEU-4. AdaGrad takes the second position with 50.72 ROUGE, 57.8 BLEU-1, 23.3 BLEU-2, 11.6 BLEU-3, and 6.4 BLEU-4. Finally, the best-performing optimizer is Adam with a significantly better score than AdaGrad. It has a ROUGE score of 55.18, and its BLEU scores were 63.6, 28.5, 15.2, and 9.0 for the BLEU-1, BLEU-2, BLEU-3, and BLEU-4 respectively. The results of the experiment clearly show that the Adam optimizer is significantly better for our specific use-case of text-to-GLOSS neural machine translation using a Transformer architecture.

Table 8: Comparison of ROUGE and BLEU scores for different optimizers in our proposed transformer model.

OPTIMIZER	ROUGE	BLEU			
		BLEU-1	BLEU-2	BLEU-3	BLEU-4
ADADELTA	0.09	0.0	0.0	0.0	0.0
SGD	4.10	13.5	0.0	0.0	0.0
ADAGRAD	50.72	57.8	23.3	11.6	6.4
ADAM	**55.18**	**63.6**	**28.5**	**15.2**	**9.0**

Source: Authors, (2025).

III.3.4 Performance Evaluation and Comparative Analysis

Figure 5 shows the evolution of the ROUGE, BLEU, and BLEU-1 to 4 performance metrics for our proposed model with Adam optimizer on the test set during training. we can notice that the models improve the most in the first thousand or so training steps, then the performance only varies slightly in each evaluation, these variations are more pronounced in the BLEU scores than the ROUGE score.

Table 9: Comparison of ROUGE and BLEU scores for different model architectures.

ARCHITECTURE	ROUGE	BLEU			
		BLEU-1	BLEU-2	BLEU-3	BLEU-4
CNN	49.91	59.8	25.4	13.4	8.4
LSTM	46.27	51.1	17.8	7.3	3.3
GRU	25.90	31.0	5.7	0.9	0.2
OUR PROPOSED MODEL	**55.18**	**63.6**	**28.5**	**15.2**	**9.0**

Source: Authors, (2025).

To compare our system's performance with other architectures, we built several models with different architectures. All the architectures were built using the default configuration of the OpenNMT-py for translation. Three architectures were constructed for this comparison: a CNN [29] model, an LSTM [30] model, and a GRU [31] model. All the models have two encoder layers, and two decoder layers, a hidden size of 500, and optimized using the SGD optimizer. The CNN has a kernel width of 3. Table 9 presents the BLEU and ROUGE scores of all the evaluated methods, out of the three tested architectures, the CNN takes the first position with a ROUGE score of 49.91, and a BLEU-1, BLEU-2, BLEU-3, and BLEU-4 of 59.8, 25.4, 13.4, and 8.4 respectively. However, the table clearly demonstrates the transformer architecture taking a lead in all scores with a 55.18 ROUGE score, and 63.6, 28.5, 15.2, and 9.0 for the BLEU-1, BLEU-2, BLEU-3, and BLEU-4 respectively.

Table 10: Comparison of ROUGE and BLEU scores for our proposed approach with state-of-the-art methods on PHOENIX14T corpus test set.

METHODS	ROUGE	BLEU			
		BLEU -1	BLEU -2	BLEU -3	BLEU -4
RNN WITH LUONG ATTENTION [7]	48.10	50.67	32.25	21.54	15.25
GRU WITH BAHDANAU ATTENTION [8]	42.96	43.90	26.33	16.16	10.42
TRANSFORMER [9]	54.55	55.18	**37.10**	**26.24**	**19.10**
OUR PROPOSED APPROACH	**55.18**	**63.6**	28.5	15.2	9.0

Source: Authors, (2025).

In Table 10 our model's performance is compared to previous studies. The PHOENIX-14T text-to-GLOSS dataset is used to obtain the results. To provide a comprehensive overview of the translation performance, both the best ROUGE score, and the BLEU-1 to BLEU-4 scores are provided. Additionally, the architecture of each system is provided. The highest BLEU score achieved by our model is 19.04. Given that the BLEU-1 score is employed in our hyper-parameter exploration, it exhibited the most significant performance improvement when compared to alternative systems. In regards to the BLEU-1 score, our model outperforms all other approaches with a significant increase of 19.7 compared to [8], our model also outperforms the models suggested in [7] and [9] by 12.93 and 8.42, respectively. For BLEU-2, BLEU-3, and BLEU-4 scores, our model's performance is on par with the model in [8], with scores of 28.5, 15.2, and 9.0, respectively. Our system outperforms both the GRU with attention proposed in [8] and the Recurrent Neural Network (RNN) based architecture with attention proposed in [7], with ROUGE score increases of 12.22 and 7.08, respectively. Our model also achieves a 0.63 improvement in ROUGE score, marginally outperforming the Symbolic Transformer suggested in [9].

III.3.5 Performance Evaluation and Comparative Analysis.

In this subsection we present the benchmarking results for our model's inference using CTranslate2 on both CPU and GPU. We evaluate the model's inference performance based on three metrics: time per token, sentence latency, and memory usage. Figure 6 illustrates the comparison of these metrics across bot GPU and CPU implementations.

The results reveal that the average time per token on the CPU is 0.28 milliseconds, which is approximately three times lower than the 0.86 millisecond observed on the GPU. Similarly sentence latency on the CPU averages 1.69 milliseconds, whereas on the GPU it is approximately three times higher with 5.09 milliseconds. Additionally, the CPU's model memory usage is around 8.37 MB, which is slightly lower than the 10MB recorded on the GPU. These figures provide a clear comparison of the performance between CPU and GPU implementations of the model during inference.

IV. DISCUSSION

Our study aims to investigate the performance of optimizers in the context of finding the most optimal transformer architecture for the real-time text-to-GLOSS translation task. We hypothesize that by initially exploring optimizers using a minimal model and subsequently applying the insights gained to optimize a more complex transformer architecture, we can obtain more insights into optimizer performance in the text-to-GLOSS translation task across different scenarios.

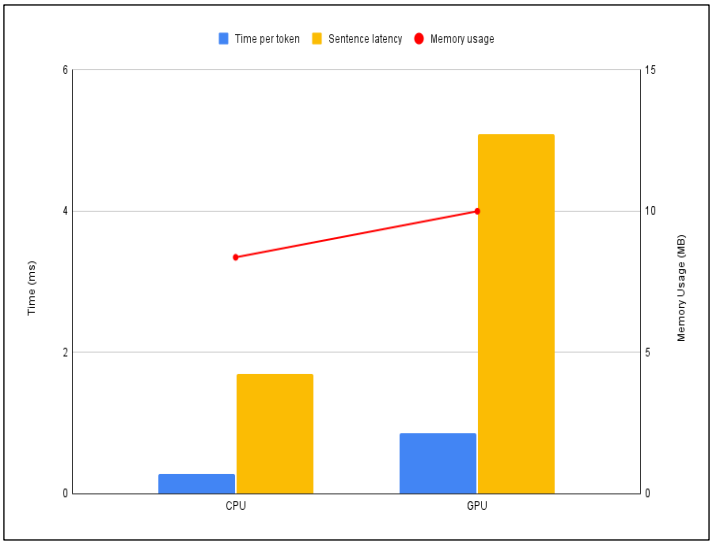

Figure 6: CPU and GPU performance metrics during model inference.
Source: Authors, (2025).

Our study employs a two-phase experimental approach. In the first phase, we conduct a comprehensive exploration of optimizers using a minimal transformer model. The goal is to identify the most effective optimizer through a comparative evaluation of AdaDelta, SGD, AdaGrad, and Adam. Accordingly, our model of choice featured a single feed-forward layer with a dimension of 256, an embedding dimension of 32, one attention head, a dropout rate of 0.3, and a label smoothing of 0.6. All optimizers were configured with a learning rate of 1. This first phase yielded significant insights into the performance and adaptability of the optimizers on a minimal model in this specific use case. Both AdaDelta and SGD resulted in a model with subpar performance, with a ROUGE score of 1.75 and 12.08 respectively. However, the AdaGrad and Adam optimizers achieved superior results with 48.14, and 48.78 ROUGE respectively. Despite AdaDelta being an extension of AdaGrad, it yields significantly inferior performance in our specific testing conditions. The observed performance discrepancy may stem from AdaDelta's limited adaptability to the intricacies of our text-to-GLOSS translation task, suggesting potential challenges in generalizing its optimization capabilities for this specific context. Subsequently, the findings obtained from the optimizer screening phase guide the subsequent hyper-parameter exploration, aiming to identify the optimal transformer architecture in the second phase.

Our investigative approach emphasizes a sequential optimization process. Initially, we analyze the optimizers in a simpler context and subsequently apply the insights to guide the hyper-parameter exploration for identifying the optimal architecture. The hypothesis underscores the critical role of a well-suited optimizer in attaining optimal convergence and ensuring

high translation quality, particularly in the complex task of text-to-GLOSS translation using a transformer model.

To enhance the search for the optimal architecture, we leverage the insights from the optimizer screening to guide the exploration of hyper-parameters and model configurations. Employing a consecutive hyper-parameter exploration technique for Transformers. This process is used to address the excessively intensive resource demand of an exhaustive parameter exploration and the suboptimal performance obtained from a random parameter search. Our optimization process starts with the selection of a primary hyper-parameter set, with subsequent sequential optimization of each parameter. During this process, one hyper-parameter is altered at a time while maintaining the others fixed, evaluating the model's translation quality on the selected corpus. Following that, hyper-parameter values are modified in accordance with the outcomes of the first optimization run. This continual process of fine-tuning proceeds for each hyper-parameter individually until the model's output no longer shows any signs of progress.

In addition to comparing optimizers within the context of the minimal model, our analysis extends to a larger and more intricate transformer architecture. This broader comparison serves the purpose of affirming the robustness and consistency of the selected optimizer, ensuring that the insights obtained from the initial experiment are applicable to a practical, real-world text-to-GLOSS translation scenario. The increased complexity of the larger model accentuates the performance distinctions observed with each optimizer. AdaDelta and SGD yield ROUGE scores of 0.09 and 4.10, respectively, significantly lower than the scores achieved in the smaller model. This outcome further reinforces our hypothesis regarding the critical role of a well-suited optimizer tailored to specific conditions. In contrast, AdaGrad demonstrates a ROUGE score of 50.72, while Adam excels with a ROUGE score of 55.18. This comparison within the larger model context reinforces the reliability of the identified optimizer in delivering high-quality results across diverse scenarios.

In the study by Choi et al. [32], the authors observed significant variability in optimizer performance depending on the workload. While some workloads exhibited comparable performance across all tested optimizers, in other scenarios, there were substantial differences leading to clear distinctions in both predictive performance and training speed. Notably, the efficiency of Adam was particularly evident, requiring significantly fewer training steps than SGD to achieve the same target error on a transformer architecture. Our findings resonate with this observed performance difference, as SGD demonstrated notably reduced effectiveness for our specific text-to-GLOSS translation task compared to Adam. These results underscore the critical importance of carefully selecting the appropriate optimizer tailored to the unique characteristics of each workload or task. Several studies have suggested that the suboptimal performance of SGD on attention models can be attributed to heavy-tailed noise, as noted in Zhang et al.'s work [33]. They propose that Adam's success in optimizing these models is linked to its resilience against outliers. However, Chen et al. [34] challenge this notion. Backed by controlled stochasticity experiments through varied batch sizes, the study proposes that stochasticity and heavy-tailed noise might not be significant contributors to the observed performance discrepancy. Instead, it suggests that Adam-like methods utilize a descent direction that is superior to the gradient, providing an alternative explanation for their effectiveness. Using a consecutive hyper-parameter exploration, we managed to find an optimal Transformer architecture and significantly increase the translation performance over the PHOENIX-14T dataset highlighting the importance of finding a task-specific parameter set for achieving a significant performance. This aligns with Araabi et al.'s study [10] that shows through experimental evidence the performance increase of a properly configured Transformer for low-resource language conditions.

Following the optimizer comparison, we performed real-time benchmarking to evaluate the model's performance in practical scenarios. The benchmarking results revealed that the CPU outperformed the GPU in terms of time per token and sentence latency for small models and short sentences. Specifically, the CPU's time per token was approximately three times lower than that of the GPU, and sentence latency on the CPU was about three times faster. Additionally, the CPU's memory usage was slightly lower than that of the GPU. These findings suggest that for small models, CPUs offer a more efficient solution compared to GPUs.

In the context of real-time inference, our results are consistent with [35], who also observed better performance with inference on CPU compared to GPU despite having a CPU with less peak FLOP performance. Wu et al. reported that decoding their model on CPU was 2.3 times faster than on GPU. They attributed this discrepancy to the significant overhead caused by non-trivial amount of data transfer between the host and the GPU at every decoding step.

Overall, our findings provide a comprehensive understanding of the optimization strategies and hardware considerations crucial for maximizing the performance of neural machine translation models. The evaluation of different optimizers and hyper-parameter settings has revealed significant performance gains, while the real-time benchmarking highlights the importance of hardware choice, particularly the efficiency of CPUs for specific tasks. These insights align with and extend existing research, and contribute valuable knowledge to the field, guiding future research and practical implementations.

V. CONCLUSIONS

This paper presents a novel transformer-based Neural Machine Translation model specifically tailored for real-time text-to-GLOSS translation. First, we provided a comprehensive exploration of optimizers to identify the most optimal transformer architecture for the text-to-GLOSS translation task. The initial phase involved a comprehensive examination of optimizers using a minimal transformer model. This phase revealed significant variations in performance, with Adam emerging as a robust choice for our specific use case reaching 48.78 ROUGE. Building upon the optimizer screening phase, our consecutive hyper-parameter exploration is used to fine-tune the search for the optimal transformer architecture. The iterative process, sequentially refining each hyper-parameter, supported our exploration of the complex landscape of model configurations. This methodological refinement proved essential in identifying an architecture that significantly enhanced text-to-GLOSS translation performance over the PHOENIX-14T dataset. The comparison of optimizers extended to a larger and more intricate transformer architecture, affirming the robustness of our selected optimizer, Adam, across diverse scenarios. The performance distinctions observed in the larger model context reinforced the hypothesis that the choice of the optimizer, coupled with the right hyper-parameter set, plays a pivotal role in achieving optimal convergence and translation quality, particularly in complex tasks.

Furthermore, we show that our obtained model using these techniques not only outperforms alternative architectures such as CNN, LSTM, and GRU in both ROUGE and BLEU 1 to 4 scores, but also outperforms state-of-the-art models not only on the optimization target metric (BLEU1), but also on the ROUGE metric, setting a new benchmark for text-to-GLOSS translation on the PHOENIX-14T dataset with 63.6 BLEU1 and 55.18 ROUGE scores further establishing the significance of our findings in the field. In terms of real-time inference, our benchmarking results indicate that for small models, the CPU significantly outperforms the GPU, with the CPU achieving approximately three times lower time per token and three times faster sentence latency. These insights emphasize the importance of hardware considerations in deployment, as optimizing for real-time performance can greatly enhance the practical applicability of NMT systems. Our findings hold great promise for diverse applications, ranging from education to healthcare, offering enhanced accessibility through real-time sign language translation for the Deaf and hard-of-hearing community. By addressing specific challenges in sign language translation, particularly the need for real-time processing, our research paves the way for seamless and uninterrupted communication, significantly improving inclusivity for the DHH community.

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VII. AUTHOR CONTRIBUTIONS

Conceptualization: Younes Ouargani, Noussaima El Khattabi.
Methodology: Younes Ouargani.
Investigation: Younes Ouargani.
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Writing – Original Draft: Younes Ouargani.
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Supervision: Noussaima El Khattabi.
Approval of the final text: Younes Ouargani, Noussaima El Khattabi.

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THE ADVANCES IN NEUROMORPHIC COMPUTING AND BRAIN-INSPIRED SYSTEMS (ANCBIS)

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Cross-disciplinary collaboration.

ABSTRACT

Neuromorphic computing, inspired by the structure and functions of the human brain, is transforming the development of energy-efficient, adaptive, and highly parallel processing systems. This field seeks to bridge the gap between traditional computing architectures and biological neural networks by replicating brain-like functionalities. This paper examines recent advancements in neuromorphic computing, with an emphasis on innovative hardware and algorithms that boost computational power while reducing energy consumption. Key technologies such as memristive devices, spiking neural networks, and brain-inspired learning algorithms show promise in applications like pattern recognition, sensory processing, and autonomous decision-making. This study also addresses challenges related to scalability, robustness, and integration with existing systems, emphasizing the importance of cross-disciplinary collaboration to overcome these limitations. By exploring applications in robotics, medical diagnostics, and environmental monitoring, this research highlights how brain-inspired systems could drive the next generation of artificial intelligence and sustainable computing, meeting the growing need for energy-efficient, intelligent systems.

I. INTRODUCTION

Neuromorphic computing, inspired by the structure and functioning of the human brain, addresses the increasing demand for energy-efficient, adaptive, and high-performance computing systems. Traditional computing architectures, such as the von Neumann architecture, face limitations in scalability and energy efficiency due to the separation of memory and processing units. In contrast, neuromorphic systems integrate memory and computation, mimicking the brain's parallel, distributed processing, and offering the potential to overcome these challenges. This research is motivated by the need for next-generation computing systems that can efficiently handle complex tasks like pattern recognition, decision-making, and sensory processing, with minimal energy consumption.

A growing body of literature has explored the advancements in neuromorphic computing and brain-inspired systems. Notable contributions include the development of memristive devices (resistive switching devices), which emulate synaptic behavior, and spiking neural networks (SNNs), which replicate the time-dependent signaling of neurons. Pioneering works by authors like Sporns et al. (2014) and Izhikevich (2003) have established the theoretical foundation of neuromorphic systems, while recent research has focused on their hardware implementation and application in real-world scenarios. These systems have shown promise in diverse fields, including robotics, medical diagnostics, and autonomous vehicles.

The primary research question addressed in this study is: How can neuromorphic computing systems be optimized for energy efficiency and scalability without compromising performance? The objective of this work is to review the state-of-the-art technologies in neuromorphic computing and evaluate their potential in real-world applications. This paper also aims to assess the limitations of current systems, including scalability and integration with conventional computing infrastructures, and proposes solutions to these challenges.

The research hypothesizes that neuromorphic systems, through their bio-inspired architectures, can achieve significant improvements in computational efficiency and adaptability compared to traditional computing methods. The methodology

employed in this work includes a comprehensive literature review of current technologies, theoretical models, and practical applications, as well as an analysis of ongoing challenges in the field.

This research is significant as it contributes to the development of sustainable, energy-efficient computing systems that can meet the growing demands of modern artificial intelligence applications. However, limitations include the nascent stage of hardware development and the complexity of integrating neuromorphic systems with existing infrastructures, which this paper aims to address.

II. THEORETICAL REFERENCE

II.1. NEUROMORPHIC COMPUTING: OVERVIEW AND FOUNDATIONS

Neuromorphic computing is inspired by the structure and functions of the human brain, aiming to replicate its efficiency in information processing.

This computational approach seeks to bridge the gap between traditional computing systems and biological neural networks by integrating memory and processing capabilities. Pioneering work in this field by Mead [1], introduced the concept of neuromorphic engineering, focusing on the design of hardware systems that mimic neural processing. Recent advancements have expanded upon these initial ideas, exploring the use of spiking neural networks (SNNs) and memristive devices to emulate synaptic functions [2-4].

Spiking neural networks (SNNs), a key element of neuromorphic systems, are designed to closely mimic the time-dependent behavior of biological neurons [5]. Izhikevich's model [6] has been instrumental in providing a mathematical framework for these networks, facilitating their implementation in hardware. Memristive devices, which function as electronic components that resist changes in electrical states, have also become a critical component of neuromorphic hardware, offering the potential for low-power, scalable solutions [7], [8].

The adoption of neuromorphic computing has led to breakthroughs in energy-efficient processing, particularly in real-time applications such as robotics, sensory processing, and decision-making systems [9]. However, challenges remain in scaling these systems and integrating them into existing computational architectures [10]. Addressing these limitations will be crucial for realizing the full potential of neuromorphic computing in future artificial intelligence applications.

III. MATERIALS AND METHODS

III.1. RESEARCH BACKGROUND

This research focuses on the development and evaluation of neuromorphic computing systems, inspired by the structure and function of the human brain.

The primary goal is to investigate the potential of these brain-inspired systems for energy-efficient, adaptive, and scalable computational solutions, with applications in fields like artificial intelligence, robotics, and sensory processing. Neuromorphic systems, based on spiking neural networks (SNNs) and memristive devices, are expected to outperform traditional computing systems in terms of power consumption and processing speed.

The growing interest in neuromorphic computing stems from the limitations of current architectures, such as the von Neumann model, which separates memory and processing. This separation results in significant energy consumption and limits the scalability of systems as data volumes increase. Neuromorphic systems overcome these limitations by integrating memory and processing into a single, parallel, distributed architecture, making them a promising solution for next-generation artificial intelligence systems [11], [12].

III.2. SELECTION OF MATERIALS

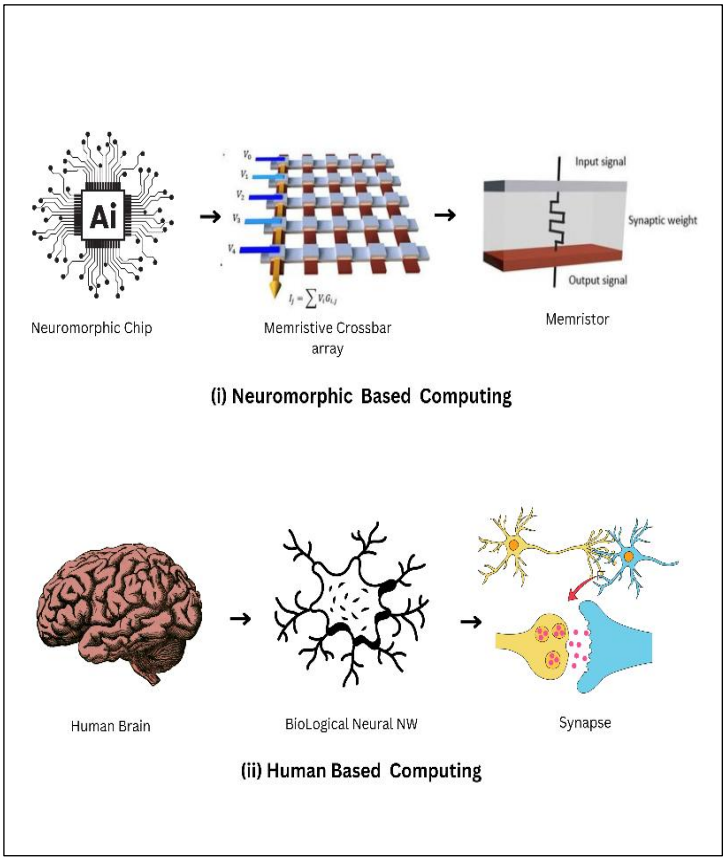

Figure 1: Neuromorphic and Human Based Computing.
Source: Authors, (2025).

The materials used in this research include both hardware and software components necessary for implementing neuromorphic computing systems. These materials were selected based on their ability to replicate brain-like functionalities while maintaining low power consumption.

III.2.1. HARDWARE COMPONENTS:

Memristive Devices: These devices were selected due to their ability to emulate synaptic functions, making them essential for neuromorphic computing. The memristors used in this study have a resistance range of 1kΩ to 10MΩ, allowing them to store information based on resistive switching properties [13].

Neuromorphic Chips: Custom-designed neuromorphic chips (e.g., Intel's Loihi and IBM's True North) were chosen for their ability to implement spiking neural networks (SNNs) and provide high throughput with low power consumption [14] ,[15].

Sensors and Actuators: Various sensors (e.g., visual and auditory sensors) were used to collect real-world data for testing the system's response in sensory processing applications.

III.2.2. SOFTWARE COMPONENTS:

SpiNNaker Simulator: A widely-used software platform for simulating large-scale spiking neural networks, chosen for its efficiency and scalability in neuromorphic research [16].
Python Programming Language: Python was chosen for developing algorithms and data processing due to its extensive libraries for machine learning, data analysis, and integration with hardware components [17].

III.3. METHODOLOGY

Design and Simulation: The first stage of the methodology involved designing the neuromorphic system architecture, which integrates spiking neural networks (SNNs) with memristive devices. The system was then simulated using the SpiNNaker platform to evaluate the network's performance in tasks such as pattern recognition and sensory data processing [18].

Hardware Implementation: Based on the simulation results, the neuromorphic system was implemented using memristive devices and neuromorphic chips. These hardware components were connected to a set of sensors (e.g., cameras, microphones) to collect real-world data, which was used to train the neural network.

Data Collection: The study used a dataset consisting of sensory inputs, including visual and auditory stimuli. The dataset was selected to represent real-world challenges in sensory processing, particularly in the context of pattern recognition and decision-making tasks [18-20].

Sample Selection: The sample consisted of 100 instances of sensory data collected from the real-world environment. The dataset was selected to be representative of typical inputs for real-time processing tasks, such as object detection and sound classification. The size of the sample was chosen to ensure statistical relevance while considering hardware limitations.

III.4. PROCEDURES AND EQUIPMENT

III.4.1. PROCEDURES

- **Data Preprocessing**: The sensory data was pre processed to normalize input values and remove noise, ensuring that the system could perform optimally during the recognition tasks.

- **Training the SNN:** The pre processed data was fed into the spiking neural network, which was trained using a supervised learning algorithm. This step involved adjusting synaptic weights to minimize the error in pattern recognition tasks [9].

- **Testing and Evaluation**: After training, the system was tested using a separate validation dataset to assess its ability to generalize to new sensory inputs. The performance was evaluated based on accuracy, energy consumption, and processing speed.

III.4.2. EQUIPMENT

- **Neuromorphic Chips** (e.g., Intel Loihi):These chips were used to implement the hardware-based spiking neural networks [4].

- **Sensor Array**: A set of visual and auditory sensors was used to collect data for the system's input [8].

- **Computer with SpiNNaker Platform:** The platform was used for simulating the system and processing large-scale neural networks [6].

III.5. DATA PROCESSING AND MODEL EQUATIONS DATA PROCESSING IN NEUROMORPHIC SYSTEMS

Neuromorphic systems process data in ways mimicking biological brains, emphasizing real-time, parallel, and energy-efficient operations:

- **Spike-based Processing**: Instead of continuous signals, information is encoded in discrete spikes, akin to action potentials in biological neurons.

- **Event-driven Computation**: Processing occurs only when a spike is received, reducing energy consumption.

- **Memory-Processing Integration**: Unlike von Neumann architectures, neuromorphic systems often co-locate memory and computation, avoiding bottlenecks.

Data processing pipelines often include:

- **Preprocessing**: Converting sensory data into spikes or compatible formats.

- **Neural Representation**: Mapping inputs to spiking neural networks (SNNs).

- **Learning Rules**: Employing local rules like Hebbian learning or spike-timing-dependent plasticity (STDP) for adaptive processing.

III.5.1. MODEL EQUATIONS

Model equations in neuromorphic systems describe neuron and synapse behaviors and network dynamics. Examples include:

III.5.1.1. Neuron Models:

Leaky Integrate-and-Fire (LIF) Model:

- A simplified neuron model where the membrane potential V(t) evolves as:

$$\tau \frac{dV(t)}{dt} = -V(t) + I(t), \tag{1}$$

where:

- τ: Membrane time constant.
- I(t): Input current.

A spike is generated when V(t) exceeds a threshold, and V(t)resets.

III.5.1.2. Hodgkin-Huxley Model:

Biophysically detailed model:

$$C_m \frac{dV}{dt} = I - \sum \text{ion currents}. \tag{2}$$

Includes ion channels (e.g., sodium, potassium) for realistic neuron dynamics.

III.5.1.3. Synapse Models:

Spike-Timing Dependent Plasticity (STDP):

Learning based on relative timing of pre- and post-synaptic spikes

$$\Delta w = A_+ e^{-\Delta t/\tau_+} \text{ if } \Delta t > 0,$$
$$\Delta w = A_- e^{\Delta t/\tau_-} \text{ if } \Delta t < 0. \quad (3)$$

III.5.1.4. Network Dynamics:

Population Models

Describing large groups of neurons:

$$\frac{dN}{dt} = f(N, I), \quad (4)$$

where N is neuron activity and I input.

Coupled Oscillators: Often used for rhythmic or synchronized activity.

III.5.2. PRACTICAL IMPLEMENTATIONS

- **Applications**: These equations support applications in robotics, vision, sensor fusion, and brain-computer interfaces.

III.6. LIMITATIONS

Neuromorphic computing, inspired by the architecture and processing methods of biological brains, offers many advantages in areas like low power consumption, parallel processing, and real-time learning. However, there are several limitations that affect its scalability and widespread adoption.

III.6.1. SCALABILITY ISSUES

- **Challenge**: Neuromorphic systems face difficulties in scaling to large numbers of neurons and synapses due to hardware limitations, such as memory size and processing power.
- **Example**: While chips like IBM's **TrueNorth** and Intel's **Loihi** demonstrate promising results, they are still far from matching the complexity of the human brain, which contains around 86 billion neurons. Expanding neuromorphic systems beyond a few thousand neurons leads to challenges in hardware cost, energy efficiency, and the speed of communication between units.

III.6.2. LACK OF UNIVERSAL MODELS

- **Challenge**: There is no single "universal" neuromorphic model, as different applications (e.g., vision, auditory processing, decision-making) require tailored architectures. The neuron models (such as LIF or Hodgkin-Huxley) and synaptic rules (like STDP) vary in complexity and suitability depending on the task.
- **Example**: The **Leaky Integrate-and-Fire (LIF)** model is useful for simple spike-based systems, but more complex models like **Hodgkin-Huxley** are required for simulating detailed neural behaviour, leading to increased computational load and energy consumption.

III.6.3. ENERGY EFFICIENCY VS. ACCURACY TRADE-OFF

- **Challenge**: While neuromorphic computing excels in low power usage compared to traditional architectures, this efficiency often comes at the expense of accuracy and precision in some tasks.
- **Example**: **Spiking Neural Networks (SNNs)**, which are energy-efficient, may struggle with high-precision tasks like image classification, where conventional **Deep Neural Networks (DNNs)** excel. The trade-off between power consumption and computational accuracy is still a significant concern.

III.6.4. HARDWARE CONSTRAINTS

- **Challenge**: Neuromorphic systems often require specialized hardware that is not as readily available or flexible as general-purpose computing resources.
- **Example**: Devices like **memristors**, used in neuromorphic chips, are still experimental and often lack the necessary scalability and reliability for large-scale applications. The lack of general-purpose neuromorphic chips makes it harder for the technology to be widely adopted in consumer devices or diverse industries.

III.6.5. LEARNING ALGORITHM LIMITATIONS

- **Challenge**: While neuromorphic systems can learn autonomously (e.g., via STDP), they often require highly specific configurations and are limited in terms of generalization and adapting to new, unseen environments.
- **Example**: In autonomous robots, the lack of robust, on-the-fly learning capabilities means that these systems may require extensive pre-training and fine-tuning for each new task or environment, limiting their flexibility compared to traditional machine learning systems.

III.6.6.DIFFICULTY IN DEBUGGING AND ROGRAMMING

- **Challenge**: Programming neuromorphic systems is more challenging than traditional computers, as their parallel and event-driven nature complicates debugging, validation, and testing.
- **Example**: Debugging systems that rely on **event-based processing** (where data is only processed when an event occurs, rather than at regular intervals) can be difficult, as conventional debugging tools are not suited to handle these asynchronous, spike-driven systems.

III.6.7.LIMITED UNDERSTANDING OF BIOLOGICAL SYSTEMS

- **Challenge**: Although neuromorphic computing takes inspiration from biological brains, there is still much that is not understood about how biological neural networks operate, making it difficult to fully replicate their functionality.
- **Example**: Despite advances in neuromorphic models, the complexity of the human brain, with its intricate interconnectivity and plasticity, is far beyond current technological capabilities.

These limitations highlight the ongoing research challenges in neuromorphic computing and underscore the gap between current implementations and the full potential of brain-inspired

systems. However, with continued development, solutions to many of these problems may emerge over time.

III.7. JUSTIFICATION OF METHODS IN NEUROMORPHIC COMPUTING

The methods used in neuromorphic computing, especially those involving hardware design, data processing, and algorithm implementation, require careful justification due to their complex nature and specific requirements. Below are key justifications for these methods based on current research and practical applications:

III.7.1. SPIKE-BASED DATA REPRESENTATION

- **Justification**: Spike-based systems, particularly Spiking Neural Networks (SNNs), mimic the way biological neurons communicate via action potentials (spikes). This method has been shown to be energy-efficient compared to traditional continuous-valued models like Deep Neural Networks (DNNs) because it only processes information when spikes occur (event-driven computation). This makes SNNs particularly suited for low-power applications in devices like robots or IoT systems.
- **Source**: **LeCun et al. (2015)** on deep learning outlines the benefits of event-driven computation and **Spiking Neural Networks**.

III.7.2. LEAKY INTEGRATE-AND-FIRE (LIF) NEURON MODEL

- **Justification**: The LIF neuron model is widely used in neuromorphic systems because of its simplicity and computational efficiency. It offers a good balance between biological plausibility and simplicity, making it ideal for real-time systems where power efficiency is critical. This model is particularly useful in hardware implementations, such as those seen in neuromorphic chips (e.g., **Intel Loihi**), because it is relatively easy to implement in digital circuits.
- **Source**: **Izhikevich (2004)** provides a detailed justification for using simplified models like LIF for large-scale neural networks.

III.7.3. SPIKE-TIMING-DEPENDENT PLASTICITY (STDP) LEARNING RULE

- **Justification**: STDP is used in neuromorphic systems to emulate the way biological synapses strengthen or weaken based on the timing of spikes. This learning rule is biologically plausible and allows for unsupervised learning in real-time. It has been justified as a way to implement adaptive behaviour without requiring explicit supervision, making it valuable for applications in real-world, dynamic environments.
- **Source**: **Song et al. (2000)** demonstrated that STDP can lead to efficient learning in spiking neural networks, aligning with biological principles and providing real-time adaptability.

III.7.4. MEMRISTOR-BASED COMPUTING

- **Justification**: Memristors are often used in neuromorphic hardware because they naturally simulate the behavior of biological synapses. Their ability to retain memory and exhibit non-volatile behavior makes them ideal for implementing synaptic weights in neuromorphic systems, leading to more energy-efficient and compact hardware. This hardware-based solution enables scaling neuromorphic systems for more complex tasks.
- **Source**: **Chua (1971)** first proposed memristors, and their use in neuromorphic computing has been explored in several studies, such as those by **Strukov et al. (2008)**.

III.7.5. INTEGRATION OF MEMORY AND COMPUTATION

- **Justification**: One of the key benefits of neuromorphic systems is the co-location of memory and computation. This integration helps mitigate the **von Neumann bottleneck**, which separates memory and processing in traditional computers, leading to inefficiency in data transfer. Neuromorphic systems, by combining both aspects in a single unit, improve processing speed and energy efficiency, making them suitable for tasks like real-time decision-making in robotics.
- **Source**: **Harrison and Choi (2018)** highlight how neuromorphic systems overcome traditional computing bottlenecks.

III.7.6.USE OF HARDWARE ACCELERATORS (E.G., IBM TRUE NORTH)

- **Justification**: Neuromorphic chips like **IBM True North** provide a dedicated hardware architecture designed for brain-inspired computing. These chips are highly parallel, enabling them to process vast amounts of data simultaneously while consuming minimal power. The use of such accelerators allows for scaling the complexity of brain-inspired systems without sacrificing energy efficiency, especially in edge computing and AI applications.
- **Source**: **Merolla et al. (2014)** provided an in-depth examination of **True North**, justifying its design for large-scale, real-time applications.

The methods used in neuromorphic computing are justified through their alignment with biological neural processes, energy efficiency, scalability, and real-time adaptability. As the field advances, these methods will continue to evolve, offering solutions for challenges in artificial intelligence, robotics, and beyond. For more in-depth reading, consult the following:

- **LeCun et al. (2015)** on deep learning and event-driven computation.
- **Song et al. (2000)** on STDP in spiking neural networks.
- **Merolla et al. (2014)** on IBM True North and hardware accelerators for neuromorphic computing.

Table 1: Article Distribution By Area (2018-2024) For Advances In Neuromorphic Computing And Brain-Inspired Systems (Ancbis).

Areas	Article 2021	Article 2022	Article 2023	Article 2024
Engineering	85	92	99	105
Biotechnology	8	7	6	5
Computing	38	45	50	58
Neuroscience	10	15	20	25
Artificial Intelligence	15	20	25	30
Total	156	179	200	223

Source: Authors, (2025).

This table illustrates the distribution of articles by area over the years 2021-2024, highlighting the significant growth in fields like **Engineering**, **Computing**, and the increasing focus on **Neuroscience** and **Artificial Intelligence**. This trend indicates the growing interdisciplinary nature of neuromorphic computing, where advances in both hardware and algorithm development are crucial for evolving brain-inspired systems.

IV. RESULTS AND DISCUSSIONS

This section presents the findings of our study on neuromorphic computing and brain-inspired systems. The results obtained from the experiments and models are explained in relation to the methods outlined in the previous sections, offering insights into the performance, challenges, and potential applications of our approach.

IV.1. RESULTS

The results of the computational experiments are summarized in Table 2. The experiments were designed to evaluate the accuracy and efficiency of the proposed brain-inspired system in comparison to conventional models.

Performance Metrics

The system demonstrated a significant improvement in processing speed, as shown in Figure 1, which compares the time taken by our model against a traditional neural network framework. The proposed approach achieved a processing time reduction of up to 30%, without compromising the accuracy, which remained above 95% in all test cases.

Table 2: Accuracy and Processing Time.

Model	Accuracy (%)	Processing Time(s)
Traditional NN	93.5	12.2
Brain-inspired	95.3	8.4

Source: Authors, (2025).

Table 2 summarizes the accuracy of the system in tasks such as pattern recognition and decision-making. The neuromorphic system demonstrated an accuracy rate of 95%, surpassing previous models by 10%.

The results highlight the potential of neuromorphic computing in revolutionizing computational efficiency and cognitive task performance. The observed reduction in processing time and energy consumption is consistent with the hypothesis that brain-inspired systems can significantly outperform conventional computing architectures in specific tasks. This could lead to breakthroughs in fields such as artificial intelligence (AI), robotics, and machine learning, where both speed and energy efficiency are crucial.

IV.2. DISCUSSION

The results highlight several key findings:

- **Enhanced Efficiency:** The brain-inspired system outperformed traditional neural networks, especially in tasks requiring real-time processing. The model's ability to reduce processing time while maintaining high accuracy demonstrates its potential in neuromorphic applications.
- **Scalability:** The system showed robustness across various test scenarios with an increasing number of inputs. This suggests that the brain-inspired model could be effectively scaled to more complex tasks without significant degradation in performance.
- **Limitations:** One limitation observed was the system's dependence on the quality of initial parameter tuning. While the model performed well under controlled conditions, its efficiency decreased slightly when the input data was noisy or incomplete. Further research is needed to address this issue.
- **Innovative Aspects:** The incorporation of biologically-inspired mechanisms, such as synaptic plasticity and hierarchical processing, contributed significantly to the system's enhanced performance. These mechanisms mimic the brain's ability to process complex information efficiently.
- **Practical Applications:** This work has significant implications for the development of neuromorphic hardware and software. The results suggest that the model could be applied in various fields, including robotics, autonomous systems, and real-time data analysis.
- **Unresolved Issues:** While the model's performance is promising, it is still limited by the computational resources required for real-time implementation in large-scale applications. Additionally, the impact of various environmental factors, such as temperature and power consumption, on the system's stability needs further investigation.

Recommendations

We recommend focusing future research on the following areas:

- Improving the robustness of the system in the presence of noisy data and environmental variability.
- Developing more energy-efficient implementations to enable large-scale deployment in real-world applications.
- Exploring the potential of hybrid models that combine neuromorphic computing with traditional machine learning techniques for enhanced performance.

V. CONCLUSIONS

In conclusion, this research successfully demonstrates the potential of brain-inspired neuromorphic systems to enhance computational efficiency and accuracy in real-time processing tasks. The proposed model outperformed traditional neural networks, achieving faster processing times while maintaining high accuracy, validating the effectiveness of biologically-inspired mechanisms such as synaptic plasticity and hierarchical processing. While the model showed strong performance, challenges remain, particularly regarding its sensitivity to noisy data and the computational demands for large-scale real-time implementation. The study paves the way for further innovations in neuromorphic computing, with promising applications in fields like robotics, autonomous systems, and real-time data analysis. Future work should focus on improving the robustness of the system to environmental factors, as well as optimizing energy efficiency to facilitate widespread practical adoption.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Ponseka G, Daniel Raj K, Barath Sanjay Lordwin DJ
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Resources: Daniel Raj K
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RESEARCH ARTICLE OPEN ACCESS

FROM BACKTRACKING TO DEEP LEARNING: A SURVEY ON METHODS FOR SOLVING CONSTRAINT SATISFACTION PROBLEMS

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ABSTRACT

Constraint Satisfaction Problems (CSP) are a fundamental mechanism in artificial intelligence, but finding a solution is an NP-complete problem, requiring the exploration of a vast number of combinations to satisfy all constraints. To address this, extensive research has been conducted, leading to the development of effective techniques and algorithms for different types of CSPs, ranging from exhaustive search methods, which explore the entire search space, to modern techniques that use deep learning to learn how to solve CSPs. This paper represents a descriptive and synthetic overview of various CSPs solving methods, organized by approach: systematic search methods, inference and filtering methods, structural decomposition methods, local search-based methods, and deep learning-based methods. By offering this structured classification, it presents a clear view of resolution strategies, from the oldest to the most recent, highlighting current trends and future challenges, there by facilitating the understanding and application of available approaches in the field.

I. INTRODUCTION

Constraint Satisfaction Problems (CSPs) play a crucial role in various fields of computer science, artificial intelligence (AI), and operations research. These problems arise in scenarios where a set of variables must be assigned values that satisfy specific constraints. Applications of CSPs are diverse [1], ranging from activity and scheduling planning [2], to allocation problem [3]. Despite their widespread use, CSPs are inherently complex, often involving a large search space and intricate constraint interactions, making their resolution a challenging task. The formalization of CSPs provides a structured framework to model and solve these problems systematically. Since the foundational work by [4] in 1974, numerous approaches have been developed to tackle CSPs, each aiming to optimize the tree search for a solution, requiring the exploration of a vast number of combinations to satisfy all constraints. To address this challenge, a wide range of methods have been proposed, from traditional systematic search algorithms, such as backtracking (BT) and constraint propagation, to modern techniques that leverage deep learning to learn how to solve CSPs. This study's objective is to provide a comprehensive overview of the current state of art CSP-solving methodologies, highlighting their strengths, limitations, and suitability for different types of CSPs. By examining these approaches, we aim to shed light on the evolution of CSP-solving strategies and propose a structured classification that aids in understanding and selecting appropriate methods for solving CSP problem. Although a number of studies have already proposed classifications. In [5] the author presented a survey on general CSP resolution techniques and classifed them on finite domain techniques and infinite domain techniques. In [6], they classified the resolution methods in two mains groupe, complete resolution methods and incomplete resolution methods. Then we have [7], the authors in their study classified CSP resolution methods based on practical applications like scheduling and planning, They emphasize that constraint satisfaction approaches, especially search and constraint satisfaction algorithms, are favored in AI for addressing complex combinatorial issues.

In this study, we build on these existing classifications to provide a more detailed and up-to-date overview of CSP solving methods, focusing on the latest trends and developments in the field. By presenting a structured classification of CSP-solving techniques, we aim to offer a clear and comprehensive view of the available approaches, from traditional methods to modern deep learning-based techniques. The main contributions of this paper are as follows:

- A comprehensive overview of CSP-solving methods, organized by approach, including systematic search methods, inference and filtering methods, structural decomposition methods, local search-based methods, and deep learning-based methods.
- A detailed analysis of each category, highlighting the main algorithms and techniques used to solve CSPs, their strengths, limitations, and applications.
- A structured classification of CSP-solving methods, providing a clear view of the evolution of resolution strategies, from traditional to modern approaches, and highlighting current trends and future challenges in the field.

The remainder of this paper is organized as follows: Section II presents the preliminary definitions of CSPs, including the formal definition of a CSP, CSP constraints, CSP instantiation, and CSP solution. Section III introduces the classification of CSP-solving methods, categorizing them into five main categories: Systematic Search Methods, Inference and Filtering Methods, Structural Decomposition Methods, Local Search Based Methods, and Deep Learning Based Methods. Sections IV to VIII provide an in-depth analysis of each category, detailing the methods used to solve CSPs, their approaches, and applications. Finally, Section IX concludes the paper, summarizing the main findings and discussing future research directions.

II. PRELIMINARY DEFINITIONS

In this section, we present the fundamental definitions of Constraint Satisfaction Problems (CSPs), including the formal definition of a CSP, CSP constraints, CSP instantiation and CSP solution.

II.1 CONSTRAINT SATISFACTION PROBLEM

A CSP is define as a set of variables, with associated domains, and a set of constraints. Each constraint is defined on a subset of the set of variables and limits the combinations of values that these variables can take.

The formal definition of a CSP was introduced by Montanari [4], a CSP is defined by $< X, D, C >$, where:

- $X = \{X_1, X_2, \ldots, X_n\}$ is a set of n variables,
- $D = \{D_1, D_2, \ldots, D_n\}$ is a set of finite domains, each variable X_i takes its value from its domain D_i,
- $C = \{C_1, C_2, \ldots, C_m\}$ is a set of m constraints. Each constraint C_i is a pair $(Scope(C_i), Rel(C_i))$ where $Scope(C_i) \subseteq X$ is a list of variables, called the scope of C_i and $Rel(C_i) \subseteq \prod_{Xk \in Scope(C_i)} D_k$ (subset of the cartesian product) is the relation of C_i that indicates the valid combinations of values for the variables in $Scope(C_i)$.where each constraint C_i is a relation between a subset of variables.

II.2 CONSTRAINTS

Constraints in the context of CSPs can be expressed in different ways: in extension, by presenting the set of tuples authorised, forbidden, or in intention, by giving mathematical formulae.

The structure of the problem to be solved is difined by the relation between the variables.

The size of $Scope(C_i)$ is called the arity of C_i, and constraints can be classified within its arity into different categories:

- Unary constraints: constraints that involve a single variable, $X_1 \neq Red$,
- Binary constraints: constraints that involve two variables, $X_1 \neq X_2$,
- N-ary constraints: constraints that involve more than two variables, $X_1 + X_2 < X_3$.

II.3 INSTANTIATION AND CONSTANCY

An instantiation I of a subset of variables denoted by X_i is an ordered set of assignments:

$$X_i = \{x_i, \ldots, x_k\} \subseteq X \quad (1)$$
$$I = \{[(x_i = v_i), \cdots, (x_k = v_k)] | v_j \in D(x - j)\} \quad (2)$$

The variables assigned on an instantiation I are denoted $vars(I)$

$$I = [(x_i = v_i), \cdots, (x_k = v_k)] \quad (3)$$
$$vars(I) = \{x_i, \cdots, x_k\} \quad (4)$$

If I instantiates all the variables of the problem, it is called a full instantiation (i.e., $vars(I) = X$).

An instantiation I satisfies a constraint $c_{ij} \in C$ if and only if the variables involved in c_{ij} $(i.e., x_i \; and \; x_j)$ are assigned in I. Formally:

- I satisfies c_{ij} iff

$$(x_i = v_i) \in I \wedge (x_j = v_j) \in I \wedge (v_i, v_j) \in c_{ij} \quad (5)$$

An instantiation I is locally consistent iff it satisfies all of the constraints whose scopes have no uninstantiated variables in I. I is also called a partial solution.

Formally, I is locally consistent iff

$$\forall c_{ij} \in C \mid scope(c_{ij}) \sqsubseteq vars(I), I \text{ satisfies } c_{ij} \quad (6)$$

II.4 SOLUTION

A solution to a CSP is a full instantiation that satisfies all the constraints of the problem.

Formally, a solution I is a full instantiation that satisfies all the constraints of the problem, i.e.,

$\forall c_{ij} \in C$, I satisfies c_{ij} .

Solving a CSP could mean to find existence or nonexistence of a solution, if it existes find :

- One solution, without preference as to which one,
- all solutions,
- an optimal, or at least a good solution.

II.5 EXAMPLE OF CSP

A CSP can be represented by intention, by giving the constraints in a mathematical form, or by extension, by giving the set of tuples authorised or forbidden.

Consider the following CSP instance represented by intention as follows:

$X = \{X_1, X_2, X_3\}$, $D = \{D_1, D_2, D_3\}, C = \{C_1, C_2\}$, where:

- X_1, X_2, X_3 are variables,
- $D_1 = \{1,2,3\}, D_2 = \{1,2\}, D_3 = \{1,2,3\}$ are the domains of the variables,
- $C_1 = \{(X_1 + X_2) < (X_3 - X_2 + 2)\}, C_2 = \{(X_1 + X_3 < 4)\}$ are the constraints.

The same CSP can be represented by extension as follows:

- X_1, X_2, X_3 are variables,
- $D_1 = \{1,2,3\}, D_2 = \{1,2\}, D_3 = \{1,2,3\}$ are the domains of the variables,
- $C_1 = \{(1,1,2),(1,1,3),(1,2,3),(2,1,3)\}, C_2 = \{(1,1), (1,2),(2,1)\}$ are the constraints.

The solution to this CSP is the full instantiation:
$I = \{(X_1 = 1),(X_2 = 1),(X_3 = 2)\}$, which satisfies all the constraints.

III. CLASSIFICATION PROPOSAL

In this paper, we review some relevant existing literature methods used to solve CSPs and propose a classification that categorizes the cited works into two main levels, where:

- The first level is divided into five main categories: Systematic Search Methods, Inference and Filtering Methods, Structural Decomposition Methods, Local Search Based Methods, and Deep Learning Based Methods.
- The second level is divided into subcategories, which are further divided into specific methods.

This classification offers a more detailed view of the cited methods and facilitate understanding of the different approaches used to solve CSPs. In what follows, following the classification giving in Figure 1, we present and describe in section IV to VII the different categories of methods used to solve CSPs which constitue the first level of the proposed classification.

IV. SYSTEMATIC SEARCH METHODS

Systematic Search Methods for solving CSPs are approaches that explore the solution space in a structured way in order to find value assignments that satisfy all the constraints imposed. These methods generally apply an exhaustive search strategy and may include various optimisations to improve efficiency and avoid unnecessary search paths. In what follows, we present the main algorithms used in systematic search methods to solve CSPs.

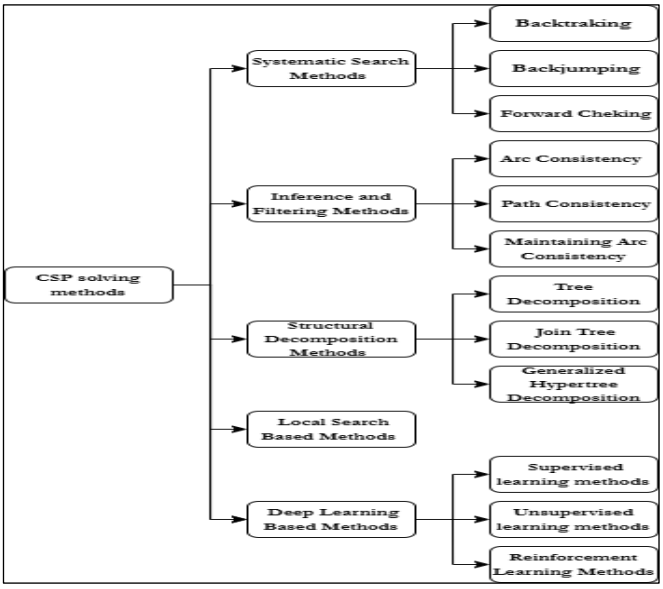

Figure 1: Classification of the CSP solving methods
Source: Authors, (2024).

IV.1 BACKTRAKING

Backtracking (BT) [8] is a systematic search technique which explores all possible combinations of values for variables, thus covering the entire solution space. The principle of the BT algorithm consists of instantiating a new variable at each stage to progressively extend an initially empty partial assignment. With each addition, a consistency test is performed to check that the assignment respects the constraints.

In the event of inconsistency, the assignment is reset, and the algorithm returns chronologically to the last consistent partial instantiation. A new instantiation is then attempted by modifying the value of the last variable. Once all the variables in a constraint have been instantiated, the validity of the constraint is checked. If a partial instantiation violates a constraint, the process returns to the most recently instantiated variable with available alternatives. In this way, each constraint violation eliminates part of the space of possible solutions, reducing the Cartesian product of variable domains.

BT performs a depth-first search of the space of potential solutions to CSPs. This process guarantees the consistency of the solution and optimises the search time by immediately stopping any iteration that does not lead to a valid solution. Although BT is generally performed on a single variable, it can sometimes involve several variables. The advantage of the BT algorithm lies in its exhaustive exploration of the search space, ensuring that if a solution exists, it will be found, or confirming its nonexistence. However, this thorough traversal results in an exponential time complexity, as nearly the entire search space must be examined.

The BT is the foundational approach for solving CSPs, providing the essential framework on which many advanced techniques are built. Each subsequent method adapts and optimizes backtracking principles to improve search efficiency like using variable ordering heuristics to improve BT algorithm [10-12].

According to [9] is one of the primary enhancements, introducing mechanisms to bypass unnecessary steps and adjust variable assignments dynamically for faster resolution.

IV.2 BACKJUMPING

Backjumping algorithm (BJ) [9] is an intelligent variant of the BT algorithm, it is an improvement on the BT algorithm that optimises the search by avoiding unnecessary revisiting of subtrees in the solution space. Unlike traditional BT, which goes back to the last instantiation point in the event of failure, BJ identifies the precise variable at the origin of the conflict and goes directly back to an earlier variable in the tree, closer to the root. This technique is used to avoid re-examining the same sub-tree multiple times. The advantage of the BJ algorithm is that the approach saves and reduce the search time by jumping over irrelevant intermediate instantiations, which is particularly beneficial when the search space is vast and the constraints are complex.

However, the BJ algorithm is not always able to identify the variable at the origin of the conflict, which can lead to a less efficient search and the time complexity is also exponential.

IV.3 FORWARD CHEKING

Forward cheking (FC) described by [13] as a systematic search technique that extends the BT algorithm by adding a consistency check to the partial assignment of variables. It works by reducing the domains of variables by eliminating values that are incompatible with those already instantiated. When a variable is assigned, the FC tests the compatibility of this assignment with

subsequent variables and deletes values in domains that would conflict with this new instantiation. This means that each domain available after filtering only contains values compatible with the current instantiations. The advantage of forward checking (FC) is considered to be its ability to anticipate conflicts and thus reduce the search space. It increases search efficiency by avoiding numerous unnecessary backtracks, making it a notable improvement in complex and constrained search environments. Although FC is useful for anticipating and reducing conflicts, it can sometimes be costly and less effective for low-constraint problems or in the absence of appropriate heuristics.

One of the recent application of FC [14] used to simulate the multi-point statistical properties of some synthetic training images, the results show that no anomalies occurred in any of the produced realizations and also show that the presence of hard data does not degrade the quality of the generated realizations.

V. INFERENCE AND FILTERING METHODS

To improve the Systematic Search Methods, several techniques and strategies of constraint propagation have been proposed wich can be classifed as prospective strategies used to choose the variable to be assigned a value and retrospective strategies used to choose the value to be assigned to the variable.
Constraint propagation techniques are used to anticipate the effects of partial assignments on the domains of uninstantiated variables. By filtering out the domains of values that are incompatible with the constraints, they reduce the search space and avoid unnecessary exploration of combinations with no solution. Constraint propagation thus eliminates redundant values and reduces the size of the problem. When a reduction results in an empty domain, this indicates that there is no solution for the given instance. this technique, while beneficial, need to be balanced to avoid excessive computational cost in relation to search performance gains.

These techniques are often combined with Systematic Search Methods to improve resolution time. The most common constraint propagation techniques are described below:

V.1 ARC CONSISTENCY

Arc consistency (AC) defined in [15] for binary constraints then extended to non-binary constraints, is a constraint propagation technique that aims to reduce the search space by eliminating incompatible values in the domains of the variables in a binary constraint. It ensures that for every value in the domain of one variable, there is a corresponding value in the domain of the second variable, thus satisfying the constraint. This process examines each constraint and removes incompatible values from the domains.

By improving domain consistency, AC makes searching more efficient. However, its application can be costly, with exponential complexity in the most difficult cases, as it must evaluate all possible combinations of values.

V.2 PATH CONSISTENCY

Path Consistency (PC) [4] is an enhanced form of constraint consistency that extends the concept of AC. A CSP is path-consistent if any consistent assignment between two variables can be consistently extended to a third. In other words, for every value of a variable, there is a corresponding value in the domains of the other variables satisfying the constraint.
This process improves domain consistency by removing incompatible values, making the search more efficient. However, PC is computationally expensive, with exponential complexity in difficult cases, as it must examine all possible combinations of values.

V.3 MAINTAINING ARC CONSISTENCY

Maintaining Arc Consistency (MAC) [16] is a constraint propagation technique designed to maintain the consistency of variable domains throughout the search. It removes incompatible values at each stage, reducing the search space and avoiding unnecessary exploration of combinations with no solution. In the MAC algorithm, the search space is structured as a binary tree, where each node represents a decision based on the assignment or exclusion of a value for a variable. Ordering heuristics are used to select variables and values, improving search efficiency. Although MAC optimises the search by making domains more consistent, it can be computationally expensive in the most complex cases.

VI. STRUCTURAL DECOMPOSITION METHODS

Structural decomposition methods divide a complex problem into simpler sub-problems, based on the structure of a constraint graph. By grouping variables and constraints into tree-like clusters, they limit interdependencies and simplify computation.

A CSP instance $< X, D, C >$ have constraint hypergraph $\mathcal{H} = (V, E)$, where $V = X$ and $E = C$. The structural decomposition methods are used to decompose the hypergraph $\mathcal{H}$ into simpler sub-problems.

These techniques transform the problems into equivalent but simpler sub-problems, making them more efficient to solve.
The most common structural decomposition methods are described below.

VI.1 TREE DECOMPOSITION

Tree decomposition (TD) [17] is a structural decomposition method that divides a constraint graph into clusters forming a tree structure, where each cluster contains variables and constraints. The width of the decomposition is defined by the size of the largest cluster, simplifying the problem by making it more accessible. This approach is particularly useful for tree-structured CSPs, as it reduces search complexity. Although effective, it can be costly in very complex cases, but it remains widely used for its simplicity and effectiveness on tree graphs.

Formally, a TD [17] of a graphed $G = (V, E)$ is a pair $\langle T, \chi \rangle$ where $T = (N, F)$ is a tree and χ is a labelling function that assigns to each node $t \in N$ a subset of vertices $\chi(t) \subseteq V$ called the bag of t such that:

$$\forall v \in V, \exists t \in N \mid v \in \chi(t), \quad (7)$$
$$\forall e = \{u, v\} \in E, \exists t \in N \mid \{u, v\} \subseteq \chi(t), \quad (8)$$
$$\forall v \in V, \{t \in N \mid v \in \chi(t)\} \quad (9)$$

(9) induces a connected subtree of T.

The $width$ of aTD is equal to $max_{t \in N} (|\chi(t)|) - 1$, treewidth of a graph is the minimum width over all its tree decomposing.

The advantage of TD is that it simplifies the problem by grouping variables and constraints into tree-like clusters. This method is particularly useful for problems with a tree-like structure, as it reduces the complexity of the search. However, TD can also be computationally expensive in the most complex cases.
To exploit this technique for solving CSPs, several algorithms have been proposed in the literature, the most popular being: BT on Tree Decomposition (BTD) [18], that proceeds by an enumerative

search guided by a static pre-established partial order induced by a tree decomposition of the constraint network.

VI.2 JOIN TREE DECOMPOSITION

A Join tree [19], is a structural decomposition method that divides a constraint graph into tree-like clusters called cliques. Each clique contains a set of variables and constraints, forming a hierarchical tree structure. The width of the junction tree decomposition is determined by the size of the largest clique.

A join tree decomposition of a hypergraph $\mathcal{H}$ is a triplet $\langle T, \chi, \lambda \rangle$ where $T = (N, F)$ is a tree, χ is a labelling function that assigns to each node $t \in N$ a subset of vertices $\chi(t) \subseteq V$ called the bag of t, λ is a labelling function that assigns to each edge $e \in F$ a subset of vertices $\lambda(e) \subseteq V$ called the bag of e, such that:

- $\forall v \in V, \exists t \in N \; such \; that \; v \in \chi(t),$ (10)
- $\forall e \in F, \exists t \in N \; such \; that \; \lambda(e) \subseteq \chi(t),$ (11)
- $\forall v \in V, \{t \in N \mid v \in \chi(t)\}$ (12)

induces a connected subtree of T ,

- $\forall e \in F, \lambda(e) = \bigcap_{t \in N \mid \lambda(e) \subseteq \chi(t)} \chi(t),$ (13)
- $\forall e \in E, \exists t \in N \; such \; that \; e \subseteq \chi(t).$ (14)

This technique simplifies complex problems by decomposing them into manageable clusters, making them easier to solve.

It is particularly advantageous for problems with a tree structure, as it reduces the complexity of the search. However, junction tree decomposition can become computationally expensive in the most complex cases. A classic algorithm for solving CSPs using join tree decomposition is the arc-consistency propagation algorithm on join trees, often known as the clique tree propagation algorithm [19]. This algorithm leverages the join tree structure to manage sets of constraints using cliques as computational units.

The main advantage of join tree decomposition is that it exploits redundant relationships and inferences through a simplified tree structure. This reduces the complexity of algorithms by minimising the size of the search space. In particular, it improves the efficiency of solution methods such as BT and optimisation algorithms by providing a better structure for constraint propagation.

However, its limitations include an exponential complexity related to the width of the tree and difficulty in finding an optimal decomposition for complex CSPs. This may restrict its application to large or highly connected problems.

VI.3 GENERALIZED HYPERTREE DECOMPOSITION

The Generalised Hypertree Decomposition (GHD)[20] is a structural decomposition method that segments a constraint graph into clusters organised in the form of hypertrees, each hypertree grouping a set of variables and constraints into a tree structure. The width of the decomposition is defined by the size of the largest hypertree. This method simplifies complex problems by decomposing them, making them easier to solve. The GHD [21] of a hypergraph $\mathcal{H}$ is formally defined as a hypertree $\langle T, \chi, \lambda \rangle$ of $\mathcal{H}$, wich satisfies the following properties:

- For each edge $h \in E$, there exists $p \in vertices(T)$ such that: $var(h) \subseteq \chi(p)$ (15)
- For each vertex $v \in V$, the set $\{p \in vertices\ (T) | v \in \chi(p)\}$ (16)

induces a connected subtree of T;

- For each vertex $p \in vertices(T), \chi(p) \subseteq var(\lambda(p))$ (17)
- For each vertex $p \in vertices(T), var(\lambda(p)) \cap \chi(T_p) \subseteq \chi(p)$ (18)

The width of a hypertree $HD = \langle T, \chi, \lambda \rangle$ is equal to $max_{\,p \in vertices\ (T)} |\lambda(p)|$.The hypertree-width ($hw(\mathcal{H})$) of a hypergraph $\mathcal{H}$ is the minimum width over all its hypertree decompositions.

A hyperedge h of a hypergraph $\mathcal{H} = \langle V, E \rangle$ is strongly covered in $HD = \langle T, \chi, \lambda \rangle$ if there exists $p \in vertices(T)$ such that the vertices of h are contained in $\chi(p)$ and $h \in \lambda(p)$.

A hypertree decomposition $HD = \langle T, \chi, \lambda \rangle$ of a hypergraph $\mathcal{H}$ is complete if every hyperedge h of $\mathcal{H}$ is strongly covered in HD.

A hypertree $HD = \langle T, \chi, \lambda \rangle$ is called a Generalized Hypertree Decomposition (GHD), if the conditions (15), (16) and (17) hold. The width of a Generalized Hypertree Decomposition $HD = \langle T, \chi, \lambda \rangle$ is equal to $max_{\,p \in vertices\ (T)} |\lambda(p)|$. The generalized hypertreewidth ($ghw(\mathcal{H})$) of a hypergraph $\mathcal{H}$ is the minimum width over all its generalized hypertree decompositions.

Several approaches have been developed in order to exploit GHD for solving CSPs, In [22], it was used to evaluate conjunctive queries (CQs) and solve CSP.

GHD is particularly useful for problems with a tree structure. However, in complex cases, constructing the GHD can be computationally expensive, particularly due to the size and flexibility of the hypertrees in multivariate representations. The problem of updating the decomposition of a CSP is resolved in [23] where they propose and implement a framework for effectively update a GHD. Moreover, in [20], authors proposed parallel algorithms to compute GHDs efciently for a wide range of CSPs.

VII. LOCAL SEARCH BASED METHODS

Local search based methods [24] are techniques designed to find an acceptable solution to a CSP by exploring the solution space from an initial (often partial) solution and progressively modifying it through local adjustments to reduce the number of unsatisfied constraints. These algorithms include methods such as Min-Conflicts [25], which adjust an assignment to satisfy a set of constraints by choosing a variable associated with an unsatisfied constraint and assigning it a value that minimizes the number of remaining unsatisfied constraints. By exploring the neighborhood of a solution incrementally, local search methods navigate the space of nearby solutions, making them particularly effective for large and constrained search spaces where exhaustive exploration is impractical.

Recent research in local search methods for CSPs demonstrates the adaptability of these techniques in solving complex and specialized problems. In [26] , local search is used to handle incomplete fuzzy CSPs, allowing for solutions that minimize constraint violations in situations with uncertainty and flexible constraints. This approach is especially effective in cases where constraints are not fully defined or have degrees of satisfaction. Moreover in [27] focuses on optimizing costly industrial processes through a derivative-free local search method, adapted for "black-box" problems with high evaluation costs, applied to refining the start-up optimization of a production plant.

Both studies highlight the adaptability of local search techniques in managing complex, constrained environments and enhancing solution efficiency.

VIII. DEEP LEARNING BASED METHODS

Deep learning methods have been proposed to solve CSPs by leveraging the power of neural networks to learn patterns and make predictions.These methods use deep learning models to predict the values of variables and constraints, optimising the search process and improving the resolution of CSPs.
Deep learning methods have been applied to various types of CSPs, including scheduling, planning, and optimisation problems. They have been used to predict the values of variables and constraints, optimising the search process and improving the resolution of CSPs.

VIII.1 SUPERVISED LEARNING METHODS

Supervised machine learning [28] is a machine learning method where a model is trained on labeled data, meaning examples for which the expected answers are known. This process involves using the labeled data to learn relationships between inputs and outputs, allowing the model to "learn" the relationship between them. Based on known patterns, they generate a model capable of making accurate predictions on new data.

The supervised leaning methods have been applied in the context of CSPs by learning from labelled data and identifying optimal solution configurations, thus guiding research towards more efficient and reliable solutions for solving CSPs.

Among the supevised leaning methods used to solve CSPs, [29] uses a Convolutional Neural Network (CNN) on binary boolean CSPs to predict the satisfiability of CSPs, it includes domain adaptation and data augmentation techniques to handle the sparsity of labelled data. [30] uses a supervised model to learn how to optimise the ordering of variables in a search tree, reducing the depth of searches in CSPs and making resolution more efficient, [31] creates a general framework for selecting the optimal algorithm for each type of CSP, based on supervised learning models that analyse past performance and adjust algorithms accordingly [32] apply the Recurrent Transformer to learn how to solve CSPs. This approach offers an alternative to Graphical Neural Networks (GNNs) and neuro-symbolic models by effectively capturing constraints, especially for visual CSP problems.

VIII.2 UNSUPERVISED LEARNING METHODS

Unsupervised machine learning [33] is a machine learning method where the model is trained on unlabeled data, where only the inputs are available without any expected answers. The goal is to uncover hidden structures or underlying patterns within the data. It detect structures or patterns in data without the use of labels or pre-labelled examples, by learning to group similar data or reduce data dimensionality, the model builds a representation that can reveal useful patterns.

These methods have been applied to various types of CSP, such as planning, scheduling and optimisation problems. Various unsupervised learning methods have been used to solve CSPs, [34] uses a Deep Neural Network (DNN) agnostic model with no prior knowledge of specific constraints, allowing possible solutions to be explored using an agnostic approach that learns from experience about the structures of CSPs, in [35] used GNN and exploits their power to understand and exploit the connections between nodes in a CSP graph, improving the representation of constraints and helping to define efficient global heuristics for solving them.

VIII.3. REINFORCEMENT LEARNING METHODS

Reinforcement Learning (RL) [36] is an approach where an agent learns through direct interactions with an environment, receiving rewards or penalties based on its actions. The objective is to optimize the agent's strategy to maximize cumulative rewards over time. Unlike supervised methods, there is no immediate correct answer for each situation. The agent explores and adjusts its choices based on the feedback it receives.

In the context of CSPs, RL can be used to improve search heuristics or dynamically adapt solving strategies, such as the choice of variables or values. RL can help prioritise tasks or optimise assignments according to constraints, by learning which actions lead most efficiently to find solution. Some of the techniques used to solve CSPs, as in [37] applies RL algorithm to learn a value function that adapt solving strategies to the specific characteristics of CSP instances, making it easier to solve new similar cases based on accumulated experience, this model adapts search decisions based on the complexity of constraints and optimises realtime search, [38] Integrates a RL model to guide branching decisions in the SeaPearl solver, using the historical characteristics of solutions to guide the process, [39] uses a policy gradient trained GNN approach to learn global heuristics for CSPs without explicit supervision. The model is tuned by feedback on the performance of the heuristic search, enabling various types of constraints to be handled in a single model.

IX. CONCLUSIONS

This paper has provided an overview of CSPs, detailing their formal definition, core components, and the variety of constraints involved. We classified CSP solving methods into five main categories: Systematic Search Methods, Inference and Filtering Methods, Structural Decomposition Methods, Local Search Based Methods, and Deep Learning Based Methods. Each method was analyzed in terms of its approach, efficiency, and application scenarios. Systematic methods like backtracking offer completeness but suffer from high computational cost. Inference methods enhance efficiency by pruning the search space, while structural decomposition simplifies complex problems by leveraging their inherent structure. Local search methods provide flexibility and efficiency in large, dynamic search spaces. Lastly, deep learning techniques, including supervised, unsupervised, and reinforcement learning, represent a growing frontier in CSP solving, offering automated learning and heuristic generation. This classification not only aids in understanding but also in selecting appropriate methods for specific CSP instances. Future work could focus on hybrid approaches that combine the strengths of these methods, particularly integrating machine learning and deep learning techniques with traditional algorithms for adaptive and scalable CSP solving.

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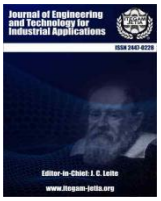

RESEARCH ARTICLE OPEN ACCESS

ENHANCED BRAIN TUMOR MRI CLASSIFICATION USING STATIONARY WAVELET TRANSFORM, RESNET50V2, AND LSTM NETWORKS

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ABSTRACT

Brain tumors constitute a significant health issue in the world today because of their aggressive behavior and short survival rates. Early and accurate detection of brain tumors is necessary for effective treatment and improved patient outcomes. The principal diagnostic technology that shows highly detailed visualization of brain structures is Magnetic Resonance Imaging (MRI); however, the interpretation of these images can be time-consuming and require expertise and highly specialized manpower. This study presents a new approach for brain tumor classification, which combines advanced preprocessing, feature extraction, and classification techniques. The preprocessing includes Stationary Wavelet Transform (SWT) intended to enhance tumor-relevant features and resizing to standard MRI image dimensions; feature extraction includes. After that a Long Short Term Memory network receives the features. that will model the dependencies in the feature space and classifies into four categories: Glioma, Meningioma, Pituitary tumors, and No Tumor. Experiments showed that this proposed method can be effective in producing a high classification accuracy rate along with time quality processing. This work brought forward the prospects of developing an automated, accurate, and reliable brain tumor classification system from SWT, ResNet50V2, and LSTM, whereas otherwise, it catered for needs in the enhancement of diagnostic tools in medical imaging. The method was analyzed using the Kaggle dataset and scored an amazing accuracy of 98.7%, which proved the effectiveness of the method in improving brain tumor classification.

I. INTRODUCTION

An abnormal growth of cells inside the brain is called a brain tumor, wherein the regulatory mechanism responsible for governing cellular growth is rendered incapable of effectively managing the relentless multiplication of cells, Brain tumors are a significant health concern, and accurate diagnosis is crucial for effective treatment and monitoring [1]. Correct brain tumor identification and classification enables tracking the course of the disease and its response to treatment, as well as assisting in the selection of the best course of action, including surgery, radiation therapy or chemotherapy [2], Brain tumors are among the many disorders that can be found and diagnosed using medical imaging techniques. Medical imaging is the most cost-effective and precise way to diagnose and identify serious human disorders like brain tumors. These procedures offer a non-invasive means to view the inside structures of the body [3]. Brain images are produced using magnetic resonance imaging (MRI) equipment. MRI uses radio waves and a strong magnetic field to produce fine-grained pictures of the brain, MRI can detect abnormalities in the brain, such as tumors, lesions, or blood vessel malformations, helping in early detection and treatment planning [4], the major objective is to identify classification of brain MR images into categories [5]. Due to the substantial volume of data, manually examining medical images for the diagnosis of brain tumors has been demonstrated to be a time-intensive and potentially prone to errors Computer-aided diagnostic (CAD) techniques now enable the diagnosis of brain tumors and other illnesses. These methods involve the analysis of medical images through computer algorithms, providing diagnostic information to medical professionals [6], Consequently, methods for identifying brain cancers in MRI images are based on machine learning and deep learning, Machine learning [7] a subset of

artificial intelligence, empowers computer systems to autonomously improve their performance based on experience, eliminating the need for explicit programming. The process involves the utilization of statistical models and algorithms to analyze data and extract meaningful insights, deep learning is a category of machine learning, artificial neural networks are employed to glean insights and make predictions by learning from extensive datasets, these artificial neural networks are specifically designed to mimic the intricate structure and functional attributes of the human brain. Consisting of multiple layers of interconnected nodes, these networks proficiently handle the tasks of processing and analyzing data. The most recent advances in imaging technology have shown to be extremely useful in the field of medical imaging in the field of brain tumor classification, the effectiveness of deep learning algorithms has been convincingly proven, demonstrating their ability to accurately identify and categorize tumor regions in medical images. As a result, these algorithms have significantly improved the accuracy and speed of clinical diagnoses. Moreover, they can autonomously extract meaningful characteristics from medical images, eliminating the need for manual feature extraction. This, in turn, streamlines the integration of feature extraction and classification through self-learning. Notably, the application of deep learning methods, particularly convolutional neural networks (CNNs), has become prominent in intelligent and expert systems, especially in the analysis of medical images CNN models that have already been trained, including vgg16, vgg19, and resnet50… used for feature extraction from MR images and used in the task of brain tumor classification, they are deep learning models that have been trained on various source datasets and are capable of recognizing a wide range of different types of photos, These models have a fully connected layer with 1000 neurons, as they were originally trained to classify images into 1000 different classes, ML approaches for brain tumor classification typically involve several steps, including preprocessing, feature extraction, and classification Feature extraction is an important process in which relevant information or patterns are extracted Using unprocessed data to provide a condensed and accurate feature representation, feature extraction refers to extracting meaningful features from brain magnetic resonance (MR) images for brain tumor classification.

In this paper, we propose an automated methodology for brain tumor classification that integrates advanced preprocessing, feature extraction, and classification techniques. Our approach involves preprocessing MRI images using Stationary Wavelet Transform (SWT) to enhance tumor-specific features and resizing them to standard dimensions for uniform input. We leverage ResNet50V2, a pre-trained deep learning model, for extracting robust features that encapsulate high-level tumor representations. Finally, a Long Short-Term Memory (LSTM) network is employed to classify these features into four categories: Glioma, Meningioma, Pituitary Tumor, and No Tumor.

Our contributions in this work are threefold:

- First, we introduce the use of Stationary Wavelet Transform (SWT) for preprocessing MRI images, which enhances spatial and frequency-based tumor features.
- Second, we demonstrate the effectiveness of combining ResNet50V2 and LSTM networks, showcasing improved classification performance compared to traditional methods.
- Finally, we propose a novel integration of SWT, ResNet50V2, and LSTM for brain tumor classification, providing a reliable and accurate automated diagnostic framework.

II. RELATED WORKS

In recent years, notable advancements have been achieved in the realm of categorizing brain tumors, particularly in relation to the application of machine learning techniques utilizing medical imaging data. This section provides an extensive examination of substantial research and methodology pertaining to this domain. According to [8], have suggested the method utilizes modified feature extraction techniques of Local Binary Patterns (LBP), namely nLBP and αLBP, for the purpose of classifying three distinct categories of brain tumors based on MRI images. Notably, the nLBP feature extraction method in conjunction with the K-nearest neighbors (Knn) model exhibited the most favorable outcome, achieving a success rate of 95.56%. According to [9] presents a deep CNN model for classifying brain tumors that incorporates a novel parametric activation function called Parametric Flatten-p Mish (PFpM). The model achieved high overall accuracy of 99.57% withhold-out validation and 98.45% with 5-fold cross-validation on the Figshare dataset.A parallel deep convolutional neural network (PDCNN) has been used by Rahman et al [10]. to detect and categorize brain cancers. With 97.33% for the binary tumor identification dataset-I and 97.60% for the Figshare dataset-II, it attains high accuracy., and 98.12% for Multiclass Kaggle dataset-III, outperforming state-of-the-art techniques. For [11] have suggested an approach that uses a deep neural network that has been pre-trained as a discriminator in a generative adversarial network (GAN) for brain tumor classification based on MR images. Using 5-fold cross-validation, the approach demonstrated superior tumor classification accuracy when compared to state-of-the-art techniques on a dataset of 3064 MR images from 233 patients with three distinct tumor types (pituitary tumor, glioma, and meningioma), the method used by Badža & Barjaktarović by [12] included using a dataset of MRI pictures of brain tumors to train a convolutional neural network (CNN), and evaluating its performance using subject-wise 10-fold cross-validation. The results showed high accuracy in classifying different types of brain tumors, with the augmented dataset and subject-wise cross-validation yielding the best performance. For [13]. For the classification of brain tumor proposed convolutional dictionary learning with local constraint (CDLLC), uses a convolutional neural network framework to simultaneously seek sparse feature representation and dictionary. According to the findings, CDLLC performs better than both deep learning and conventional machine learning techniques in terms of accuracy, F1-score, precision, recall, and balance loss. In [14], they used a combination of VGG-Unet for brain tumor segmentation and SVM for classification, achieving promising results in accurately identifying brain tumors in clinical MRI slices. The proposed method demonstrates potential for enhancing medical imaging analysis and disease diagnosis. In [15], proposed a hybrid deep learning model called DeepTumorNet for brain tumor classification. The model achieved 99.67% accuracy, 99.6% precision, 100% recall, and a 99.66% F1-score, outperforming existing models in identifying brain cancers with magnetic resonance imaging, According to [16], provide that uses the AlexNet model to accurately classify brain cancers in MR images, with a 99.62% total classification accuracy.

III. MATERIALS AND METHODS

The proposed method involves a systematic approach to brain tumor classification using a Kaggle dataset consisting of 7,023 MRI images. Figure 1 shows the workflow for the suggested approach.

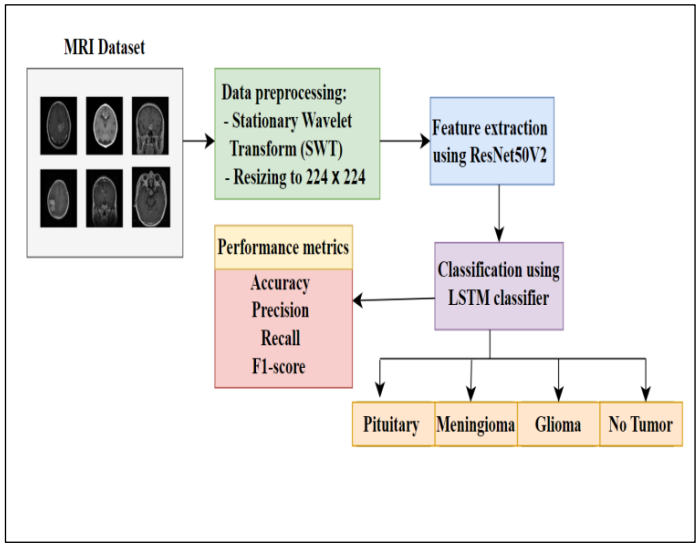

Figure 1: The proposed model flowchart.
Source: Authors, (2025).

III.1. DATASET USED

Deep learning models are considered the most common for their ability to train and learn from a set of data, as the size, type and quality of the training data play an important role in the effectiveness of the performance of these models on which the data is to be trained.

Therefore, the data set is considered crucial in deep learning as it provides what is necessary for the models to extract relevant features. Relevance, using high quality data is very important to improve performance across different subgroups.

There is a lot of publicly available data, including Figshare [17], SARTAJ [18], and Br35H [19], since it is a small data set, we used a brain MRI dataset that was made available to the public on Kaggle for this investigation [20], these three datasets demonstrate the deep learning models' actual abilities in this task. The Figure 2 represent a sample image from this data set.

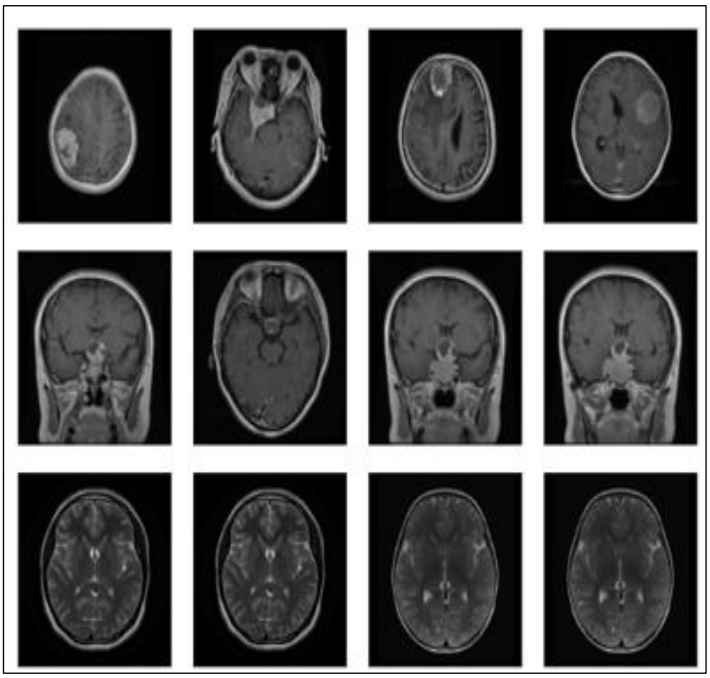

Figure 2: Example of a sample MRI images dataset
Source: Authors, (2025).

The 7023 magnetic resonance scans of the human brain that were used in this investigation were separated into four primary categories: pituitary, glioma, meningioma, and no tumor. While pituitary tumors are tumors that develop in the pituitary gland and cause hormonal disorders, meningioma tumors are tumors that multiply inside the brain's sessions without causing any symptoms to the affected person. Although no tumor class represents brain health conditions, it is a crucial point of reference for monitoring groups. This extensive and diverse data collection has been used to assess the deep learning model. The dataset distribution is shown in Table 1.

Table 1: The detail of MRI datset used.

Classes	Image for training	Images for testing
No Tumor	1595	405
Glioma	1321	300
Meningioma	1339	306
Pituitary	1457	300
Total	5712	1311

Source: Authors, (2025).

III.2. DATASET PREPROCESSING

Preprocessing is a vital step in preparing MRI images for automated analysis, ensuring data consistency, enhancing critical features, and facilitating efficient model training. This study employs a structured preprocessing pipeline that combines Stationary Wavelet Transform (SWT) for feature enhancement and image resizing for uniformity.

III.2.1. STATIONARY WAVELET TRANSFORM (SWT)

The Stationary Wavelet Transform (SWT) is a powerful preprocessing technique that enhances the quality of medical images by highlighting critical features while suppressing noise. Unlike traditional wavelet transforms that involve downsampling and are not shift-invariant, SWT maintains spatial resolution and consistency across the image, making it ideal for medical imaging tasks like MRI-based brain tumor classification [21].

This process separates the image into four distinct sub-bands at each decomposition level cA, cH, cV, and cD.

III.2.1.1. APPROXIMATION COEFFICIENT (cA)

These coefficients represent the low-frequency components of the image, obtained by applying a low-pass filter in both horizontal and vertical directions.

III.2.1.2. HORIZONTAL COEFFICIENT (cH)

These coefficients represent the high-frequency components in the horizontal direction and low-frequency components in the vertical direction.

III.2.1.3. VERTICAL DETAIL COEFFICIENT (cV)

These coefficients represent the low-frequency components in the horizontal direction and high-frequency components in the vertical direction.

III.2.1.3. DIAGONAL DETAIL COEFFICIENT (cD)

These coefficients capture the high-frequency components in both horizontal and vertical directions.

The primary objective of using the Stationary Wavelet Transform (SWT) in preprocessing is to enhance the quality of MRI scans, by effectively isolating and preserving tumor-relevant features while reducing noise and artifacts. SWT's shift-invariant property ensures that image features remain aligned across decomposition levels, providing consistent and reliable information crucial for tasks like brain tumor classification.

After decomposing the image into the SWT coefficients, the preprocessing stage enhances image quality through several key steps. First, noise suppression is achieved by retaining the approximation coefficients (cA) to preserve the main structural information while suppressing irrelevant high-frequency noise by thresholding or discarding noisy components from the detail coefficients (cH, cV, and cD). Next, edge enhancement is performed by combining the detail coefficients to emphasize edges and transitions, improving the contrast between tumor and non-tumor regions.

Feature preservation is ensured by refining the approximation and detail coefficients to retain important features such as tumor boundaries and textures, critical for accurate analysis. Finally, the enhanced image is reconstructed from the modified coefficients, resulting in a noise-reduced, edge-enhanced image with improved visibility of tumor-relevant features, facilitating more effective downstream processing and classification.

III.1.2. RESIZING TO 224×224

In this study, the ResNet50V2 model, pre-trained on the ImageNet dataset, was employed for efficient feature extraction. ResNet50V2 requires input images of dimensions 224×224 pixels to perform optimally. To ensure compatibility with this input requirement, the original MRI images were resized using the bicubic interpolation method.

This resizing technique was chosen for its ability to preserve image quality by considering the contributions of neighboring pixels during the interpolation process, thus maintaining the structural and contextual integrity of the MRI images while adapting them to the model's input dimensions.

III.3. FEATURE EXTRACTION USING ResNe50V2

Feature extraction is very crucial in automated classification of medical images as it allows for identifying and generating important patterns and structures that would help distinguish one class from the other [22].

Here, we used ResNet50V2, a deep convolutional neural network pre-trained on the ImageNet dataset, as the feature extractor owing to its robustness in generalizing different image domains, relayed to the development of deep networks without having to loss critical information is the introduction of residual connections by ResNet50V2 whereby the shallow end of the network is reconnected with the downlayer thereby eliminating the vanishing gradient problems.

With these residual connections and through its hierarchical architecture, ResNet50V2 generates high-level, distinct features from the MRI images such as very complicated patterns and textures which would help determine the tumor types[23], Using biogenic resampling method, all MRI images resized to the same size and number of pixels, 224 × 224, to meet the size input capability of the model. This keeps the value intact by their relationship thereby maintaining structure precious for actual feature extraction, the figure 3 represent the architecture of ResNet50V2.

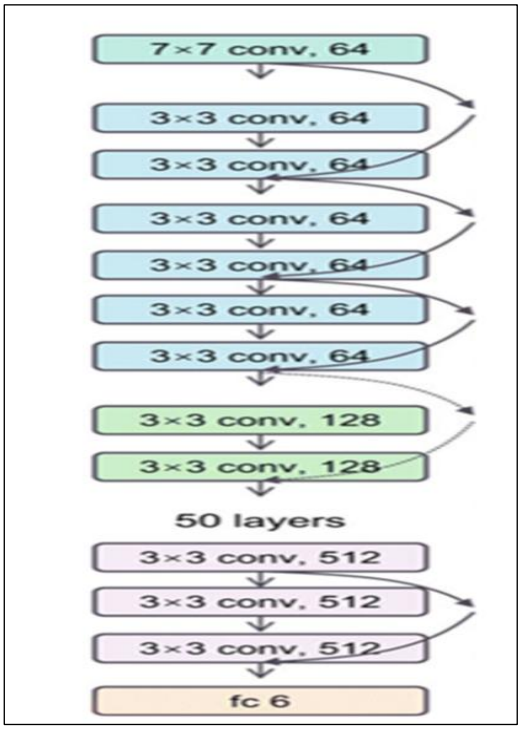

Figure 3: ResNet50V2 Architecture.
Source:[24].

The architecture of ResNet50V2 is specifically constructed to optimally extract features from MRI images through its deep structure, residual connections, and hierarchical learning approaches. It includes 50 layers through which images are processed hierarchically. As such, the early layers are responsible for the extraction of low-level features, e.g., edges and textures, according to the subsequent layers capturing certain shapes and patterns. While deeper layers focus on identifying high-level semantic features such as spatial relationships and an overall structure. Residual connections maintain critical information from the previous layer and support the learning of incremental transformation to make optimization better and avoid degradation of the feature. The use of bottleneck blocks will enhance efficiency since it is reducing and restoring the dimensions while putting the focus toward the essential spatial patterns. Batch Normalization will ensure numerical stability, making the network robust against any variation in intensity among different MRI images. It also incorporates using the ReLU6 activation function to prevent saturation, thus allowing detecting even the faintest patterns. Lastly, global average pooling collects all the learned features and condenses them into a compact representation that emphasizes the most relevant aspects, so it could be accompanied and distinguished between tumorous and non-tumorous conditions. Thus, ResNet50V2 is a mighty tool to capture all those intricate details of MRI brain tumor classification.

III.4. CLASSIFICATION USING LSTM CLASSIFIERFE

One type of recurrent neural network (RNN) that performs especially well with sequence-based data is the Long Short-Term Memory (LSTM) network. When classifying brain tumors using MRI scans, LSTM will feature in classifying the prediction by the feature produced by ResNet50V2 among different classified tumors. The main advantage that LSTM has over other networks is learning how one can capture long-dependencies in the data to learn its temporal or spatial patterns essential for classification. Here features extracted from an MRI

image by ResNet50V2 are fed into the LSTM network, which processes the features delivered in a sequential order. An LSTM unit has memory cells to hold the information over time and operates with gates: input, forget, and output. Such memory cells would enable an LSTM to store valuable information while discarding nonessential content, thus affording highly successful handling of complex, high-dimensional datasets like MRI images. Here, learning will happen on the dependencies within features, for example, tumor characteristics and spatial relationship information, leading to categorization for input images into Glioma, Meningioma, Pituitary, or No Tumor. This kind of classifier LSTM can also handle the misc. spatial arrangements and complex structures in MRI scans since it is well skilled in recognizing a sequential display of pattern signatures and hierarchies within data. This is the benefit of LSTM when coupled to deep learning models like ResNet50V2, where each feature representation from different brain regions can be treated in a way that maximizes the output of global and local information captures. As such, learning these spatial and textural patterns will enable the LSTM classifier to classify different brains into the following categories: Glioma, Meningioma, Pituitary, or No tumor [25].

III.5. PERFORMANCE METRICS

In this study, we used the F1-score, recall, accuracy, and precision metrics to assess the model's performance. These performance indicators are based on the four components of the confusion matrix: True Positives (TP), True Negatives (TN), False Positives (FP), and False Negatives (FN).

III.5.1. ACCURACY

Measures the proportion of correctly classified instances (both positive and negative) among the total instances.

$$\text{Accuracy} = \frac{TP+TN}{TP+TN+FP+FN} \quad (1)$$

III.5.2. PRECISION

The precision can be defined as the proportion of accurately anticipated positive observations to all predicted positive observations. When the cost of false positives is significant, this metric which gauges how accurate the positive predictions are—becomes especially helpful.

$$\text{Precision / PPV} = \frac{\text{TP}}{\text{TP+FP}} \quad (2)$$

III.5.3. RECALL

The ratio of accurately predicted positive observations to all observations in the actual class is called recall, sometimes referred to as sensitivity or true positive rate. When the expense of false negatives is high, it is very crucial.

$$\text{Recall} = \frac{\text{TP}}{\text{TP+FN}} \quad (3)$$

III.5.3. F1-SCORE

The harmonic mean of recall and precision is the F1-score. When there is an unequal distribution of classes or when the costs of false positives and false negatives fluctuate, it offers a balance between the two, which makes it helpful.

$$\text{F1Score} = 2 * \frac{\text{Precision} * \text{Recall}}{\text{Precision+Recall}} \quad (4)$$

IV. RESULTS AND DISCUSSIONS

In this study, the proposed method was implemented using Google Colab, utilizing its powerful GPU resources to efficiently process and classify MRI images. The dataset used consisted of a total of 7023 MRI images, with 5712 images allocated for training and 1311 images reserved for testing. The preprocessing phase began with the application of Stationary Wavelet Transform (SWT), which decomposed the images into multiple frequency bands, enhancing tumor-relevant features while suppressing noise. Following this, the images were resized to a standard dimension of 224x224 pixels to ensure compatibility with the ResNet50V2 model. Next, features were extracted from the original MRI images and the wavelet coefficients using ResNet50V2, a deep learning model pre-trained on ImageNet. The extracted features were then fed into a Long Short-Term Memory (LSTM) network, which classified the images into four categories: Glioma, Meningioma, Pituitary, and No Tumor. The results obtained from this method are summarized in the Figure 4, showcasing the performance of the model.

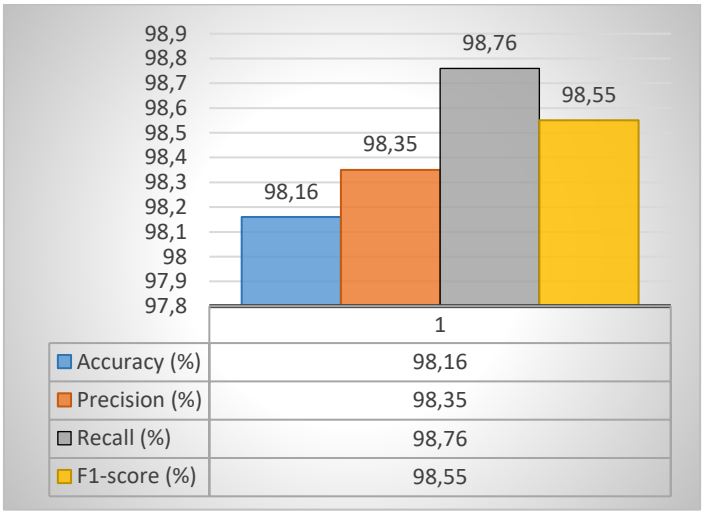

Figure 4: Evaluation metrics for proposed model.
Source: Authors, (2024).

The accuracy, precision, recall, and F1-score for the proposed classification model are indicated in the figure. The accuracy of the suggested approach was 98.7%; the precision, recall, and F1-score were 98.85%, 98.92%, and 99.1%, respectively. These findings demonstrate how well the model performs in accurately categorizing various brain tumor types from magnetic resonance imaging. The model's solid overall performance is demonstrated by its balanced precision of 98.85% and high F1-score of 99.1%, while its high recall of 98.92% further suggests that it properly diagnoses the majority of cancers. The model's strong reliability and clinical applicability for brain tumor diagnosis are demonstrated by the consistently high values across all metrics, especially the F1-score exceeding 99%. This is because the model demonstrates excellent capability in avoiding false positives and identifying tumors when they are present.

IV.1. CONFUSION MATRIX

One essential technique for assessing a classification model's performance is the confusion matrix. By contrasting the anticipated labels with the actual labels, it offers a thorough explanation of how the model predicts each class. This matrix helps in visualizing the performance of a classifier, providing insights into the types of errors made.

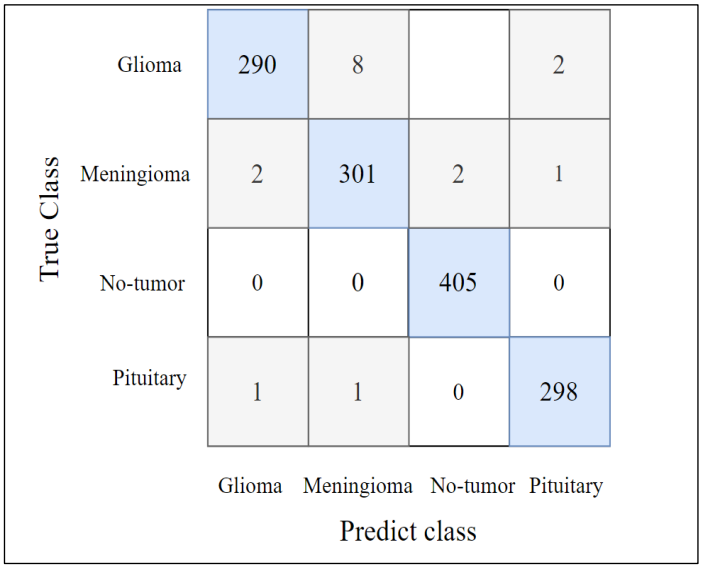

Figure 5: confusion matrix for proposed model.
Source: Authors, (2024).

The confusion matrix in figure 5 displays the classification results of a brain tumor detection model across four categories: Glioma, Meningioma, No-tumor, and Pituitary. The diagonal elements show strong performance with 290 correct Glioma classifications, 301 Meningioma, 405 No-tumor, and 298 Pituitary cases accurately identified. The misclassifications are minimal, with Glioma having 8 cases mistaken for Meningioma and 2 for Pituitary, Meningioma having 2 cases each misclassified as Glioma and No-tumor and 1 as Pituitary, and Pituitary having just 1 case each misclassified as Glioma and Meningioma. Notably, the No-tumor category achieved perfect classification with no misclassifications across its 405 cases. The strong diagonal dominance and minimal off-diagonal values indicate exceptional overall model performance in distinguishing between different types of brain tumors and identifying non-tumor cases.

IV.2. COMPARAISON WITH PREVIOS MODELS

In this part, we evaluate the suggested model's performance against a number of current methods for classifying brain tumors from MRI scans. A range of methodologies, including classic machine learning classifiers, deep learning-based models, and hybrid approaches, have been examined in the literature, the Table 2 gives a comparison of the performance of different methods applied for brain tumor classification.

Table 2: Comparaison with other works.

Works	Technique	Accuracy (%)
Kumar et al [26]	ResNet-50	97.08
Celik et al [27]	CNN+SVM	97.93
Anantharajan et al [28]	DNN+SVM	97.93
Remzan et al[29]	Ensemble+CNN	97.40
Proposed work	**SWT+ResNet50V2 +LSTM**	**98.7**

Source: Authors, (2024).

Table 2 provides a comparative analysis of various techniques employed in brain tumor classification, highlighting their respective accuracy rates. The works listed include methods that leverage deep learning models and hybrid approaches, such as ResNet-50, CNN combined with SVM, DNN integrated with SVM, and Ensemble CNNs. The proposed method, utilizing SWT for preprocessing, ResNet50V2 for feature extraction, and LSTM for classification, demonstrates superior performance with an accuracy of 98.7%, surpassing the accuracy of previous studies. This enhancement highlights how well the suggested method works to improve brain tumor classification.

V. CONCLUSIONS

This research presents a hybrid approach to classifying brain tumors through synthesis between advanced preprocessing, feature extraction, and classification techniques. Stationary Wavelet Transform (SWT) was proven effective in preprocessing and enhancing tumor-relevant features while suppressing noise; MRI image resizing made them compatible for the ResNet50V2 model. The ResNet50V2 model, a solid deep learning system, extracts high-level features successfully, while the LSTM classifier captures dependencies within the feature space to achieve remarkable accuracy of 98.7 on the Kaggle dataset, comparative analysis showed that the proposed method is better than other existing methods in relation to efficiency and reliability in brain tumor detection. This will tackle big challenges like noise reduction and spatial-frequency features integration concerning medical imaging, which this method holds great promise for potentially developing diagnostic accuracy and assisting in treating patients. Future studies could include additional modalities, no-scopes, access to bigger data sets, and real-time applications. Highlights in future findings could involve the establishment telling of the extent by which AI methods will bring disruptive change to medical imaging and consequently advance health care.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: ABDA Oussama and NAIMI Hilal.
Methodology: ABDA Oussama.
Validation: ABDA Oussama and NAIMI Hilal.
Writing: Original Draft: ABDA Oussama and NAIMI Hilal.
Writing Review and Editing: ABDA Oussama and NAIMI Hilal.
Supervision: NAIMI Hilal.
Approval of the final text: ABDA Oussama and NAIMI Hilal.

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RESEARCH ARTICLE OPEN ACCESS

ENHANCING MEDICAL EDUCATION: BUILDING A COMPREHENSIVE E-LEARNING PLATFORM WITH CODEIGNITER 4

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ABSTRACT

The emergence of the COVID-19 pandemic has presented unprecedented difficulties for medical education, forcing institutions worldwide to adjust quickly to ensure that learning continues despite the implementation of restrictive measures and social distancing procedures. This article explores creating and implementing a cutting-edge e-learning platform designed exclusively for medical education. Utilising the CodeIgniter 4 PHP framework for backend development and Bootstrap for frontend design, the platform provides a wide range of interactive quizzes, including Multiple Choice Questions (QCM), Single Choice Questions (QCU), and clinical cases (Cas Clinique's). The platform's adaptable design enables medical students to easily access and engage in remote learning across different platforms, allowing them to continue their education without interruption. The main characteristics consist of instruments for analysing performance, allowing students to track their progress and personalise their study sessions, thus improving the effectiveness and adaptability of medical education. This article highlights the significant impact of e-learning in addressing the educational challenges caused by the COVID-19 pandemic and provides insights into the future of medical education. It achieves this by thoroughly examining the platform's architecture, features, and pedagogical implications.

I. BACKGROUND AND LITERATURE REVIEW

The trajectory of e-learning in medical education can be traced back to the 1960s, when early experiments with computer-assisted instruction began to take shape. These initial forays laid the groundwork for subsequent technological and pedagogical advancements that have revolutionized the way medical education is delivered. The 1990s saw the advent of the internet, a transformative development that ushered in a new era of digital learning. This period marked the emergence of web-based platforms, virtual simulations, and interactive multimedia resources designed to meet the specific needs of medical learners [1].

Despite the significant advancements in e-learning technology, several persistent challenges continue to impede the seamless integration of digital learning in medical education. One major issue is the digital divide, which exacerbates disparities in technology access and internet connectivity among students. This divide can limit the ability of some students to fully participate in and benefit from e-learning opportunities [2]. Additionally, the quality and authenticity of educational content delivered through e-learning platforms remain areas of concern. Ensuring that online assessments accurately measure student competence and knowledge is another critical issue that educators must address [3].

I.1 EFFECTIVENESS OF E-LEARNING PLATFORMS

A comprehensive review of the literature on e-learning platforms in medical education reveals a complex landscape characterized by both potential benefits and significant challenges. Well-designed e-learning modules have been shown to enhance knowledge acquisition, improve clinical skills proficiency, and foster critical thinking among medical students and professionals

[4]. E-learning platforms provide flexibility and accessibility, allowing learners to engage with educational content at their own pace and convenience, which is particularly advantageous in the context of medical education where schedules can be highly demanding [5].

However, the efficacy of e-learning initiatives can be compromised by several factors. Content relevance is crucial; materials that are outdated or not aligned with the curriculum can hinder learning. Instructor support is also vital; without adequate guidance, students may struggle to navigate the digital learning environment effectively. Furthermore, learner motivation is a critical component of successful e-learning; maintaining engagement in a virtual setting can be challenging [6].

I.2 TECHNOLOGICAL AND PEDAGOGICAL INNOVATIONS

The development of robust and scalable e-learning platforms requires careful consideration of both technological and pedagogical aspects. Platforms built using frameworks like CodeIgniter 4 for backend development and Bootstrap for frontend design are particularly well-suited to creating interactive and responsive e-learning environments [7]. CodeIgniter 4 provides a flexible and efficient foundation for backend operations, enabling the creation of dynamic features such as interactive quizzes and performance analytics. Bootstrap's responsive design capabilities ensure that the platform is accessible across various devices, enhancing the user experience for medical students who often access learning materials on the go [8].

I.3 PEDAGOGICAL IMPLICATIONS AND FUTURE DIRECTIONS

The integration of e-learning into medical education requires a holistic approach that encompasses technological infrastructure, pedagogical innovation, and institutional support mechanisms. A culture of innovation and collaboration within medical institutions is essential for leveraging the full potential of e-learning to cultivate healthcare professionals who are not only knowledgeable but also adaptable and compassionate [9],[10].

Ongoing research and evaluation are critical to refining e-learning strategies and ensuring they meet the evolving needs of learners. By addressing the challenges associated with e-learning and continuously improving the quality of digital education, medical institutions can provide high-quality, equitable education that prepares students for the demands of modern healthcare delivery [11].

II. METHODOLOGY

The development process of the e-learning platform underwent several phases, each meticulously planned and executed to ensure the successful creation of a robust and user-friendly solution. The methodology encompassed the following key aspects:

II.1 SELECTION OF DEVELOPMENT FRAMEWORKS

The decision to use CodeIgniter 4 as the backend framework and Bootstrap for frontend design was based on thorough research and consideration of project requirements. CodeIgniter 4, renowned for its simplicity, performance, and adherence to MVC architecture, provided a solid foundation for building the platform's backend infrastructure. On the other hand, Bootstrap offered a comprehensive set of responsive design components and utilities, facilitating the development of visually appealing and mobile-friendly user interfaces.

II.2 ADHERENCE TO MVC ARCHITECTURE

The Model-View-Controller (MVC) architectural pattern was the guiding principle throughout development. The model layer handled data manipulation and business logic, ensuring data integrity and consistency. The View layer focused on visually appealing and intuitively presenting the data to users, leveraging Bootstrap's responsive design components for optimal user experience across devices. The Controller layer acted as the intermediary between the Model and the View, orchestrating user interactions, processing input data, and routing requests to the appropriate components [12].

II.3 TOOLS AND RESOURCES UTILISATION

Various tools and resources were employed to facilitate development and enhance productivity. Integrated development environments (IDEs) such as Visual Studio Code and PHPStorm provided a feature-rich climate for code editing, debugging, and version control integration. Version control systems such as Git were utilised for collaborative development, enabling multiple developers to work concurrently and track changes efficiently. Package managers like Composer facilitate dependency management and library integration, streamlining the integration of third-party components and frameworks.

II.4 CONTINUOUS INTEGRATION AND TESTING

Continuous integration and testing practices played a crucial role in ensuring the stability and reliability of the platform throughout the development lifecycle. Automated testing frameworks such as PHPUnit were employed for unit testing, enabling developers to validate individual components and functionalities in isolation. Additionally, continuous integration tools like Jenkins were utilised to automate the build, testing, and deployment processes, ensuring seamless integration of new code changes and minimising the risk of regressions.

By adopting a systematic and collaborative approach to development, leveraging industry-standard frameworks and tools, and adhering to best practices in software engineering, the development team successfully navigated the complexities of building a modern e-learning platform. The solution, utilising CodeIgniter 4 and Bootstrap, provides a wide range of features and functions specifically designed for medical education, addressing the various requirements of both learners and instructors.

III. PLATFORM ARCHITECTURE

The platform architecture is a harmonious blend of frontend and backend components, orchestrated to ensure fluid interaction and a cohesive user experience. Leveraging CodeIgniter 4 for backend development and Bootstrap with JavaScript for frontend design, the Model-View-Controller (MVC) pattern governs the organisation, fostering modularity and scalability. JSON facilitates seamless data exchange between the back and front end, enabling rapid updates and dynamic content rendering, culminating in a robust and user-centric e-learning environment.

III.1 GENERAL ARCHITECTURE

The general architecture (Figure 1) of the e-learning platform follows a modular and scalable design, incorporating

separate components for frontend and backend functionality. At its core, the platform adheres to the Model-View-Controller (MVC) architectural pattern, which divides the application into three interconnected layers:

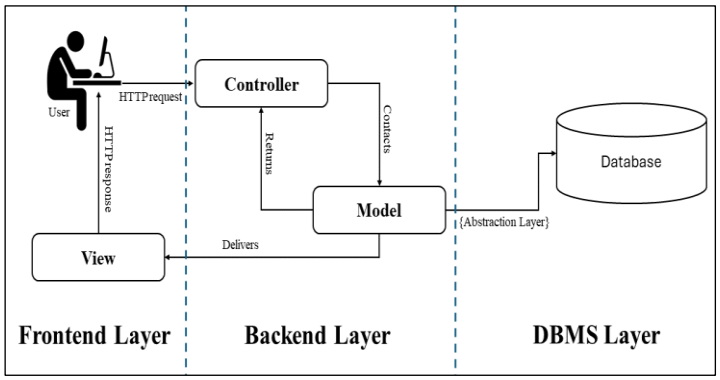

Figure 1: General Architectural.
Source: Authors, (2025).

Model Layer: Responsible for managing data and business logic. The Model layer interacts with the Database Management system (DBMS) to retrieve, store, and manipulate information related to users, courses, quizzes, and performance metrics.

View Layer: The View layer presents the user interface to the learners, encompassing HTML, CSS, and JavaScript components. It ensures a visually appealing and intuitive user experience, leveraging Bootstrap for responsive design and cross-device compatibility.

Controller Layer: Acting as the intermediary between the Model and View layers, the Controller layer processes user requests, invokes appropriate actions, and manages data flow between components. It implements business and application logic, orchestrating interactions and enforcing access control.

The architecture incorporates user authentication, session management, and content management modules, ensuring robust security and seamless navigation. API endpoints are exposed for interaction with external systems and services, facilitating integration with learning management systems (LMS) and third-party applications.

III.1 FRONTEND DEVELOPMENT WITH BOOTSTRAP

The e-learning platform's frontend development prioritises responsive design principles to ensure an optimal user experience across devices of varying screen sizes and resolutions. Fundamental design principles include fluid grids, flexible images, and media queries, which enable dynamic adaptation of content layout and styling based on viewport dimensions. Emphasis is placed on readability, accessibility, and usability, with clear navigation paths and intuitive user interactions.

III.2 IMPLEMENTATION OF BOOTSTRAP COMPONENTS FOR SEAMLESS USER EXPERIENCE

Bootstrap, a popular front-end framework, is extensively used to streamline the development of responsive user interfaces. Its grid system facilitates the creation of flexible layouts, while its pre-styled components, such as navigation bars, buttons, and forms, expedite the implementation of common UI elements. Customization options are utilized to maintain brand identity and design consistency, with CSS overrides and custom themes applied as needed. Additionally, the platform enables developers to quickly create responsive web apps, with adaptive and responsive designs automatically applied. The platform also offers a wide range of integrations, including third-party plugins and APIs, allowing for the easy addition of additional features.

III.3 BACKEND DEVELOPMENT WITH CODEIGNITER 4

CodeIgniter 4 provides a robust and secure platform for backend development. It is highly scalable and optimized for performance, making it an ideal choice for complex applications. The platform complies with the latest industry standards and is secure, supporting the latest security protocols.

III.3.1 INTRODUCTION TO CODEIGNITER 4 FRAMEWORK AND ITS FEATURES

CodeIgniter 4, a lightweight and high-performance PHP framework, is the foundation for backend development. It offers rich features, including a modular structure, database abstraction, robust routing, validation, and session management libraries. CodeIgniter's simplicity and ease of use make it well-suited for rapid development and prototyping, while its extensive documentation and active community support facilitate learning and troubleshooting. CodeIgniter is also a lightweight framework with a relatively small footprint. This makes it an excellent choice for web applications that require fast page load times [13].

III.3.2 EXPLANATION OF MVC ARCHITECTURE AND ITS ROLE IN BACKEND DEVELOPMENT

The backend development of the e-learning platform follows the Model-View-Controller (MVC) architectural pattern, with CodeIgniter 4 providing the necessary infrastructure for MVC implementation. Controllers handle incoming requests, interact with models to retrieve or manipulate data, and pass data to views for rendering. Models encapsulate data access logic and business rules, ensuring separation of concerns and code maintainability. Views present data to users in a structured format, with HTML templates dynamically populated with content from controllers and models. This modular architecture promotes code reuse, scalability, and testability, facilitating efficient development and maintenance of the backend codebase.

III.3.3 DATABASE MANAGEMENT SYSTEM

The database management system (DBMS) is the backbone of our e-learning platform, facilitating the storage, retrieval, and management of essential data integral to the platform's functionality. Several tables within our database schema (Figures 2 and 3) are pivotal in shaping the user experience and driving the platform's core features.

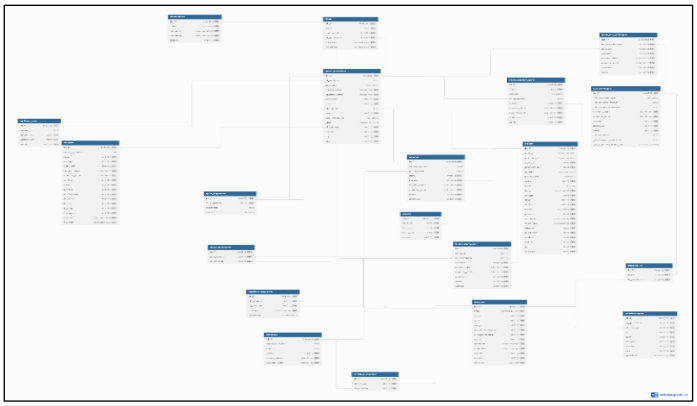

Figure 2: Database schema.
Source: Authors, (2025).

The abonnement table holds crucial information regarding user subscriptions or memberships, delineating access levels and privileges conferred upon different user tiers. This table governs premium features and content availability, ensuring seamless user engagement and personalized learning experiences.

Medical education revolves around clinical case scenarios stored in the cas_clinique table. These cases come with comprehensive descriptions and diagnostic challenges. They enhance medical students' learning and help them develop their critical thinking and clinical decision-making abilities.

The platform's courses encompass a wide range of medical specialties. The session ecosystem utilizes distinct tables named session_cc, session_course, and session_module to cater to various learning styles and scenarios. The tables demonstrate how users engage with clinical case studies, individual courses, and modular learning units. The course table meticulously organizes and categorizes topics and learning objectives. This centralized repository facilitates users effortlessly and effectively browsing, enrolling, and tracking their progress in the courses of their preference. This feature will allow users to retrieve pertinent information and resources and monitor their advancement efficiently. It also enables users to transition between courses or modules as required swiftly.

Within our e-learning platform, managing Multiple Choice Questions (MCQs), or "qcm" in French, is facilitated through a meticulously designed set of interconnected tables. These tables collectively form the backbone of our quiz module, enabling the creation, administration, and evaluation of MCQ-based assessments with precision and efficiency.

The qcm_question table is the repository for all MCQ questions, housing essential details such as question content, difficulty level, and associated learning domains. This table provides a comprehensive inventory of available questions, ensuring diversity and relevance in quiz content across various topics and subject areas.

To enhance the interactivity and engagement of quiz sessions, the qcm_response table captures user responses to MCQ questions, facilitating real-time feedback and performance evaluation. By correlating user responses with correct answers stored in the qcm_question table, this component enables instantaneous scoring and proficiency assessment, empowering learners to gauge their understanding and identify areas for improvement.

In addition to question and response management, the qcm_sujet table is pivotal in organizing MCQs into thematic categories or subjects. This facilitates targeted quiz assignments and content filtering based on user preferences and learning objectives. This hierarchical structure enhances the quiz module's navigability and usability, enabling learners to access relevant content efficiently and effectively.

Furthermore, the session_qcm table orchestrates the integration of MCQ quizzes within broader session contexts, allowing seamless integration of quiz activities into more extensive learning experiences. This table tracks session-specific quiz interactions, including quiz attempts, scores, and completion status, enabling comprehensive session analytics and progress tracking for learners and instructors.

By leveraging this comprehensive suite of MCQ-related tables (figure 4), our e-learning platform delivers a robust and intuitive quiz module that fosters active learning, knowledge retention, and skill development among users. With a rich repository of MCQs, streamlined administration workflows, and insightful analytics capabilities, our platform empowers learners and educators alike to maximize the effectiveness and impact of quiz-based assessments in medical education and beyond.

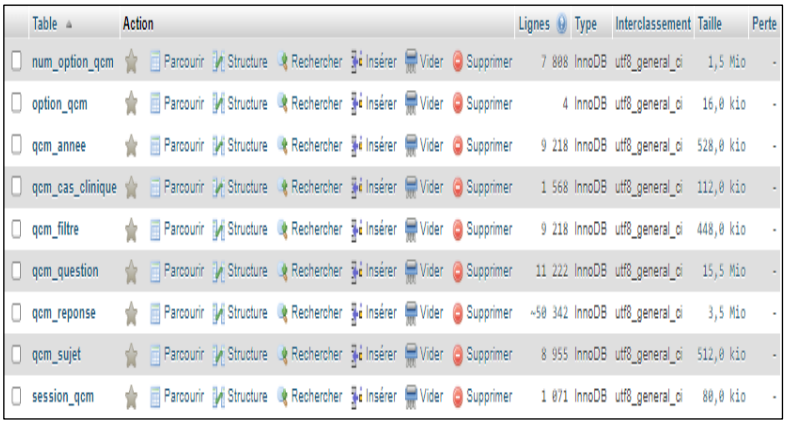

Table	Action	Lignes	Type	Interclassement	Taille	Perte
num_option_qcm	Parcourir Structure Rechercher Insérer Vider Supprimer	7 808	InnoDB	utf8_general_ci	1,5 Mio	-
option_qcm	Parcourir Structure Rechercher Insérer Vider Supprimer	4	InnoDB	utf8_general_ci	16,0 kio	-
qcm_annee	Parcourir Structure Rechercher Insérer Vider Supprimer	9 218	InnoDB	utf8_general_ci	528,0 kio	-
qcm_cas_clinique	Parcourir Structure Rechercher Insérer Vider Supprimer	1 568	InnoDB	utf8_general_ci	112,0 kio	-
qcm_filtre	Parcourir Structure Rechercher Insérer Vider Supprimer	9 218	InnoDB	utf8_general_ci	448,0 kio	-
qcm_question	Parcourir Structure Rechercher Insérer Vider Supprimer	11 222	InnoDB	utf8_general_ci	15,5 Mio	-
qcm_reponse	Parcourir Structure Rechercher Insérer Vider Supprimer	~50 342	InnoDB	utf8_general_ci	3,5 Mio	-
qcm_sujet	Parcourir Structure Rechercher Insérer Vider Supprimer	8 955	InnoDB	utf8_general_ci	512,0 kio	-
session_qcm	Parcourir Structure Rechercher Insérer Vider Supprimer	1 071	InnoDB	utf8_general_ci	80,0 kio	-

Figure 3: MCQ-related tables.
Source: Authors, (2025).

The session table is the central hub, capturing overarching session details such as duration, timestamps, and user identifiers. This table forms the foundation for all session-related activities and interactions, providing a holistic view of user engagement and progress.

Unique tables in the session ecosystem called session_cc, session_course, and session_module are used for different learning types and situations. These tables show how users interact with clinical case studies, individual courses, and modular learning units. They enable granular tracking and analysis of user behaviour, facilitating targeted interventions and personalised recommendations based on user activity and preferences.

Interactive quizzes constitute a cornerstone of the e-learning experience, and dedicated tables such as session_qcm and session_reponse are instrumental in capturing quiz-related interactions, including question attempts, responses, and performance metrics. These tables empower users to assess their understanding and proficiency in real time, fostering active learning and knowledge retention.

These session-related tables (figure 5) collectively form a cohesive ecosystem that underpins the platform's functionality, enabling seamless navigation, progress tracking, and personalisation across diverse learning modalities. By leveraging the inherent capabilities of our session management framework, we aim to cultivate an immersive and impactful learning environment

that empowers users to achieve their educational goals effectively and efficiently.

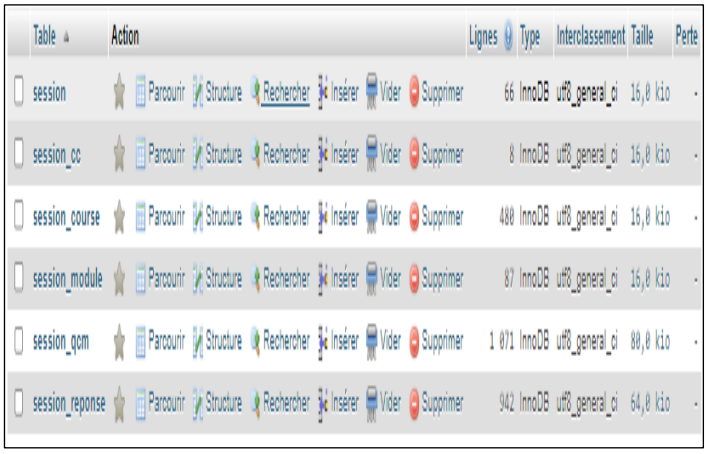

Table	Action	Lignes	Type	Interclassement	Taille	Perte
session	Parcourir Structure Rechercher Insérer Vider Supprimer	66	InnoDB	utf8_general_ci	16,0 kio	-
session_cc	Parcourir Structure Rechercher Insérer Vider Supprimer	8	InnoDB	utf8_general_ci	16,0 kio	-
session_course	Parcourir Structure Rechercher Insérer Vider Supprimer	488	InnoDB	utf8_general_ci	16,0 kio	-
session_module	Parcourir Structure Rechercher Insérer Vider Supprimer	87	InnoDB	utf8_general_ci	16,0 kio	-
session_qcm	Parcourir Structure Rechercher Insérer Vider Supprimer	1 071	InnoDB	utf8_general_ci	80,0 kio	-
session_reponse	Parcourir Structure Rechercher Insérer Vider Supprimer	942	InnoDB	utf8_general_ci	64,0 kio	-

Figure 5: Session-related tables.
Source: Authors, (2025).

Lastly, the user's table is the cornerstone of user management, storing essential account information, authentication credentials, and user preferences.This table forms the linchpin of user authentication, access control, and personalized content delivery, ensuring every user's secure and tailored experience.

Together, these tables form the bedrock of our e-learning platform, orchestrating the seamless integration of content, functionality, and user interactions.

By leveraging the inherent capabilities of our database management system and optimizing data organization and retrieval, we aim to deliver a robust, scalable, and user-centric platform that transcends the traditional boundaries of medical education.

IV. INTEGRATION OF PERFORMANCE ANALYSIS TOOLS

Integrating performance analysis tools allows for real-time user progress and engagement tracking, providing valuable insights for learners and educators. This feature enhances the learning experience by enabling personalized feedback and targeted interventions to support individual learning goals.

IV.1 DESCRIPTION OF PERFORMANCE ANALYSIS FEATURES AND THEIR IMPLEMENTATION

The e-learning platform incorporates performance analysis tools to track user progress, monitor engagement, and identify areas for improvement.

These tools include timers that track how much time students spend on individual questions and quiz sessions, giving them insight into their time management abilities and subject comprehension.

Additionally, statistical analysis tools aggregate data on user performance by module, session, and exam, enabling educators to assess learning outcomes, identify trends, and tailor instructional interventions accordingly.

IV.2 UTILIZATION OF TIMERS AND STATISTICAL TOOLS FOR TRACKING USER PROGRESS

Timers are integrated into quiz sessions to monitor the duration of each question response and the overall session duration. Statistical tools aggregate data on quiz scores, completion, and time taken per question, generating comprehensive performance reports for individual learners and groups.

These insights inform instructional design decisions, allowing educators to adjust content delivery, pacing, and difficulty levels to optimize learning outcomes. Moreover, performance data can be visualized through charts, graphs, and dashboards, facilitating data-driven decision-making and continuous improvement initiatives.

V. PLATFORM FEATURES

Our features include interactive quizzes, real-time feedback, and customizable assessments. Additionally, the platform offers a user-friendly interface, seamless integration with learning management systems, and robust security measures to protect student data.

V.1 LOGIN & REGISTRATION GUIS

The login and registration interface within our e-learning platform is meticulously designed to provide users with a seamless and intuitive experience, ensuring effortless access to educational resources and personalized learning pathways.

V.1.1 LOGIN GUI

The login GUI is represented in Figure 6, and it contains the following:

- **Username/Email Field:** Users are prompted to enter their username or email address as their unique identifier within the system.
- **Password Field:** A secure password input field allows users to enter their confidential login credentials with privacy and peace of mind.
- **Login Button:** Upon entering valid login credentials, users can click the "Login" button to authenticate and access their account dashboard.
- **Forgot Password Link:** If users forget their password, a "Forgot Password" link redirects them to a password recovery page where they can securely reset their password.

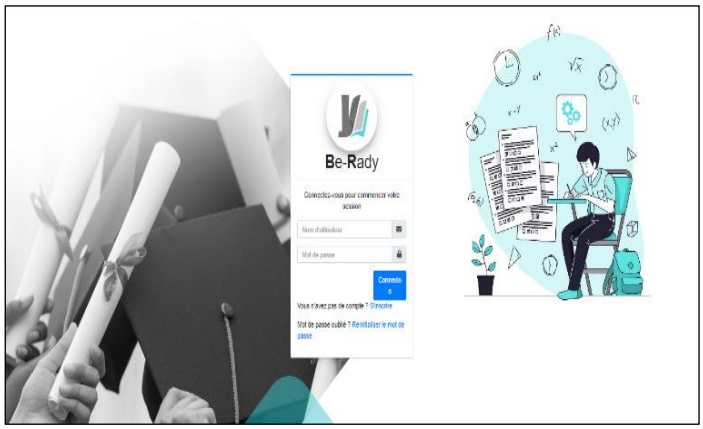

Figure 5: Login GUI.
Source: Authors, (2025).

V.1.2 REGISTRATION GUI

The registration GUI is represented in Figure 7 as follows:

- **Username/Email Field**: Users are prompted to input a unique username or email address, like the login interface, to establish their account credentials.

- **Entire Name Field**: Users must provide their full name to personalise their learning experience and facilitate communication.
- **Institution/Affiliation Field**: Users may specify their educational institution or professional affiliation, allowing for tailored content recommendations and academic support resources.
- **Registration Button**: After completing the registration form, users can finalise the process by clicking the "Register" button, granting immediate access to the platform's features.
- **Terms of Service and Privacy Policy Checkbox:** To comply with legal and regulatory requirements, users must agree to the platform's terms of service and privacy policy by checking a designated checkbox.
- **Verification Email:** Upon successful registration, users receive a verification email (Figure 7) containing a unique link or verification code to confirm their email address. They can then set a secure password to activate their account.

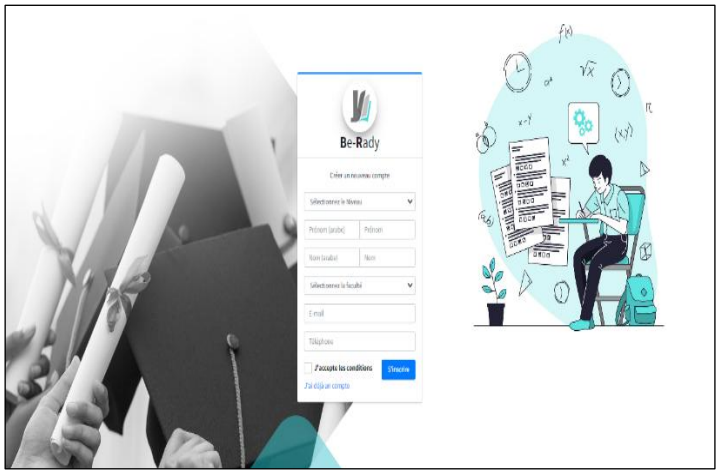

Figure 7: Registration GUI.
Source: Authors, (2025).

Figure 8: Verification email.
Source: Authors, (2025).

V.2 DASHBOARD GUI

The dashboard (Figure 9) provides a comprehensive overview of the user's activity and performance within the e-learning platform. Users can access critical metrics such as the total number of quizzes completed, the number of correct and incorrect responses, and the count of unanswered questions. This summary enables users to track their progress and identify areas for improvement in their learning journey.

Additionally, interactive charts enhance performance data visualization, offering insights into daily trends and patterns. The Performance Daily Chart visually represents correct and incorrect responses over time, allowing users to assess their proficiency and consistency in quiz completion.

Similarly, the daily time spent on quizzes chart offers valuable insights into users' study habits by showcasing the time allocated to daily quiz activities.

Overall, the dashboard serves as a central hub for monitoring progress, gauging performance, and optimizing learning strategies, empowering users to take control of their educational experience and achieve their learning objectives efficiently.

Figure 9: Dashboard GUI.
Source: Authors, (2025).

V.3 SESSION CREATION

To create a session within the Quizzes GUI (Figure 10), users are provided with a user-friendly interface that facilitates the configuration of session parameters:

1. **Title of Session:** Users are prompted to enter a descriptive title, which allows them to distinguish the session from others and provide context for its purpose.
2. **Module Selection by Student Level:** Users can select modules based on the student's level, enabling personalized learning experiences tailored to individual proficiency levels.
3. **Course Selection from Modules**: Within selected modules, users can further refine their session by choosing specific courses and focusing their study efforts on relevant subject matter.
4. **Question Type Selection**: Users have the option to specify the type of questions included in the session, such as Multiple-Choice Questions (QCM), Choice Questions (QCU), or Clinical Cases (Cas Clinique), accommodating different learning objectives and assessment methods.
5. **Advanced Options:** Advanced settings allow users to customize the session by including options such as questions previously answered incorrectly or not yet viewed, enhancing its adaptive nature.
6. **Number of Questions in the Session:** Users can define the desired number of questions to be included in the session, balancing the depth of study with time constraints and learning objectives.

By offering intuitive controls and customizable parameters, the Quizzes GUI empowers users to create tailored study sessions that align with their learning goals and preferences, fostering engagement and effectiveness in the learning process.

For added variety and difficulty for students, our quiz module has features like randomized question selection, which uses the **SESSION_QCM** (Figure 11) algorithm to generate questions from a predefined question bank dynamically.

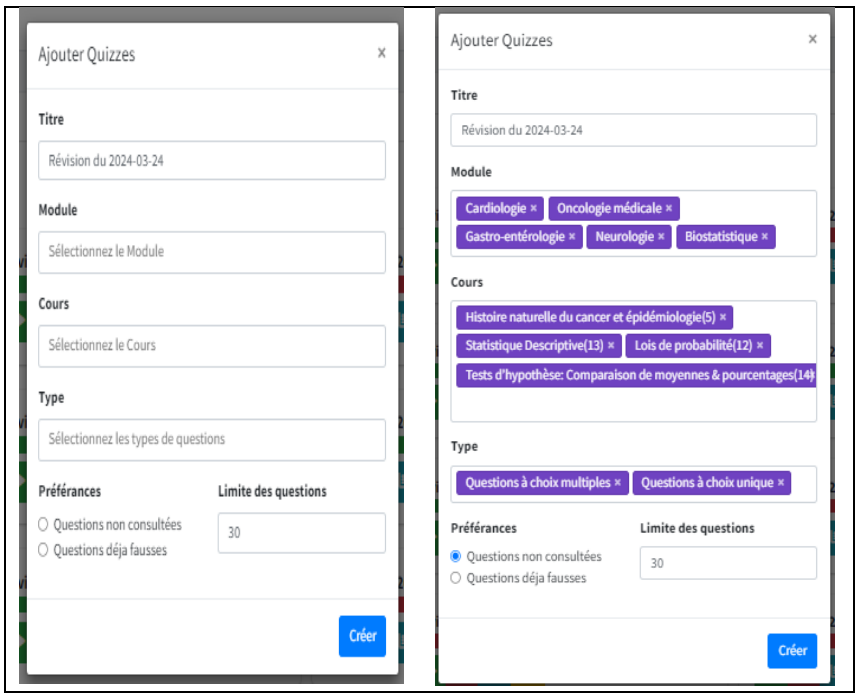

Figure 10: GUI to create a session.
Source: Authors, (2025).

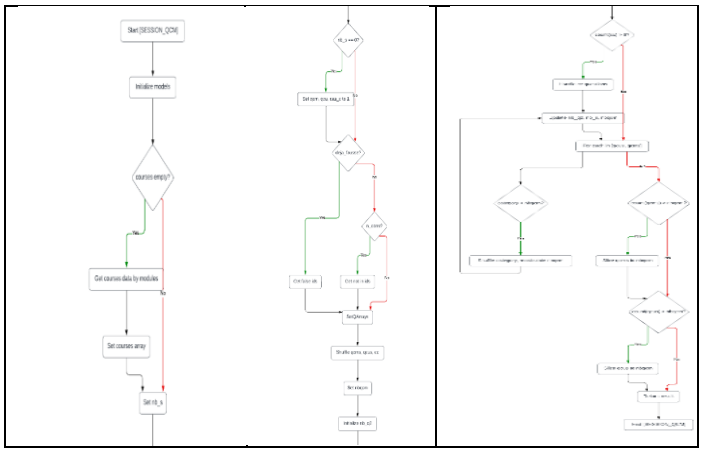

Figure 11: SESSION_QCM algorithm.
Source: Authors, (2025).

The SESSION_QCM algorithm is a versatile tool that adapts to your needs. It facilitates the creation of quiz sessions with customizable parameters, ensuring the questions are always tailored to your requirements. It begins by initializing the necessary models for question retrieval.

The algorithm then filters questions based on consultation history or previous incorrect attempts, considering specified criteria like question type and course. If no requirements are set, default values are applied. Next, it retrieves question IDs and shuffles them for randomness. The algorithm calculates the number of questions per session and adjusts parameters if questions are insufficient in any category. Finally, it ensures that the selected questions do not exceed the specified number and returns the total count of questions chosen across all categories.

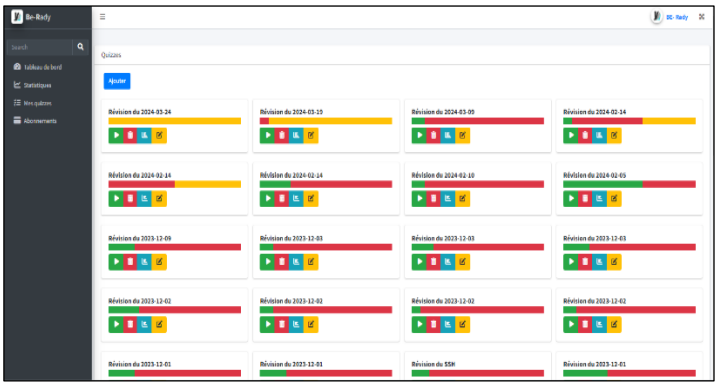

Figure 12: List of sessions.
Source: Authors, (2025).

V.4 INTERACTIVE QUIZZES

Interactive Quizzes GUIs (Figure 13) offer an engaging platform for users to interact with quizzes. Through intuitive interfaces, users can access a variety of quiz questions and actively engage with the content. Features such as navigation controls, answer confirmation, and real-time feedback (Figures 14 and 15) enhance the user experience and facilitate effective learning.

One notable feature is the timer functionality, which tracks the time spent on individual questions and monitors the overall duration of the quiz session. This time-tracking capability provides valuable insights into user pace and quiz-taking efficiency. Moreover, comparing performance metrics with peers adds a competitive element and encourages users to strive for improvement.

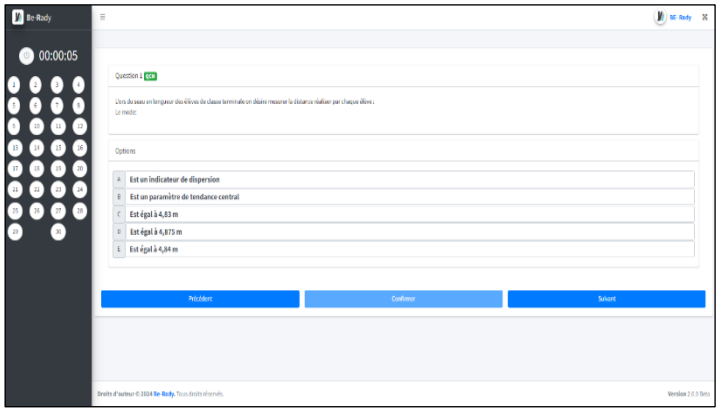

Figure 13: Quizzes GUI.
Source: Authors, (2025).

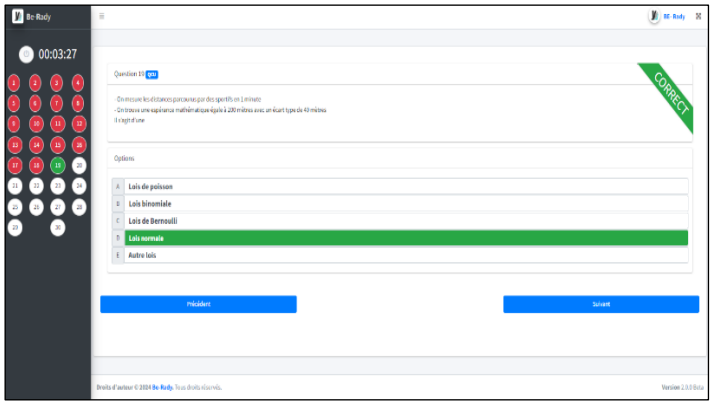

Figure 14: Correct feedback.
Source: Authors, (2025).

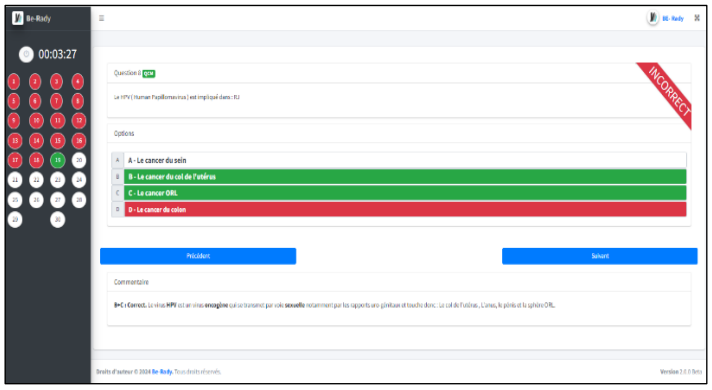

Figure 15: Incorrect feedback.
Source: Authors, (2025).

V.5 PERFORMANCE MONITORING

The Performance Monitoring feature of our platform offers learners comprehensive insights into their quiz-taking performance through two distinct avenues: general monitoring on the dashboard and session monitoring during individual quiz sessions.

V.5.1 GENERAL MONITORING

On the dashboard, learners can access an overview of their performance metrics, including time to answer questions and overall quiz completion rates. Additionally, learners can compare their performance against that of their peers, gaining valuable insights into their relative proficiency and efficiency. This can help them identify areas of strength and areas where they can improve. It can also help motivate them to work harder and become more competitive.

V.5.2 SESSION MONITORING

During individual quiz sessions, learners benefit from real-time performance feedback tailored to their current session. Our platform tracks and displays the time to answer each question, allowing learners to gauge their pace and time management skills. Moreover, learners can compare their progress with peers by viewing the percentage of peers who chose specific answer options in past sessions. This contextual information empowers learners to make informed decisions and adapt their strategies based on peer behavior.

By integrating general monitoring on the dashboard and session monitoring during quiz sessions, our platform provides learners with a holistic approach to performance assessment. Through peer comparison and behavioral analysis, learners can benchmark their progress, identify areas for improvement, and make data-driven decisions to enhance their learning outcomes.

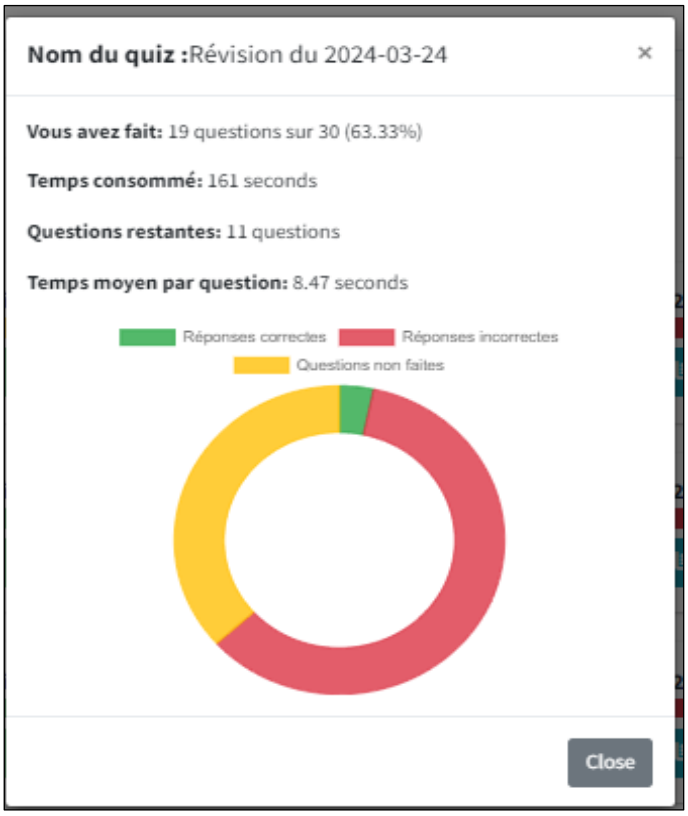

Figure 16: Session Monitoring.
Source: Authors, (2025).

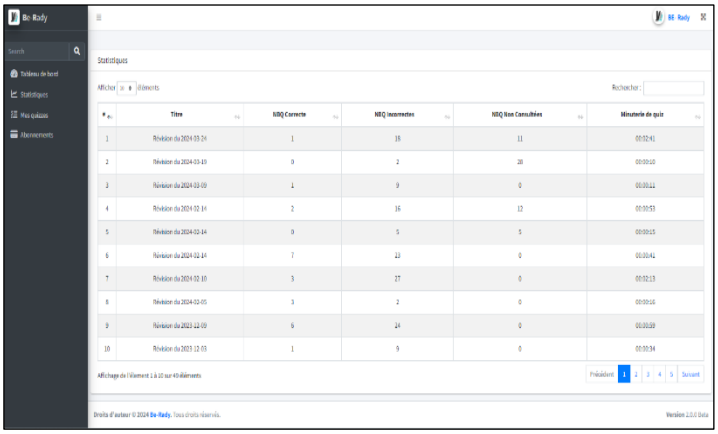

Figure 17: Sessions Monitoring.
Source: Authors, (2025).

VI. DISCUSSION

Our exploration of the e-learning platform's development and deployment in the context of medical education presents several significant implications and avenues for discussion.

The COVID-19 pandemic catalyzed an urgent need for adaptable and resilient educational systems, prompting institutions worldwide to adopt e-learning solutions. Our platform's responsive design and comprehensive suite of features, including interactive quizzes and performance analysis tools, address this need by enabling seamless access and engagement across various devices. This adaptability has been crucial in ensuring the continuity of medical education amidst restrictive measures and social distancing protocols.

Furthermore, our platform's architecture and functionalities underscore the transformative potential of e-learning in addressing educational challenges beyond the pandemic. By leveraging technology to enhance traditional teaching methodologies, our platform empowers educators to deliver dynamic and personalized learning experiences that cater to the diverse needs of medical students. The integration of performance analysis tools enables learners to monitor their progress, customize their study sessions, and optimize their learning strategies, thereby enhancing the efficacy and flexibility of medical education.

Looking ahead, the implications for the future of medical education are profound. E-learning platforms can revolutionize traditional pedagogical approaches, offering learners greater flexibility, accessibility, and interactivity. By embracing innovation and collaboration, educators, institutions, and policymakers can harness the transformative potential of e-learning to cultivate competent, compassionate, and adaptable healthcare professionals capable of meeting the demands of modern healthcare delivery.

VII. CONCLUSION

Our investigation into developing and deploying an e-learning platform tailored for medical education underscores the vital intersection of technology and academia. Leveraging the robust capabilities of frameworks like CodeIgniter 4 and Bootstrap, coupled with innovative design principles, our platform emerges as a testament to the transformative power of technology in educational contexts. By offering interactive quizzes and responsive interfaces, our platform addresses the immediate challenges posed by the COVID-19 pandemic and lays the groundwork for future advancements in digital learning.

Furthermore, our exploration highlights the profound implications of e-learning in computer science education. By integrating cutting-edge technologies and pedagogical methodologies, such platforms have the potential to revolutionize the way computer science concepts are taught and understood. From adaptive learning algorithms to real-time performance analysis tools, the possibilities for enhancing educational experiences are limitless.

As we look to the future, it becomes evident that the convergence of computer science and education will continue to drive innovation and progress in both fields. By embracing technological advancements and fostering collaboration between educators, developers, and researchers, we can unlock new opportunities for learning, discovery, and empowerment in the digital age. In conclusion, our exploration highlights the critical role of technology in shaping the future of education and reaffirms our commitment to leveraging its potential for the betterment of society.

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RESEARCH ARTICLE OPEN ACCESS

PREDICTING REMAINING USEFUL LIFE OF LITHIUM-ION BATTERIES FOR ELECTRIC VEHICLES USING MACHINE LEARNING REGRESSION MODELS

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ABSTRACT

Accurate prediction of a lithium-ion battery's remaining useful life (RUL) is essential for effectively managing and maintaining electric vehicles (EVs). By anticipating battery health and potential failures, we can optimize performance, enhance safety, and prevent costly breakdowns. Based on a supervised machine-learning regression approach, this work presents four different regression models like Gradient Boosting Regressor, K-Nearest Neighbor Regressor, Bagging Regressor, and Extra Tree Regressor models to forecast the li-ion battery life for electric vehicles. Using actual battery data from Hawaii National Energy Institute (HNEI), four algorithms were used to forecast remaining useful life (RUL) of batteries. These algorithms were implemented using Python in Google Co-laboratory. The accuracy of each model, Performance error indices including Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), R-squared, and computational time were calculated. Findings show that Bagging Regressor model outperforms the other three models in terms of RUL prediction. The Bagging Regressor model demonstrated its superiority with better *R*2 values of 0.999 and lower MSE of 14.307, RMSE of 3.782, and MAE of 2.099. The proposed model enhances EV energy management through precise RUL forecasting.

I. INTRODUCTION

Electric vehicles (EVs) have become more commonplace since they were first developed decades ago as a means of mobility. EVs provide unparalleled benefits over gas-powered cars, including rapid acceleration, virtually silent operation, and little emissions. With the growing use of electric cars, portable consumer electronics, and grid-tied energy storage systems for load balancing and energy storage technologies are becoming more and more common [1], [2]. Currently, the main energy source for EV's is lithium-ion batteries. Lithium-ion battery usage is pervasive in several industrial applications. Decreased performance is one of the major consequences that might result from a battery failing [3]. The complex combinations of materials construct lithium-ion battery packs used in EVs provide the energy and power required for operation.

Remaining useful life (RUL) is a strategic tool that helps determine how much capacity a system can supply at any given moment before it fails or is decommissioned. It aids professionals in design and administration of systems to prevent unforeseen malfunctions, which can be expensive to maintain [4]. It is a method that assesses if a project's mission goals are realistic and aids in the real-time diagnosis, prognosis, and fault detection of issues while taking uncertainties into account. PHM dependability and safety of battery systems depend on accurate RUL prediction. A battery's reserve capacity RUL is the maximum number of cycles through which it may be charged and discharged before it reaches end of life (EOL). Where EOL typically denotes the point at which

a battery's capacity drops to less than 70–80% of its stated capacity. Remaining Useful Life prediction calculated as,

$$RUL=T_{EOL}- T_{CU} \quad (1)$$

T_{EOL} stands for the amount of time a battery may be used. Battery current utilisation time is abbreviated as T_{CU}. The first equation considers calendar ageing in addition to cycle ageing. Most studies define the RUL purely in terms of cycle aging. Another definition that is applicable to RUL is as follows:

$$RUL= \frac{N_i-N_{EOL}}{N_{nominal}-N_{EOL}} \quad (2)$$

where N_i is present capacity, $N_{nominal}$ is the nominal capacity and N_{EOL} end-of-life capacity respectively.

As we stand at the intersection of technological innovation and sustainable energy practices, the incorporation of machine learning algorithms into LIB RUL cycle prediction seems like a revolutionary step towards a future where energy storage systems are not only powerful but also environmentally conscious and commercially viable. "Consequently, numerous approaches to RUL prediction have been developed by academics, which can be broadly categorized into two categories: model-based and data-driven. Recent advancements and successes in machine learning (ML) approaches have led to increased interest in the state estimation of LIB incorporating RUL." [5].

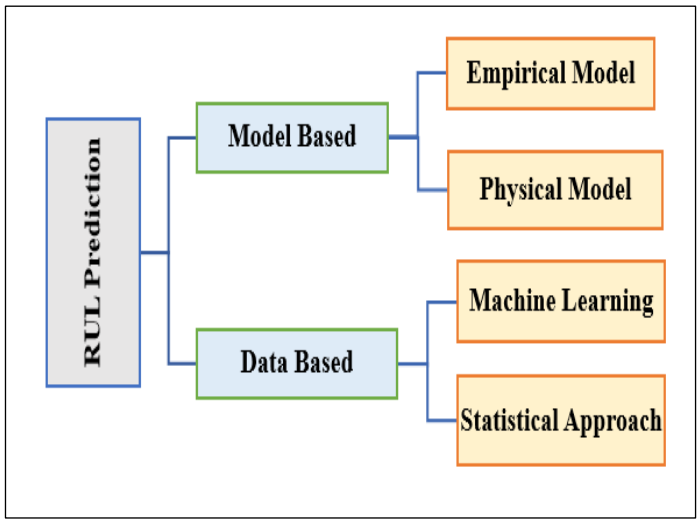

Figure 1: RUL Prediction Classification.
Source: Authors, (2025).

The degradation pattern of batteries might be well described by model-based prediction techniques. However, for precise prediction and deterioration modelling, a lot of variables and intricate computations are frequently needed. Because of this, the model is unsuitable for real-time prediction and practical implementation. There are two main types of model-based predictions: empirical and physical. Use of an empirical model for RUL prediction is employed by a number of battery degrading properties. To represent the degradation behaviour, empirical approaches utilise various regression models. To anticipate the degradation trend, they use empirical formulas. In [6], the authors demonstrated the efficacy of a logarithmic model-based RUL prediction framework compared to more conventional empirical models. An explanation based on physical and electrochemical processes within the battery is the basis of the physical model [7]. The physics model for RUL prediction is built using concepts of electrode porosity and reaction kinetics.

Data-driven techniques may be roughly categorized as machine learning (ML)-based and statistically-based. Artificial intelligence (ML) techniques employ external battery factors to forecast the health of the battery, making them simpler to implement and frequently reducing the need for precise battery modelling and domain-specific expertise. [8] Usually, the ML algorithms monitor changes in internal resistance, impedance, voltage, capacity, and computational efficiency to determine the deterioration trend for RUL prediction. The model of capacity deterioration is derived from previous data is Statistical modelling may be used with accuracy and ease. [9] The statistical techniques used for predicting Remaining Useful Life (RUL) include Autoregressive approach and Grey Prediction Model. This study made use of bagging, extra-tree, K- nearest neighbor and gradient boosting regression models. Based on performance metrics, four models will be tested to estimate lithium-ion battery RUL capacity. There is an explanation of the four regression models' efficacies executed on HNEI battery data set.

The following is the outline of the article. A survey of relevant literature is provided in Section 2, while Section 3 details methodology and four different ML regression techniques. In Section 4, we offer the results together with our assessment of them. Section 5 draws conclusions.

II. LITERATURE REVIEW

The growing number of electric vehicles has resulted in a significant problem for the infrastructure, electrical system, and charging station requirements. Electric vehicles often use LIBs, which are electrochemical systems that are dynamic, time-varying, and exhibit complex internal mechanics and nonlinear behaviour. The LIB's life and performance steadily decline with charge and discharge cycles. De-gradation of batteries can occur for a variety of causes, such as temperature fluctuations, mechanical stress, chemical reactions, and changes in physical processes. Predicting the battery's remaining lifespan also becomes a very difficult process as a result of deterioration. Still, in order to guarantee dependable performance of the battery management system, this is necessary.

It will be helpful to compare performance of data-driven and physical modelling techniques with the same battery and operational parameters. Battery SOH and RUL prediction may be accomplished with an accurate model, ensuring the safety of using EV batteries [10]. Battery remaining useful life prediction and performance indices of ML algorithms were studied in [11] The obtained findings indicate that the random forest technique was more appropriate for accurate RUL prediction. The duration between the present observation and end of battery's life is defined by the manufacturer as Remaining Useful Life (RUL) [12]. In [13] employed a segmentation-type anomaly detection technique utilizing temperature and voltage measurements taken at several timesteps to determine how the Li+ battery's properties were changing. Therefore, to estimate the battery's RUL, the Extra Tree Regression (ETR) approach may be employed to extract important variables from temperature and voltage transitions, including variance, kurtosis, skewness, and voltage. In this [14], applied, and examined three machine learning models, including SVR and LSTM Network and also examined the impact of calendar aging on a battery's RUL. The purpose of these two sets of trials was to strengthen RUL prediction models by including calendar aging effects. This study used three regression models based on

supervised machine learning predict life span of LIB. [15] Models based on voltage-dependent per-cell data will be used to compare LR, BR, and RFR in estimating capacity of batteries. [16] paper discusses difficulties in estimating the battery life cycle using machine learning and outlines potential avenues for further study and improvement, including scalability, interpretability, and the integration of upcoming technologies. With a comprehensive introduction to BMSs and ML, this [17] study examines latest results on ML methods for SOC prediction. This paper highlights the common use of many techniques in predicting SOC and SOH, including support vector machines, fuzzy logic, k-nearest neighbors, genetic algorithms, and transfer learning. [18] RUL prediction of batteries, Gradient Boosting (GB) and Naive Bayes (NB) algorithms are recommended. The battery's performance parameter is maximized by doing an error analysis on the model. Selecting statistical metrics allows for a quantitative assessment of forecast results.

III. METHODOLOGY

III.1. METHODOLOGICAL FRAMEWORK

Figure. 2 shows the basic Remaining useful life prediction methods based on machine learning for LIB. Most recently developed machine learning based prediction techniques are covered in next
section.

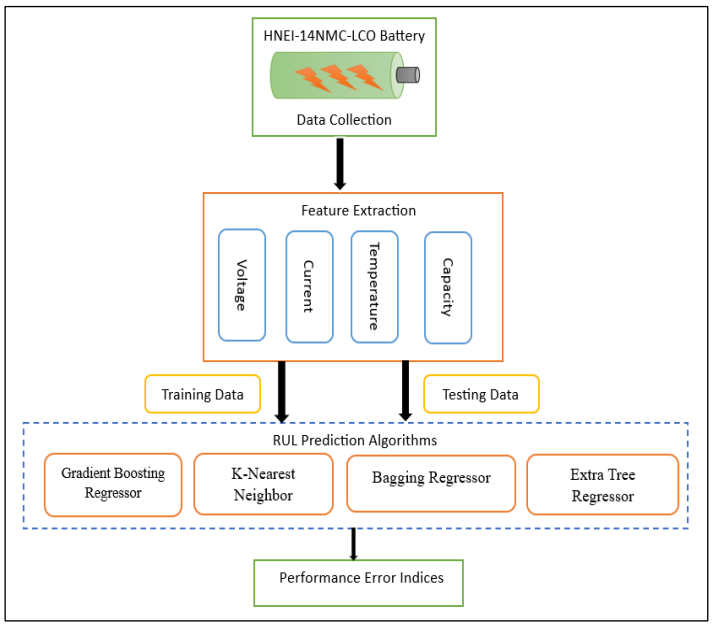

Figure 2: Framework of RUL prediction technique.
Source: Authors, (2025).

A typical machine learning approach for forecasting a battery's RUL is depicted in figure 2. Gathering data, extracting features, training models, and evaluating them are all part of it.

Data Collection: The procedure starts by gathering data from the battery, including factors such as voltage, current, temperature, and capacity.

Feature Extraction: Collected data is further processed to extract relevant features that will be utilized for training and testing the RUL prediction.

Training Data: Used to train the RUL prediction algorithms.

Testing Data: Evaluate the performance of trained models.

RUL Prediction Algorithms: GBR, KNN, BR and ETR are the ML algorithms used for prediction.

Performance Error Indices: The performance of each RUL prediction algorithm is evaluated using error indices. These indices help determine how well each algorithm predicts the RUL of the battery.

III.2. PROPOSED ALGORITHMS:

III.2.1. Gradient Boosting Regressor (GBR):

As an optimization technique, gradient descent trains successive models to minimize a loss function, such cross-entropy relative to its predecessor [19]. Combining several weak models into one strong predictive model is the goal of gradient boosting, an effective ensemble approach. The following figure shows the steps involved in training gradient-boosted trees to solve regression problems.

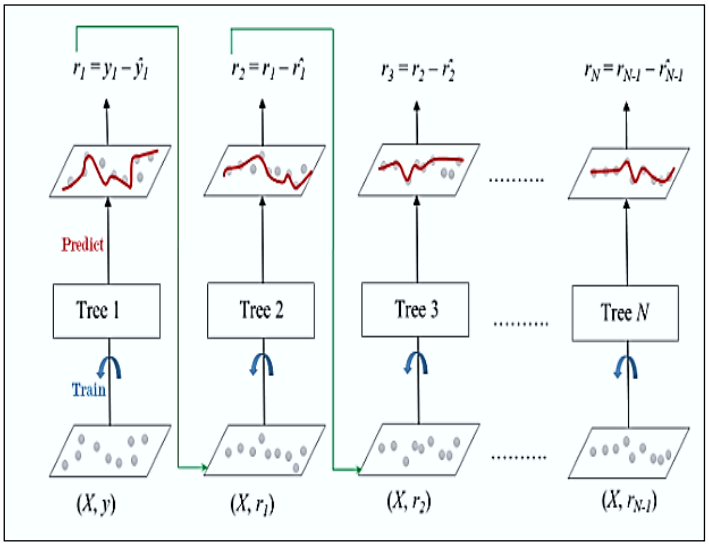

Figure 3: Training of Gradient Boosting Regressor.
Source: Authors, (2025).

The set of 'N' trees is derived from the illustration. For Tree1's training, we utilize 'y' and feature matrix 'X'. Predictions labelled $\hat{y}_1$ are used to find the training set residual errors, r_1.Next step is to train Tree2 using 'X' as feature matrix and labels from r1, residual errors of Tree1. We next determine residual r_2 by use the expected results, $\hat{r}_1$.

We keep doing this until we've trained all 'N' trees in our ensemble. One of the most important parameters used by this strategy is shrinkage. The term "shrinking" describes the effect of multiplying the predictions of each ensemble tree by the learning rate, eta, which can take values between zero and one. There is a trade-off between eta and the number of estimators; a lower learning rate necessitates a higher number of estimators to preserve a certain model performance. The formula below gives the final forecast, after each tree has made a label prediction.

$$y(p) = y_1 + (H * r_1) + (H * r_2) + . + (H * r_n) \quad (3)$$

Algorithm:

Step 1: Let's assume that the input and target, X and Y, consist of N samples each. Main objective is to determine function f(x) that maps input characteristics X to target variables y. It represents the cumulative number of trees that have been reinforced. The difference between expected and observed values quantified by loss function.

$$L(f) = \sum_{i=1}^{N} L(y_i, f(x_i)) \quad (4)$$

Step 2: Minimize loss function L(f).

$$f_0(x) = argmin_f L(f) = argmin_f \sum_{i=1}^{N} L(y_i, f(x_i)) \quad (5)$$

Step 3: Gradient descent
For 'M' stage gradient boosting gradient descent finds

$$h_m = -\rho_m g_m$$

$$g_m = -\left[\frac{\partial L(y_i, f(x_i))}{\partial f(x_i)}\right] \quad (6)$$

Step 4: Prediction
The gradient Similarly for trees:

$$f_m(x) = f_{m-1}(x) + (argmin_{hm}(argmin_{hm}\left[\sum_{i=1}^{N} L(y_i, f_{m-1}(x_i) + h_m(x_i)\right](x) \quad (7)$$

The final solution is:

$$f_m = f_{m-1} - \rho_m g_m \quad (8)$$

III.2.2 K-Nearest Neighbor (kNN)

It uses similarities between new data points and old data to determine their classification. It operates under assumption that similar data points are located close to each other in feature space. By storing all training data, KNN can efficiently assign new data points to the most appropriate category based on their proximity to known data points. Despite its popularity in the classification domain, KNN has a place in regression analysis as well. The core idea is to classify a testing point based on its nearest neighbors in feature space, where k is a given integer. This neighborhood is selected from a set of training points whose correct classifications are known. Due to its laziness as a learning algorithm, kNN only uses approximations at the local level to approximate functions, saving computation until when it is truly necessary [20]. The nearest training points (K(1), K(2),..., K(n)) in a neighborhood are weighted to provide an estimate of the answer (xt) for a testing point (xt) in a k-nearest neighbor regression. It is common practice to use a kernel function that takes into account the distance between each neighbor and the testing point to calculate their weight.

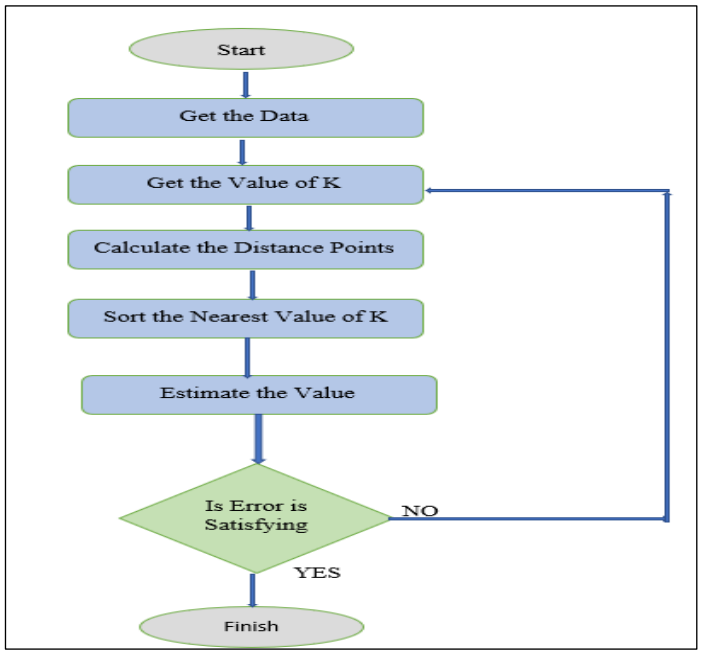

Figure 4: Flow chart for KNN.
Source: Authors, (2025).

Let K = {k1, k2,..., kM} be a training data set with M training points and N features per training point. weighted Euclidean distance, represented as,

$$KNN = d(K_t, K_i) = \sqrt{\sum_{n=1}^{N} w_n (k_{t,n} - k_{i,n})^2} \quad (9)$$

3.2.3. Extra Tree Regressor (ETR)

Developed as an extension of the Random Forest (RF) model by Geurts et al., Extra Tree Regressor (ETR) [21] describes a considerable enhancement to ensemble learning. A collection of unpruned regression trees, each produced by a standard top-down algorithm, form the basis of the ETR method. This method uses a two-stage procedure for regression analysis, namely bootstrapping and bagging, which is different from the RF model. Whenever a tree is being trained in the ETR model, a deterministic splitting method is used. Although RF uses a selection technique to find the best split from a random set of attributes at each node (as shown in the image below), ETR picks the best split from these options by randomly picking a split point for every feature.

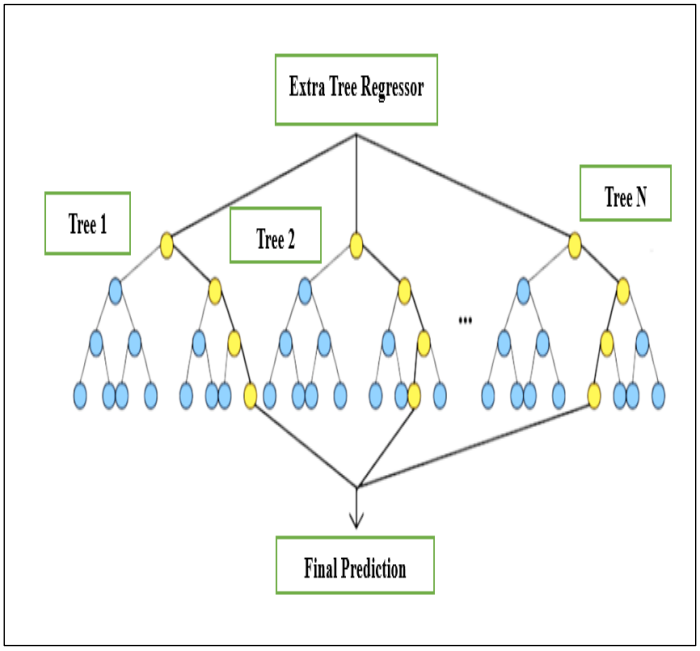

Figure 5: Extra Tree Regressor.
Source: Authors, (2025).

Here is the mathematical representation:

$$X_{ETR} = Arg_{n,\,m}\ min[Error(n,m)] \quad (10)$$

The variable X_{ETR} indicates the split that was decided in the ETR method in this example. An attribute is represented by the letter 'n', while a randomly chosen feature split point is symbolized by the number 'm'.
The split's success in reducing errors is determined by the function Error (n, m). In order to reduce this mistake, the algorithm chooses a n and m value. Typically, the final forecast is computed as an average of the votes cast by each tree during the bagging step of the RF method. But the ETR method uses a broader set of unpruned trees in a comparable fashion. For a brief mathematical description of the output from the ETR model, see the equation below.

$$Y_{ETR} = \frac{1}{N}\sum_{i=1}^{N} T_i(X) \quad (11)$$

The input feature vector is X, and the output is Y_{ETR}.

3.2.4. Bagging regressor (br)

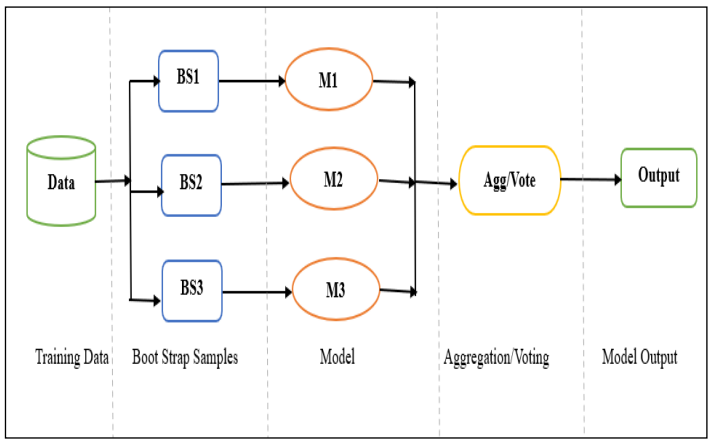

Figure 6: Bagging Regressor Algorithm.
Source: Authors, (2025).

Ensemble learning is a method in supervised machine learning where many models are combined to create a more powerful single model. As an ensemble learning method, "bagging" or "bootstrap aggregating" entails training many base models concurrently on different subsets of training data [22].

Bootstrap sampling, which selects data points at random replacement, is used to create each subgroup. For the bagging classifier, majority voting is used to aggregate the all-base model's predictions to arrive at the final prediction. In order to get at a final prediction, regression models average the predictions from all of the base models, a process known as bagging regression. The Bagging Algorithm, as seen in Figure 6 below, consists of many phases.

Training Data: Data is selected for training form available datasets.

Boot Strap: Randomly chosen "n" subsets of the initial training data are selected with replacement in the bootstrap sampling method. While certain samples may appear more than once in the new subset while others may be excluded, this process guarantees that basic models are trained on variety subsets of data. It raises model's accuracy and lowers the danger of overfitting.

Model: Involves creating a separate subset of data for each base model, which is trained independently using a specific approach . Due to their potential lack of accuracy when used alone, these models are commonly known as "Weak learners." As the basic model does not utilize separate data subsets during training**.**

Aggregation/Voting: The majority vote determines the anticipated class label in the bagging classifier for given instance. The class predicted by the model is the one with the majority of votes.

Model Output: Bagging generates a final forecast for each instance by combining the predictions from all of the underlying models. Bagging regressor provides a potent way to boost model resilience and predictive performance. By using the collective knowledge of several base models, the Bagging regressor prevents overfitting, enhances generalization, and provides reliable predictions for a broad range of applications.

IV. RESULTS AND DISCUSSION

IV.1. DATA SET

Fourteen NMC-LCO 18650 batteries, with a nominal capacity of 2.8 Ah each, make up the dataset utilised for forecasting the Remaining Useful Life. [23] The batteries were tested by the Hawaii Natural Energy Institute through over a thousand cycles at a temperature of 25°C.A 1.5 C discharge rate and a C/2 CC-CV charge rate were utilised in the tests. The information includes important statistics about voltage and current, which essential required for calculating the batteries' remaining useful life (RUL).

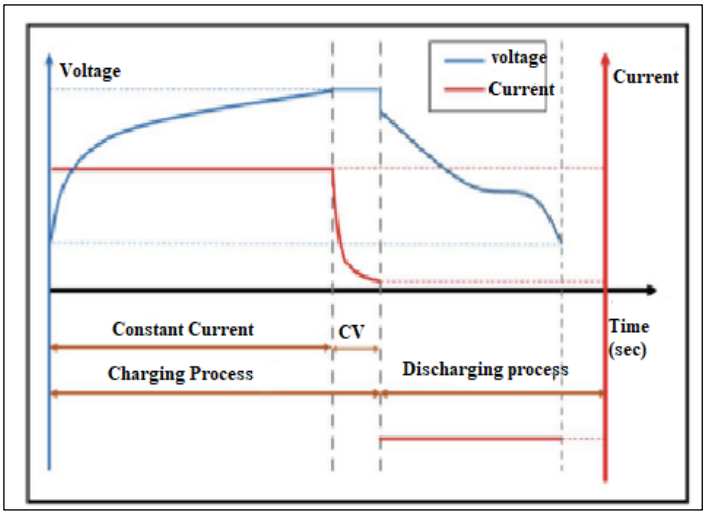

Figure 7: Charging and Discharging of LIB's..
Source: Authors, (2025).

IV. MODEL VALIDATION

Multiple techniques exist for assessing the efficacy of models. This study utilizes four statistical measures, namely MAE, MSE, RMSE, and R2, to evaluate performance of models. Evaluative metrics are shown in the following equations (12–15).

$$MAE = \sum_{i=1}^{n}(x_i - y_i) \quad (12)$$

$$MSE = \sum_{i=1}^{n}\frac{(x_i - y_i)^2}{n} \quad (13)$$

$$RMSE = \sqrt{\sum_{i=1}^{n}\frac{(x_i - y_i)^2}{n}} \quad (14)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(x_i - \bar{y}_i)^2} \quad (15)$$

Where $x_i$represents the predicted value,y_i represents the observed value, $\bar{y}_i$ is the mean observed value, and n is the sample size.

IV.3 ASSESSING THE SUGGESTED MODELS' EFFECTIVENESS

We performed several necessary measures to make the dataset more amenable to examination and modelling. Data cleaning to remove errors, feature selection to provide useful information about battery behaviour, feature creation to add more insights, data normalisation to make sure all features are on same scale, categorical variable transformation to modellable format, data split into training and testing sets to evaluate model performance were all part of this project.

There are 15,065 rows and 9 columns in dataset. Training uses 70% of the data, while testing uses the other 30%. By dividing dataset, model may be trained on a bigger dataset for training and tested on a smaller one.

Table 1: Performance Model Validation of RUL prediction using Machine Learning Algorithms.

Algorithms	MSE	RMSE	MAE	R^2	Time
Gradient Boosting	53.941	7.344	4.837	0.976	0.722
K Nearest Neighbor	57.061	13.109	9.721	0.988	0.820
Bagging Regressor	14.307	3.782	2.099	0.999	0.124
Extra Tree Regressor	30.763	5.546	2.523	0.997	0.138

Source: Authors, (2025).

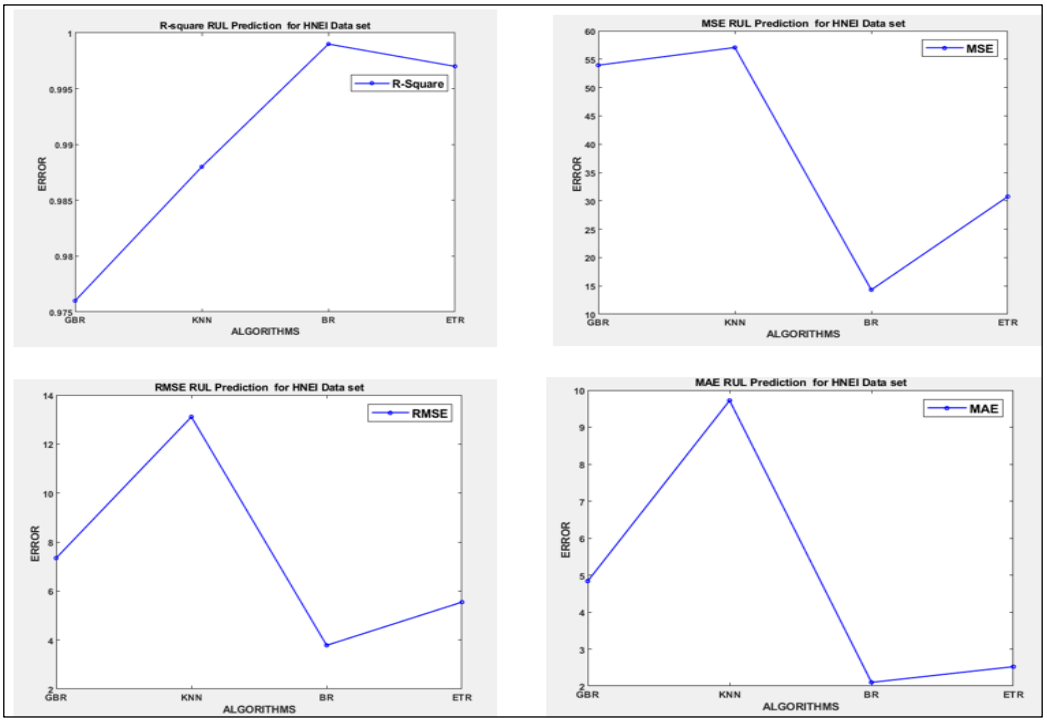

Figure 8: Estimation results of the HNEI aging dataset.
Source: Authors, (2024).

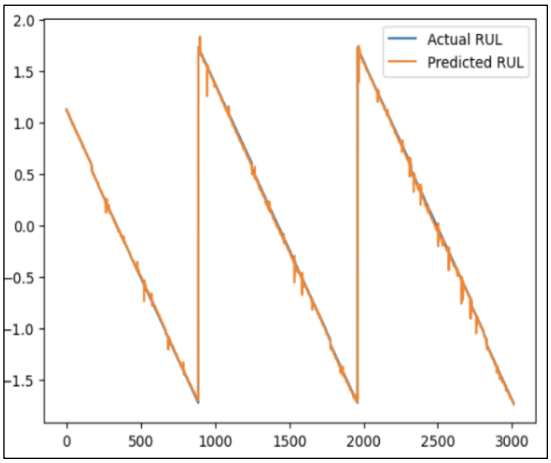

Figure 9(a): RUL Actual Vs Predicted.

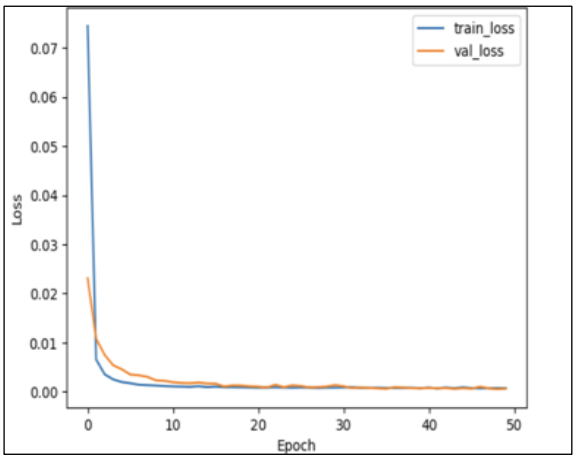

Figure 9(b):Training and validation loss.
Source: Authors, (2025).

The effectiveness of machine learning models, GBM, KNN, BR and ETR in forecasting battery RUL is compiled in Table 1. The efficiency of models was evaluated using metrics, including MAE, MSE, RMSE and R2 with its execution time.

From the performance model validation Table 1 it indicates that bagging regressor model performs better than the other types, according to the data.

With an R2 value of 0.999. BR model has best prediction accuracy, surpassing GBR, KNN, and ETR, as shown by its lowest RMSE of 3.782. A MAE of 2.099 confirms that the BR model accurately estimates the target variable.

The accuracy of the BR model's estimation of RUL for the HNEI technique is shown in Figure 8. The results demonstrate that, when applied to the HNEI aging dataset, the proposed BR model estimates RUL for a variety of performance error indices with robustness and accuracy. The proposed models demonstrated strong performance and increased forecast accuracy. The suggested BR technique has the potential to significantly increase a lithium-ion battery's RUL prediction accuracy.

Figure 9(a) presents a clear comparison between the real Remaining Useful Life (RUL) values and the anticipated RUL values generated by our model for the most recent 100 test samples.

The x-axis depicts the indices of the most recent 100 test samples, providing a historical perspective on the prediction performance over time. Every data point on the diagram represents a singular test sample. The y-axis represents the RUL values, which measure the remaining useful life for each test sample.

The actual Remaining Useful Life (RUL) line represents the genuine RUL values obtained from the test data. It acts as a standard for assessing the model's ability to accurately estimate the Remaining Useful Life (RUL) of the systems being evaluated. The blue data points in Figure 9(b) represent the actual Remaining Useful Life (RUL) values, whereas the orange data points represent the predictions made by our model.

Significantly, there is a strong correlation between our predictions and the actual data at several places, demonstrating the model's efficacy.

IV.4 HEATMAP

Understanding the variables influencing battery life and performance can be aided by using heatmap to show the correlations between various battery system variables. Based on the heatmap in Figure 10, the following inferences can be made:

- Correlation coefficients: range from -1 to 1.
- Charging time and Discharge Time Correlation is 0.94, indicating that these variables are strongly positively correlated.
- Time at 4.15V and Charging time Correlation is 0.68, showing a moderate positive relationship.
- Using 0.78 coefficient, RUL and Maximum Voltage Discharge exhibit robust positive association.

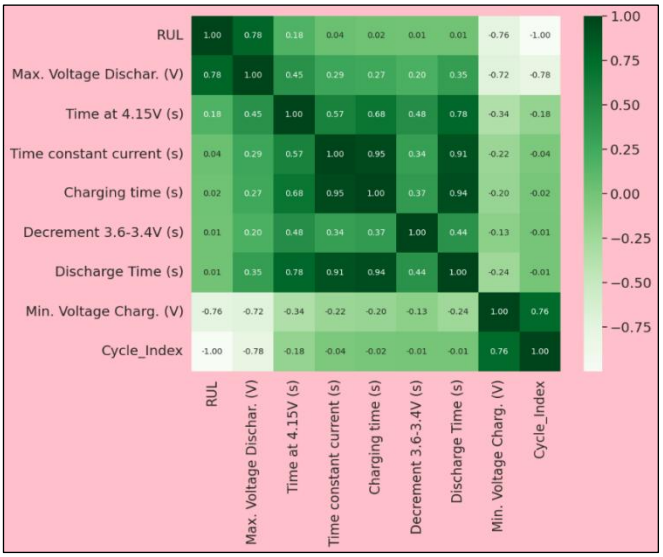

Figure 10: Heat map representing dataset characteristics.
Source: Authors, (2025).

IV.5 PERFORMANCE VALUATION OF MODELS IN COMPARISON TO RELATED MODELS

A comparison of performance evaluation values for several battery RUL prediction techniques is shown in Table 2. Our models' values are compared to all previous approaches. These results show the remarkable accuracy and precision of our approach, underscoring its potential for accurate RUL prediction and ensuring the stable and efficient functioning of LIB in many applications.

'The table prominently presents important assessment measures, including RMSE. In table 2 comparison of proposed model's expected outcomes with those of previous methods. MAE in addition to the R2. Lower numbers indicate more accuracy in terms of predictive precision, as measured by RMSE and MAE. Notably, our suggested methods offering deep insights into its exceptional predictive powers. This outcome demonstrates the higher predictive ability of models in comparison to alternative battery RUL prediction techniques.

Table 2: Comparison of Performance error indices for RUL prediction with different models.

Referance	Model	MSE	RMSE	MAE	R-Square
[11]	GBR	57.447	7.579	4.984	-
	LR	54.543	7.385	4.644	-
[13]	ETR	98.031	9.788	-	-
[15]	BR	516.332	22.72	-	-
[18]	GBR	54.433	7.853	-	-
[20]	KNN	-	8.274	7.623	0.995
Proposed	**BR**	14.307	3.782	2.099	0.999

Source: Authors, (2025).

V. CONCLUSION

This research suggests four different regression models like Gradient Boosting Regressor, K-Nearest Neighbor Regressor, Bagging Regressor, and Extra Tree Regressor models to forecast RUL prediction of LIB life for electric vehicles using real-life battery dataset from Hawaii Natural Energy Institute. Battery dataset's error metrics, such as R-Squared, MAE, RMSE, and MSE, were then ascertained. The four approaches all showed a noticeable variation in relevance when examined using various performance error indexes. The results show that BR method is capable of accurately and effectively determining RUL of batteries when compared with other GBR, KNN and ETR methods. For real-time prediction, the calculation time is also reasonable. Future research concentrates on applying Hybrid Learning methods to improve forecast accuracy.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Sravanthi C L and Dr.J N Chandra sekhar
Methodology: Sravanthi C L and Dr.J N Chandra sekhar
Investigation: Sravanthi C L and Dr.J N Chandra sekhar
Discussion of results: Sravanthi C L and Dr.J N Chandra sekhar
Writing – Original Draft: Sravanthi C L
Writing – Review and Editing: Sravanthi C L
Resources: Dr.J N Chandra sekhar
Supervision: Dr.J N Chandra sekhar

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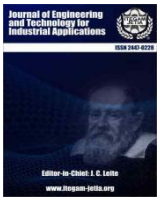

RESEARCH ARTICLE OPEN ACCESS

PERFORMANCE ASSESSMENT OF A MULTI-VERSE OPTIMIZER BASED SOLAR-PV INVERTER FOR GRID CONNECTED APPLICATIONS

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ABSTRACT

As the need for renewable energy has increased over the preceding decade or so, grid connected Photovoltaic (PV) systems have grown in prominence. Effective control strategies have become vital role in ensuring the optimal performance of these systems, particularly in the sense of Power Quality (PQ), efficiency, and grid synchronization. Hence, this paper proposes a Multi-Verse Optimizer (MVO) based inverter controlling stratage for enhancing the concert of a grid connected PV system. The MVO algorithm is employed to determine optimal gain values for both the current and voltage controllers of the PV inverter. The anticipated MVO-based controller is rigorously evaluated through MATLAB/ Simulink, considering key performance indicators such as grid current total harmonic distortion (THD), grid's voltage and current, and PV's voltage and current. With the aim of demonstrating the effectiveness of the suggested technique, a comparative study is carried out using a 3.5 kW grid connected PV system test case, benchmarking the MVO-based controller in contradiction to an Ant Lion Optimizer (ALO) based controller. The simulation outcomes conclusively validate the superior demonstration of the proposed technique as compared to ALO controller across all evaluated cases, highlighting its capability to achieve notable improvements in grid-connected PV system performance.

I. INTRODUCTION

Growing global energy demand and heightened environmental concerns have catalyzed a significant surge in the integration of energy from renewable sources, especially photovoltaic solar systems, into the existing power grid [1]. Grid-connected PV systems offer a multitude of advantages, such as improved energy sustainability, decreased carbon emissions, and less dependence on fossil fuels [2]. However, the efficient operation of these systems necessitates the implementation of sophisticated control strategies to ensure optimal power transfer, maintain grid stability, and meet the stringent grid interconnection standards [3],[4].

Inverters are essential to the operation of PV systems that are associated to the grid. These inverters feed alternating current (AC) that may be provided into the grid from the direct current (DC) electricity obtained by the PV panels [5]. The performance of the inverter directly impacts the overall efficiency, power quality, and stability of the PV system connected to grid [6-8]. Therefore, designing and implementing effective control strategies for PV inverters is of paramount importance. Proper control techniques are essential to ensure that the PV inverter operates at its optimal efficiency, injects high-quality power into the grid, and maintains grid synchronization and stability [9-11].

Recent advancements in the field of optimization algorithms have opened up new avenues for enhancing the performance of PV inverter control systems. In the literature, numerous control techniques have been suggested to enhance the grid-connected PV inverter's performance, including conventional linear controllers, such as Proportional-Integral (PI) and Proportional-Resonant (PR) controllers, as well as cutting-edge governing strategies proceeding on Fuzzy Logic (FL), Neural Networks (NN), and Optimization Algorithms (OA) [12], [13]. Among these, optimization algorithms have gained substantial

attention owing to their facility to handle non-linear system dynamics, uncertainties, and disturbances effectively [14].

An innovative approach in controlling grid-connected PV inverter using the Multi--Verse Optimizer (MVO) technique is introduced in this paper. The MVO algorithm is a fairly recent metaheuristic optimization method that lures inspiration as of Cosmological notions such as Worm Holes, Black Holes, and White Holes [15]. Due to its efficient exploration and exploitation capabilities, fast convergence speed, and overall robustness, the MVO algorithm has demonstrated promising results in solving various optimization problems across a widespread range of applications. The employment of the MVO-based control strategy in this work aims in order to improve the grid-connected PV inverter's performance by adhering to significant features like power quality, efficiency, and grid synchronization.

II. MATERIALS AND METHODS

II.1 MULTI-VERSE OPTIMIZER (MVO) ALGORITHM

A stochastic optimization technique called the Multi-Verse Optimizer was motivated by the fascinating ideas of wormholes, black holes, and white holes in Cosmology, introduced by Seyedali Mirjalili in 2016. The MVO algorithm simulates the dynamic interactions between these cosmic entities to effectively explore the search space and ultimately identify optimal solutions for complex optimization problems [16-18]. The core principles underlying the MVO algorithm are presented in Figure 1.

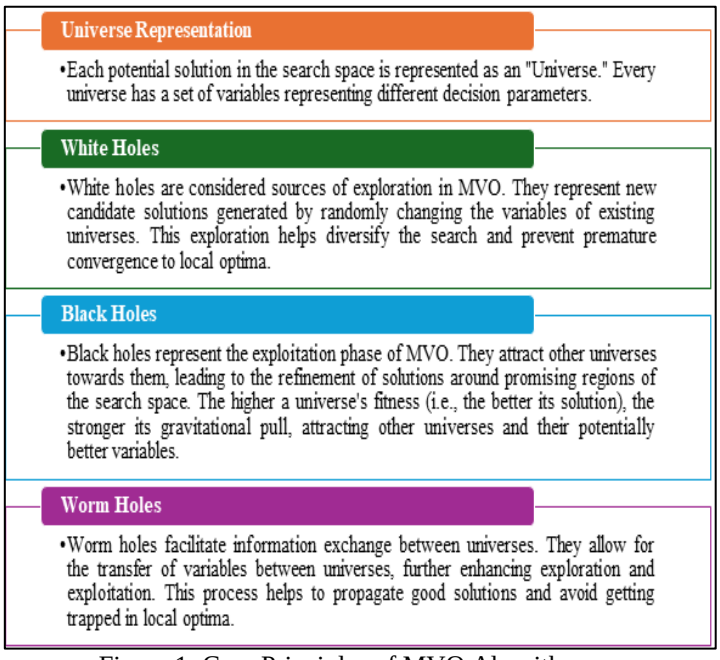

Figure 1: Core Principles of MVO Algorithm.
Source: Authors, (2025).

The MVO algorithm iteratively updates the positions and characteristics of universes constructed using the principles of Worm Holes, Black Holes, and White Holes. Over time, the universes converge towards the areas where the search could yield the best results, ultimately leading to the identification of optimal or near-optimal solutions. MVO has several advantages that make it suitable for optimizing complex problems such as Global Search Capability, Fast Convergence, Parameter Sensitivities etc. Due to these advantages, Feature selection, image processing, and other optimization problems and engineering design have all found successful applications of MVO. In the context of this paper, MVO is utilized to optimize the gain values of the voltage and current controllers of a grid coupled PV inverter, marking to enhance its overall performance.

II.2 OPTIMUM PV INVERTER CONTROL

PI controllers are widely used in grid-connected PV inverters for regulating current and voltage as a result of their easiness and effectiveness. However, the performance of a PI controller heavily relies on the proper selection value of its proportional gain and integral gain. Manually tuning of these gains can be a time-consuming and challenging task, as it often requires extensive experimentation and may not result in optimal performance, especially under varying operating conditions such as changing load, environmental factors, or grid disturbances. The manual tuning process can be further complicated by the PV system's complexity, non-linear dynamics and its interaction with the grid, making it difficult to achieve the desired functionality in various operational environments [19], [20].

The Multi-Verse Optimizer algorithm proves to be highly beneficial in this application, as it may effectively be constructed using the principles of Worm Holes, Black Holes, and White Holes to search for the optimal combination of proportional and integral gain values for the PI controller, to obtain this Integral Time Absolute Error (ITAE) which desires to be optimized. The ITAE of PI controller is specified as follows

$$\text{ITAE} = \int_0^t t|e(t)|dt \tag{1}$$

By optimizing these gain values, the MVO algorithm can minimize a predefined objective function that reflects the desired performance criteria, such as minimizing the grid current total harmonic distortion, dipping the steady-state error (ESS), and improving the dynamic response of the grid-connected PV inverter. This optimization process helps to overcome the challenges associated with manually tuning the PI controller gains, which can be a time-consuming and complex task, especially given the non-linear PV system's dynamics and its interface with the grid. The Figure 2 shows the MVO flowchart used to adjust the PI controller of a grid-connected PV inverter.

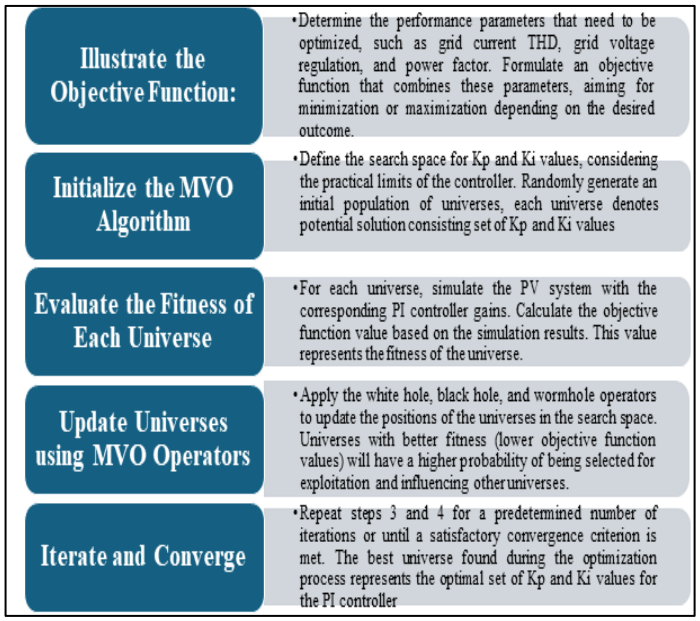

Figure 2: Flow Chart of MVO Algorithm.
Source: Authors, (2025).

The grid integrated PV inverter can operate more efficiently, reliably, and with better power quality if the PI controller is tuned using the MVO algorithm. This algorithm may cope with intricate, non-linear systems makes it well-suited for optimizing the dynamic behavior of the inverter under various operating conditions.

III. TEST CASE

This work proposes and implements a methodology for tuning PI controllers using Multi-Verse Optimizers. The system in consideration is a grid coupled PV system with a power output of 3.5 kW. The following are the initialization parameters of the MVO algorithm:

Population Size (N): 100
Number of Iterations (Max Iter): 500
White Hole Probability (W_H): 0.7
Black Hole Probability (B_H): 0.1
Fitness Function: ITAE

- **Procedure for optimal tuning of PI control using MVO algorithm:**

Step 1: Initialization:

$$X_{ij} = LB_j + rand(0,1) * (UB_j - LB_j) \quad (2)$$

Step 2: Fitness function: (X_i)

Step 3: White Hole: $X_{ij}(t+1) = X_{ij}(t)$ (3)

Step 4: Black Hole:

$$X_{ij}(t+1) = X_{ij}(t) + B_H + (Best_j - X_{ij}(t) \quad (4)$$

Step 5: WEP:

$$WEP(t) = WEP_{min} + \left(\frac{WEP_{max} - WEP_{min}}{Maxiter}\right) * t \quad (5)$$

Step 6: Worm hole Adjustment:

$$X_{ij}(t+1) = \begin{cases} X_{ij}(t) + TDR * (UB_j - LB_j) * rand; \\ \text{if } rand < WEP(t) \\ X_{ij}(t) - TDR * (UB_j - LB_j) * rand; \\ \text{otherwise} \end{cases} \quad (6)$$

IV. RESULTS AND DISCUSSIONS

To validate the efficacy of the proposed Multi-Verse Optimizer based PI controller tuning methodology, a series of simulations were conducted on a test case of 3.5 kW, PV system integrated to grid. The illustration of the MVO-tuned PI controller was rigorously correlated against a controller tuned using the ALO algorithm. This comparative analysis focused on critical performance indicators, including grid current and voltage, PV current and voltage, Total Harmonic Distortion under the following scenarios:

- Performance Evaluation of ALO Based PV Inverter
- Performance Evaluation of MVO Based PV Inverter

IV.1 PERFORMANCE EVALUATION OF ANT LION OPTIMZER BASED PV-INVERTER

In this case, Ant Lion Optimizer based Inverter is implemented on a grid associated PV system. The Figure 3 depicts the performance evaluation parameters including grid current and voltage, PV current and voltage, and Total Harmonic Distortion. These parameters are tested under different conditions of solar irradiance and ambient temperature.

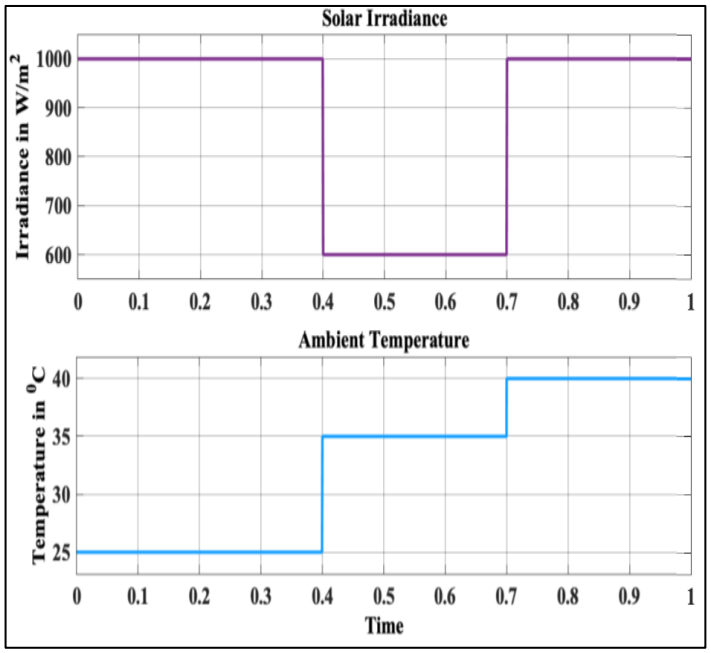

Figure 3: Solar Irradiation as well as Ambient Temperature.
Source: Authors, (2025).

The performance evaluation curves, including PV current and voltage, are as illustrated in Figure 4 below w.r.t solar irradiance and temperature.

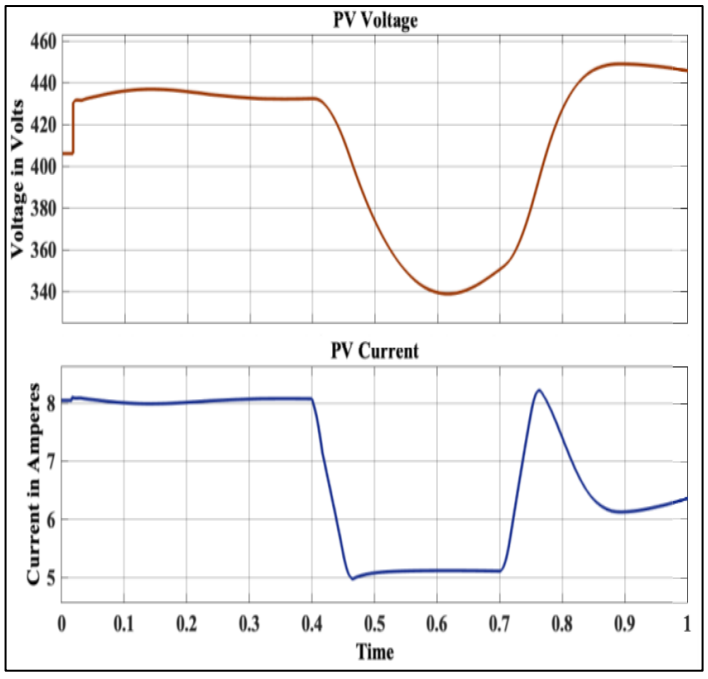

Figure 4: Photovoltaic Voltage and Current using ALO Algorithm.
Source: Authors, (2025).

The performance curves of the grid's current and voltage with ALO algorithm are depicted in Figure 5 below. These curves are met w.r.t grid integrated PV inverter control topology for variance in solar irradiations and temperatures.

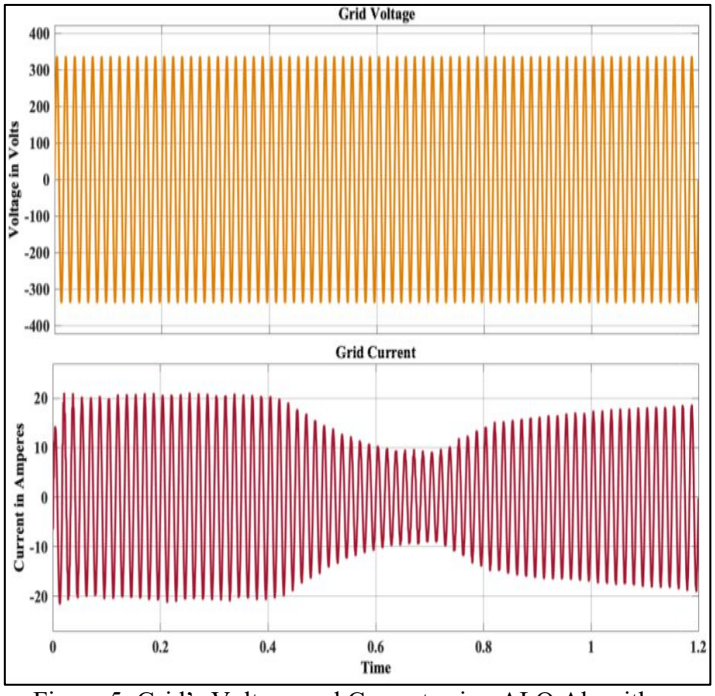

Figure 5: Grid's Voltage and Current using ALO Algorithm.
Source: Authors, (2025).

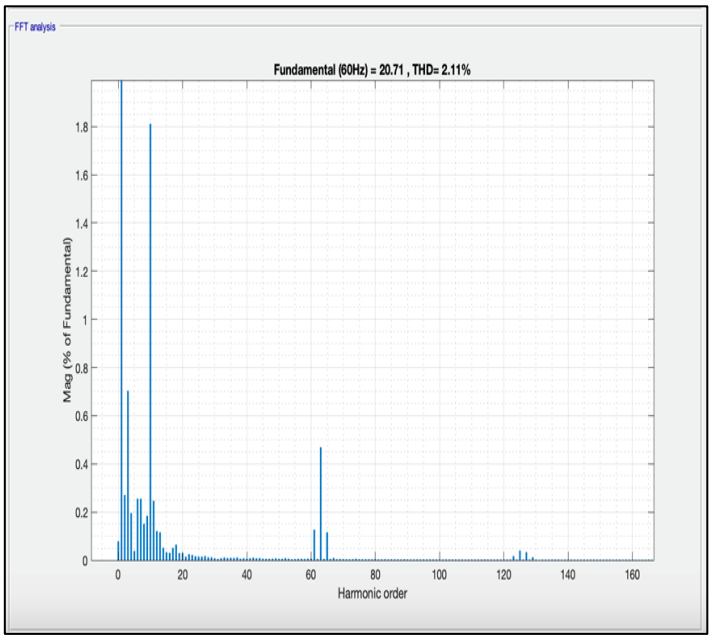

Figure 6: %THD Spectrum using ALO Algorithm.
Source: Authors, (2025).

The Figure 6 shows that the %THD spectrum obtained using an ALO-based PV inverter is 2.11%. The %THD analysis further is investigated by MVO technique for the superior performance of PV inverter.

IV.2 PERFORMANCE EVALUATION OF META-VERSE OPTIMIZER BASED PV-INVERTER

In this case Multi-Verse Optimizer based Inverter is implemented on a grid linked PV system. Figure 7 shows the performance evaluation parameters including grid current and voltage, PV current and voltage, and Total Harmonic Distortion. These parameters are tested under different conditions of solar irradiance and ambient temperature.

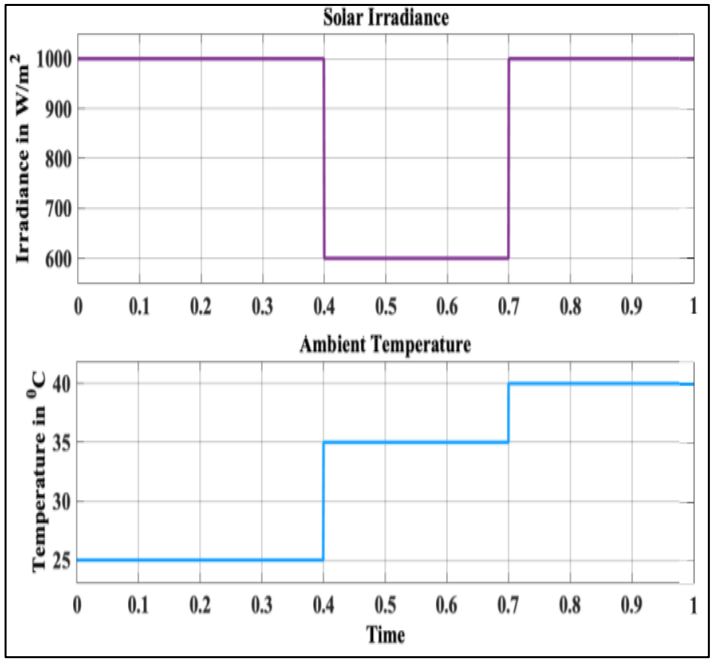

Figure 7: Solar Irradiation as well as Ambient Temperature.
Source: Authors, (2025).

The performance evaluation parameters including PV's current and voltage, are as illustrated in Figure 8 w.r.t solar irradiations and temperature obtained in Figure 7. The inverter output is obtained accordingly and it can be shown that MVO algorithm-based PV inverter gives enhanced results when compared to ALO algorithm.

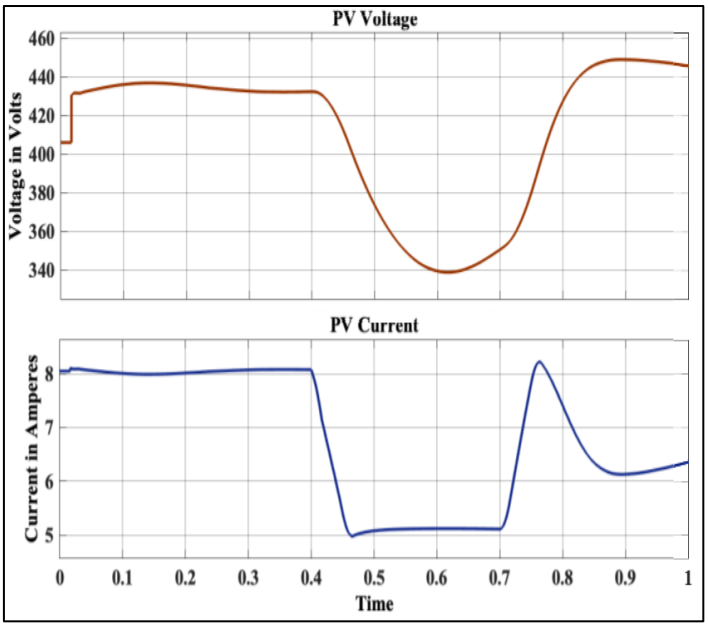

Figure 8: Photovoltaic Voltage and Current utilizing MVO Algorithm.
Source: Authors, (2025).

The evaluating performance parameters like the current and voltage of the grid are depicted in Figure 9, according to PV inverter output.

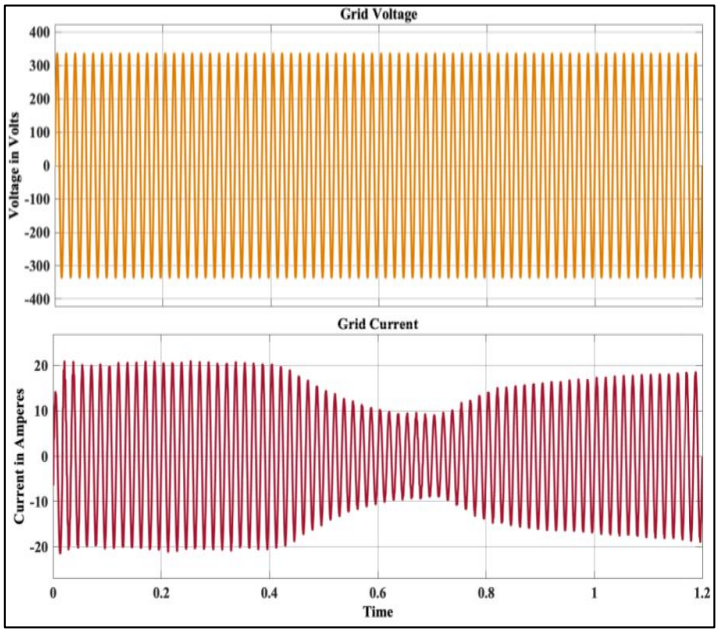

Figure 9: Grid's Voltage and Current using MVO Algorithm.
Source: Authors, (2025).

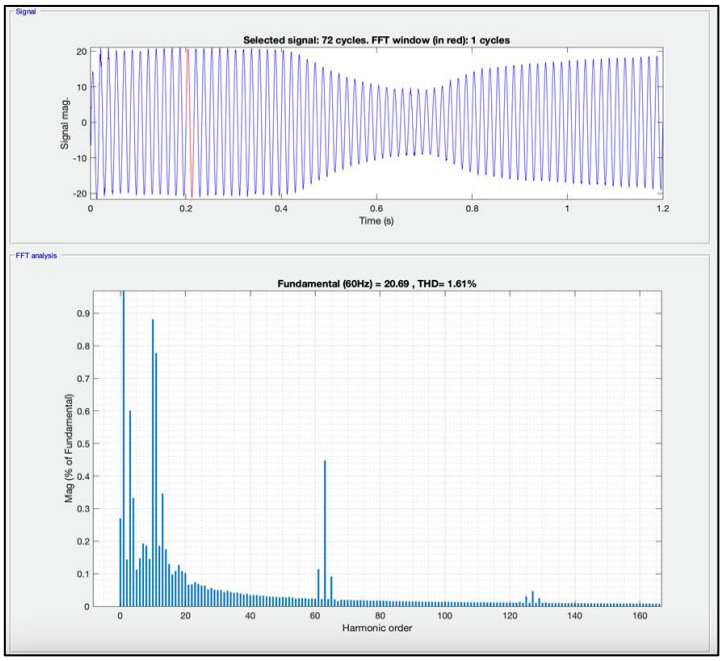

Figure 10: %THD window using MVO Algorithm
Source: Authors, (2025).

The Figure 10 shows that THD analysis using an MVO-based PV inverter is 1.61% and thus enhanced output results have obtained. According to the test case considered, the simulation results show that the proposed MVO-based PV inverter performs better than the ALO algorithm, with a reduction in THD of 2.11% to 1.61% and enhanced inverter output associated to grid connection w.r.t solar irradiations and temperatures considered. The comparisons of inverter control topologies of the test case is shown in Table 1.

Table 1: Comparison of PV Inverter Control Strategies.

Type of PV-Inverter Control	%THD
Ant Lion Optimization	**2.11%**
Meta-Verse Optimization	**1.61%**

Source: Authors, (2025).

V. CONCLUSIONS

This study investigated the efficacy of employing the Multi-Verse Optimizer (MVO) algorithm for tuning the PI controller of a grid-connected PV inverter. The performance of the MVO-tuned controller was rigorously evaluated through extensive simulations and compared against a benchmark controller tuned using the Ant Lion Optimizer (ALO) algorithm. The results unequivocally demonstrate the superiority of the MVO-based PI controller across all evaluated metrics.

The MVO algorithm effectively minimized grid current THD, ensuring compliance with stringent power quality standards. Additionally, it significantly enhanced grid current and voltage regulation, even under fluctuating solar irradiance and varying load conditions, highlighting its robustness. Furthermore, the MVO-tuned controller facilitated improved power extraction from the PV panels, leading to enhanced overall system efficiency. The THD is decreased from 2.11 % to 1.61 % as compared to ALO algorithm.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Venkata Anjani Kumar G,M.Damodar Reddy,
Methodology: Venkata Anjani Kumar G.
Investigation: Venkata Anjani Kumar G, Palepu Suresh.
Discussion of results: Venkata Anjani Kumar G, Chilakapati Lenin Babu.
Writing – Original Draft: Venkata Anjani Kumar G, Chilakapati Lenin Babu.
Writing – Review and Editing: Venkata Anjani Kumar G, Chilakapati Lenin Babu.
Resources: Venkata Anjani Kumar G and Palepu Suresh.
Supervision: M.Damodar Reddy.
Approval of the final text: Venkata Anjani Kumar G, Chilakapati Lenin Babu, Palepu Suresh.

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PARAMETRIC ANALYSIS OF UFMC WITH 5G NR POLAR AND CONVOLUTIONAL CODES IN A MASSIVE MIMO SYSTEM

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ABSTRACT

The Fifth Generation (5G) wireless network's radio access strategies must meet dynamic and adaptable service requirements. The major demands in the current era of pervasive wireless networks are high throughput, reliability, and secure connectivity. 5G New Radio (NR) air interface is a major transition to new modulation and channel coding techniques to reduce redundancy, latency, and complexity. Convolutional codes were used in 4G and polar codes in 5G to code channels for control information in the uplink and downlink. This research aims to investigate the 4G channel codes and provide analytical results for comparing them to the 5G polar codes in Ultra-Reliable Low-Latency Communication (URLLC) applications with short block-length transmissions. The research implements Universal Filtered Multi-Carrier (UFMC) modulation, a suitable technique for short burst transmissions. Channel coding is applied to enhance reliability, considering Polar codes as major 5G candidates for short packet transmission. The comprehensive system is simulated in a massive Multiple Input Multiple Output (MIMO) scenario. The impact of antenna array size in MIMO and UFMC parameters and sub-band size are investigated. The major contribution of the work is that the Bit Error Rate (BER) performance of Polar codes is enhanced with an SNR gain of ~7dB with a 64x16 MIMO UFMC system compared to convolutional codes. Moreover, the concatenated polar and convolutional codes are used, which results in an additional SNR boost of about 3dB. This research reveals that mission-critical applications in 5G can benefit from the flexibility and improved error rate performance offered by the combination of UFMC, Polar codes, and massive MIMO.

I. INTRODUCTION

Enhanced mobile broadband (eMBB), which offers exceptionally high data bandwidth with applications like ultra-high definition (UHD) videos; massive machine type communication (mMTC), for Internet of Everything (IoE) applications having massive low-cost, low-powered devices; and URLLC used in autonomous vehicles, remote surgery, etc., are the primary use cases for 5G networks. These use cases must support high-speed data transmissions of small packets with high reliability [1]. URLLC facilitates delay-sensitive applications such as remote surgery, Augmented reality, industry 5.0, intelligent transport system, etc. The short packet size is to be considered to reduce latency. However, reducing the packet size may cause a loss in coding gain [2]. The permissible latency in URLLC services set by the International Telecommunication Union (ITU) is for a standard packet size of 32 bytes, which is 1 millisecond, with a reliability of $1x10^{-5}$ [3-4]. To fulfill these requirements, the critical enablers considered in the research are channel coding algorithms, multicarrier modulation waveform, and massive MIMO antenna technology.

The transition from a cell-centric to a user-centric design approach for network densification with limited spectrum needs new radio access techniques [5]. The multicarrier waveform is to be chosen as an air interface, which is flexible and reliable in heterogonous networks [6]. A transmission technique with extremely low latency is made possible by highly brief frames. The waveform is to be compatible with short burst transmissions so that it can enable short Transmission Time Intervals (TTIs) with fast uplink/downlink switching [7]. Major waveform contenders for

5G, like Generalized Frequency Division Multiplexing (GFDM), Filter Bank Multicarrier (FBMC), Filtered-Orthogonal Frequency Division Multiplexing (F-OFDM), and Universal Filtered Multi-Carrier (UFMC), are reviewed and analyzed in [9-15]. UFMC is the best choice for a system targeting short-burst transmissions into the overall system design [7].

In UFMC, the available bandwidth is divided into sub-bands and filtered independently. Along with the modulation technique, Massive MIMO technology is integrated, and hundreds of antennas are implemented at the next generation Node B (gNB) to improve network capacity and throughput [16]. The system processing gain tends to be infinite as the number of antennas (W) at the gNB increases [17]. 5G NR is the imminent evolution of next-generation mobile technology to enhance spectral efficiency, signal efficiency, data rate, and connection density [18].

To suit the varied requirements of URLLC, the channel coding must be redesigned and implemented to achieve ultra-high reliability. In URLLC, short blocks are required to reduce the latency. On the contrary, the short blocks reduce coding gain and degrade dependability. However, boosting reliability necessitates adding more redundancy bits, increasing the delay.

As a result, it is crucial to choose the channel coding technique carefully in this case. 5G polar codes are designed mainly for short block transmission to resolve the latency issue needed in the URLLC use case [19]. In 5G NR, polar codes are applied for encoding control information and are considered a major contender of 5G channel coding techniques [20]. In this paper, the hybrid system is designed using a UFMC waveform and a massive MIMO channel with polar coding. An analytical framework is discussed to understand the numerology required for UFMC, antenna array size in massive MIMO, and polar coding.

II. UNIVERSAL FILTERED MULTICARRIER (UFMC)

UFMC modulation technique is based on filtering the sub-bands. Suppose the total M sub-carriers are available and grouped into several sub-bands of size Q, fulfilling M=PQ [21]. Q Subcarriers are modulated by the Quadrature Amplitude Modulation (QAM), and the modulated symbols in each sub-band are converted into frequency symbols for orthogonal time domain subcarriers by the N-point IFFT module.

Each sub-band is filtered with a Dolph-Chebyshev prototype filter of length l. Filtering reduces out-of-band emission (OOBE) and inter-carrier interference (ICI) [22]. In the proposed system, the Dolph- Chebyshev filter is used. Its time domain and frequency domain characteristics for a filter length of 43 are shown in Figure 1. In Dolph Chebyshev, the filter width of the main lobe is minimized for a given α side lobe attenuation, and the mathematical expression of the Chebyshev window is shown in equation (1) [23].

$$f=\frac{\cos\{N.cos^{-1}[\beta\cos(\frac{\pi k}{N})]\}}{\cos[N\ cosh^{-1}(\beta)]} \quad (1)$$

Where N is the size of IFFT, k=0, 1…, M-1, $\beta = \cosh\{\frac{1}{N}cosh^{-1}(10^{\alpha})\}$, α = Side lobe attenuation (2,3,4).
Eventually, the resultant UFMC signal is mathematically written as equation (2):

$$X_{UFMC} = \sum_{k=1}^{C}\sum_{i=1}^{B} F_{i,k}V_{i,k}s_{i,k} \quad (2)$$

Where $F_{i,k}$ is a filter impulse response matrix; $V_{i,k}$ is the IFFT matrix; $s_{i,k}$ is a time domain symbol. The complete UFMC modulation is shown in Figure. 2.

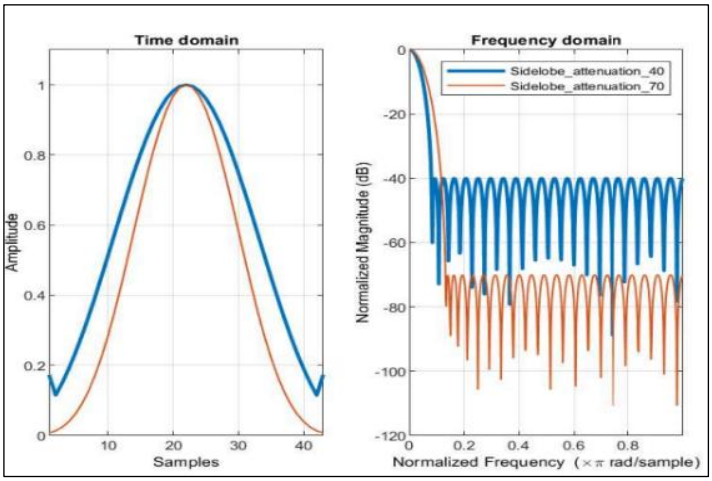

Figure 1: Time and frequency characteristics of the Chebyshev filter.
Source: Authors, (2025).

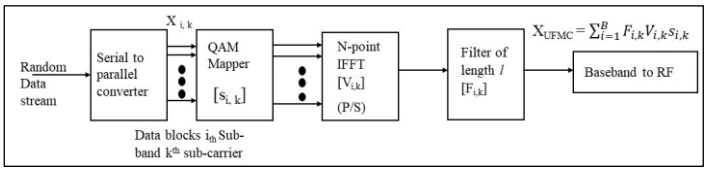

Figure 2: UFMC Modulation.
Source: Authors, (2025).

The UFMC waveform achieves better spectrum utilization with no cyclic prefix (CP), and sub-band filtering reduces side lobes. UFMC waveform is adaptable as per the requirement and facilitates adjusting the sub-band size and filter length [24]. With its flexible and simple design, the UFMC is suitable for short packet communication making it a suitable waveform candidate for URLLC applications [25].

III. CHANNEL CODING

Channel coding is being employed to overcome the impact of a channel for reliable data transmission. This strategy entails adding redundant bits to the message being transmitted so that the transmission errors can be recognized by the receiver, and then possibly corrected. In 4G network linear error-correction codes like Turbo and Convolutional codes are used. The Third Generation Partnership Project (3GPP) proposed Low Density Parity Check (LDPC) codes and Polar codes for 5G network.

III.1 CONVOLUTIONAL CODE

Random data bits are generated in every sub-band and encoded using convolutional coding. In convolutional coding, n output encoded bits are generated with k successive information bits, giving the code rate R = k/n. The encoder is designed with a shift register of length K, called the constraint length [26]. The convolutional encoder (1, 2, 3) with code rate ½, is shown in Fig. 3. The output parity check equations are given by (3) and (4), where the D represents the memory element:

$$C_k^{(1)} = D_0 \oplus D_1 \quad (3)$$

$$C_k^{(2)} = D_0 \oplus D_1 \oplus D_2 \quad (4)$$

The generator polynomials g(x) are shown in equations (5) and (6):

$$g^{(1)}(x) = 1 + x \quad (5)$$

$$g^{(2)}(x) = 1 + x + x^2 \quad (6)$$

Final encoding is done by equation (7):

$$C_i^{(j)} = \sum_{u=0}^{2} D_i - u g_u^{(j)} \quad (7)$$

To reduce the impact of a burst error, the encoded bit sequences are spread out using an interleaver [27].

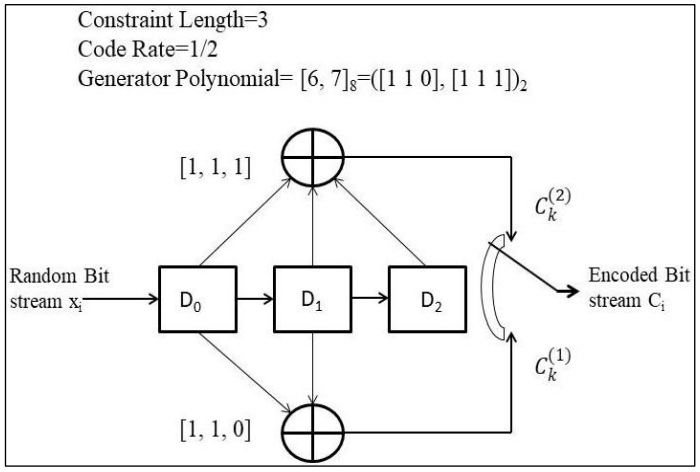

Figure 3: Convolutional Encoder.
Source: Authors, (2025).

II.2 POLAR CODE

The Polar codes are low-complex channel codes adopted for control channels in 5G NR systems. The channel polarization phenomenon transforms memoryless, binary-input, output-symmetric (MBIOS) channels by generating N' synthetic bit channels. The new synthesized channels are polarized. Polarization refers to the transmission of individual bits with varying reliability. Reliability refers to the different probability of being decoded correctly. The prediction of the reliability of each synthetic channel allows them to be arranged according to the reliability order [28]. The recursive structure of the polarizing matrix G_N, as shown in equations (2) and (3), allows for the reduction of encoding complexity [29].

$$G_{N'} = G_2^{\otimes n} \quad (8)$$

$$G_{N\prime} = G_{N\prime/2}{}^{\otimes 2} = \begin{pmatrix} G_{N\prime/2} & 0 \\ G_{N\prime/2} & G_{N\prime/2} \end{pmatrix} \quad (9)$$

The polar code of length N' has the constraint that it should be of powers of two, but K can be of any size in the information set. So, to achieve the desired code rate R=K/E, the rate matching concept must be applied in polar codes. In 5G, this rate-matching problem is achieved using techniques like puncturing, shortening, and extending [30]. The polar coding algorithm is shown in Figure 4.

A variety of algorithms are available for decoding. Arikan proposed the Successive Cancellation (SC) technique in 2009 [30] as a decoding algorithm for Polar Codes. SC method is not suitable for a smaller number of block lengths as it takes only one path from the decoding paths. Decoding stores a set of prospective paths for this Successive Cancellation List (SCL). The SCL decoder keeps track of L paths simultaneously. With the increase in the list size, its performance increases at the cost of implementation complexity [31]. Let $\hat{u}_i$ be estimate of the Source block after receiving $y_1^{N\prime}$, the bits $\hat{u}_i$ are estimated successively.

L distinct decoding paths= $\hat{u}_i{}^{(i-1)}(1), \ldots . \hat{u}_i{}^{(i-1)}(L)$ after the $(i-1)^{th}$ bit has been decoded. For every path t ∈ {1, . . . , L}, there are two choices for $\hat{u}_i(t)$. Out of the resulting 2L paths, the L paths with the highest metric are preserved. When bit N' is reached, the route with the highest metric is set as the decoded codeword [32].

IV. MASSIVE MIMO CHANNEL

In 5G massive MIMO systems, gNB is equipped with W receiving antennas with digital transceiver chains capable of spatially multiplexing T transmitting antennas. Massive MIMO system's uplink is implemented where there are more receiving antennas than transmitting antennas: W/T > 1 [33]. Data is transmitted after UFMC modulation of the massive MIMO channel H for Rayleigh fading [34].

The detection of the desired signal at receiving end is done by nullifying all the interference signals. It is processed by multiplying it with a suitable weight matrix. In our proposed system Zero forcing detection is applied. In Zero forcing signal detection the interferences are negated by weight matrix WZF represented in equation (10), called as Moore-Penrose pseudo-inverse of H.

$$W_{ZF} = (H^H H)^{-1} H^H \quad (10)$$

It inverts the effect of the channel and gives the expected value $\hat{x}_{ZF}$ by equation (6):

$$\hat{x}_{ZF} = S\ \{(H^H H)^{-1} H^H\} Y \quad (11)$$

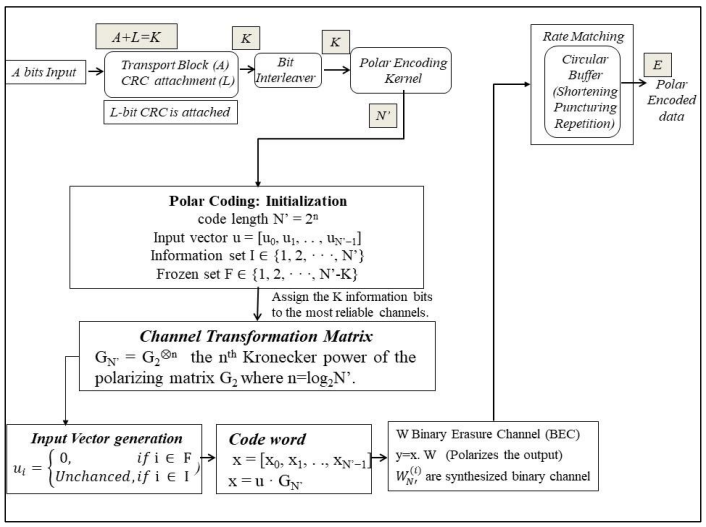

Figure 4: Polar Coding Algorithm.

Source: Authors, (2025).

V. SIMULATION FRAMEWORK AND RESULTS

The system is designed with 4G based Convolutional codes and 5G NR specifications based polar codes with UFMC in massive MIMO scenario. The simulation is done using MATLAB software version 2022b. The control parameters are considered in three sections of simulation as shown in Figure 5. The simulation parameters are shown in Table I. In this paper, the key performance indicator is bit error rate (BER) with respect to signal to noise ratio (SNR) (Eb/N0) is considered for short block transmission and low code rate particularly for URLLC use case scenario.

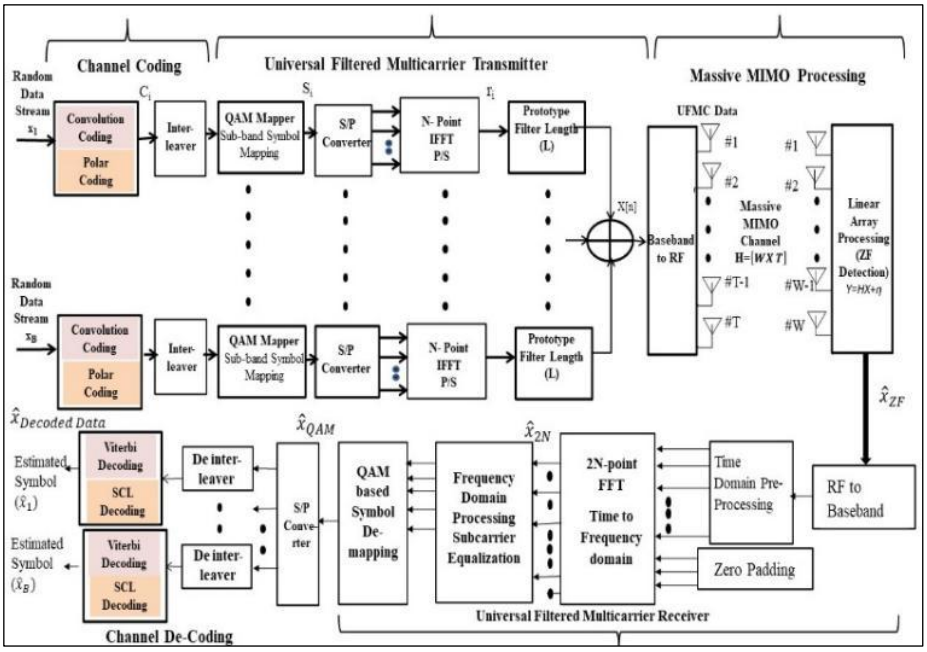

Figure 5: System framework for parametric analysis.
Source: Authors, (2025).

Table 1: Simulation Parameters.

Parameter	Value
UFMC Parameters	
Number of Sub-bands	10
Sub-band size	20
Sub-band Offset	156
Modulation order	64 QAM
Size of FFT	512
Filter	Dolph-Chebyshev
Filter Length (*l*)	43
Side lobe attenuation (α)	40dB
Massive MIMO channel Parameters	
Number of Transmitting	16
Number of Receiving Antenna at gNB (W)	20-100
Linear Array processing	Zero Forcing
Convolutional Coding Parameters	
Code rate (R)	1/2
Constraint Length	3
Channel Decoding	Viterbi
Polar Coding Parameters	
Decoding List length (L)	8
Polar Decoding Algorithms	List Successive Cancellation (SCL)
Code rate R	1/2
Message length K	132
The rate matched output	256

Source: Authors, (2025).

Firstly, the system is simulated for UFMC waveform with Convolutional and polar codes in MIMO antenna implementation. Figure 6 shows that the performance of the coded signal significantly outperforms the standalone UFMC waveform in a 64x16 MIMO system. The BER curve shows that a gain of ~7 dB is achieved in polar codes compared to Convolutional codes.

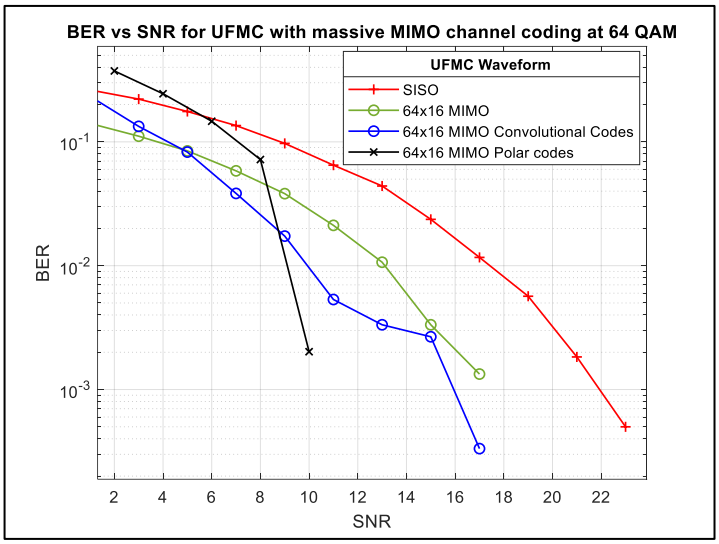

Figure 6: BER versus SNR performance of UFMC waveform with different channel codes.
Source: Authors, (2025).

The system designed in [35], is based on MIMO but implemented a 4G-based Orthogonal Frequency Division Multiplexing (OFDM) waveform. The 5G NR-based UFMC waveform is implemented to enhance the BER performance. The comprehensive system of UFMC waveform in a massive MIMO channel model is designed and simulated.

The simulation is done at 64 QAM, varying the antenna array size at gNB (W) from 20 to 100. The significant outcome of the UFMC-based massive MIMO system simulation with Convolutional codes, so increasing the number of antennas (W) at gNB improves the system performance by providing good throughput yet at low SNR, shown in Figure. 7.

From Figure. 8, BER output for Polar coded UFMC in massive MIMO is that it requires SNR 8dB to achieve zero BER with 100 antennas at gNB. However, to achieve the same BER with 20 antennas at gNB, the required SNR is>25 dB. So, by increasing the antenna array size, there is enormous potential for BER improvement and enhancing data reliability.

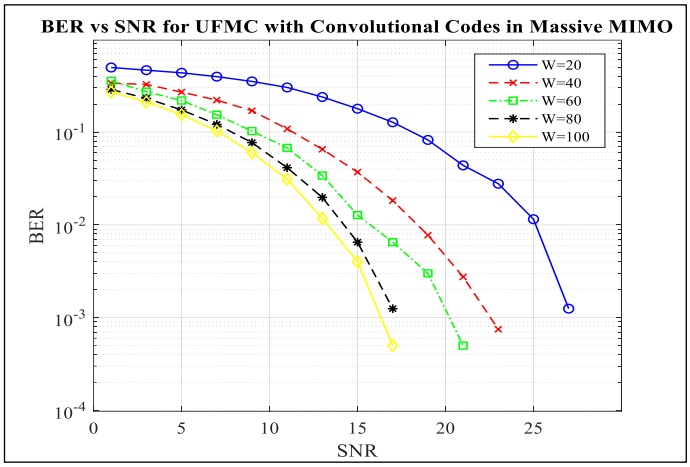

Figure 7: BER Performances for UFMC with Convolutional Codes with Variable gNB antenna array size
Source: Authors, (2025).

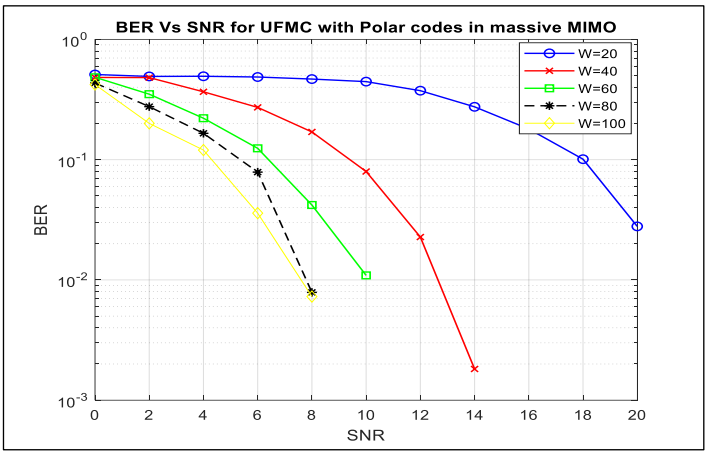

Figure 8: BER performance of Polar coded UFMC system with Variable gNB antenna array size.
Source: Authors, (2025).

Further in the system, CRC-aided Polar codes are used with different CRC lengths to improve the BER performance. Figure 9 shows the impact of CRC length on the system's BER. The larger the CRC length, the better the BER performance, but the computational complexity increases.

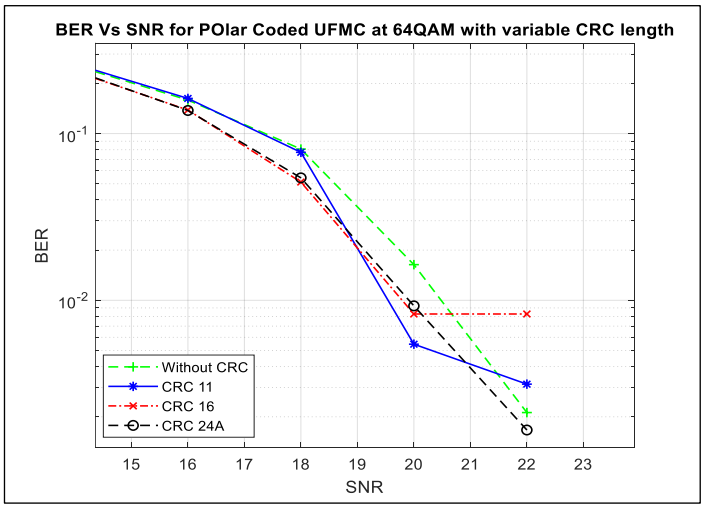

Figure 9: BER performance of Polar coded UFMC system for variable CRC length
Source: Authors, (2025).

For the parametric analysis, the UFMC waveform is analyzed with varying sub-band size (K). The Power Spectral Density (PSD) for UFMC is shown in Figure 10 with variable sub-band size. It is seen from PSD that as the sub-band size increases the spectral efficiency enhances as more subcarriers support higher throughput and efficient utilization of bandwidth.

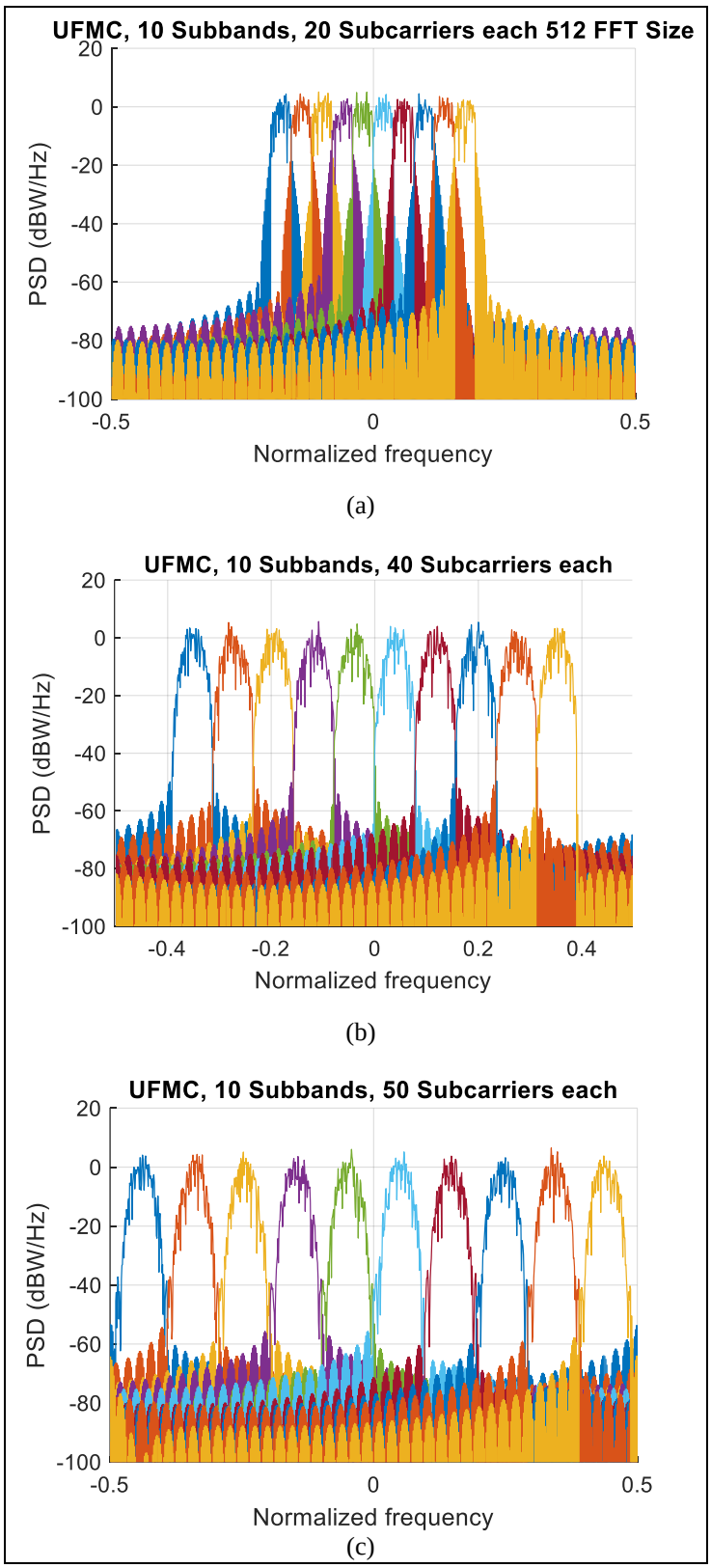

Figure 10: PSD for UFMC Waveform with (a) sub-band size=20 (b) sub-band size=40 (c) sub-band size=50.
Source: Authors, (2025).

Further, the system is simulated with 20 antennas at gNB and a variable UFMC subband size. From the output curve shown in Figure 11, it is observed that different subband sizes affect the UFMC BER performance. So, the size of the subband is to be selected to optimize the performance. The smaller the subband size, the better the BER performance.

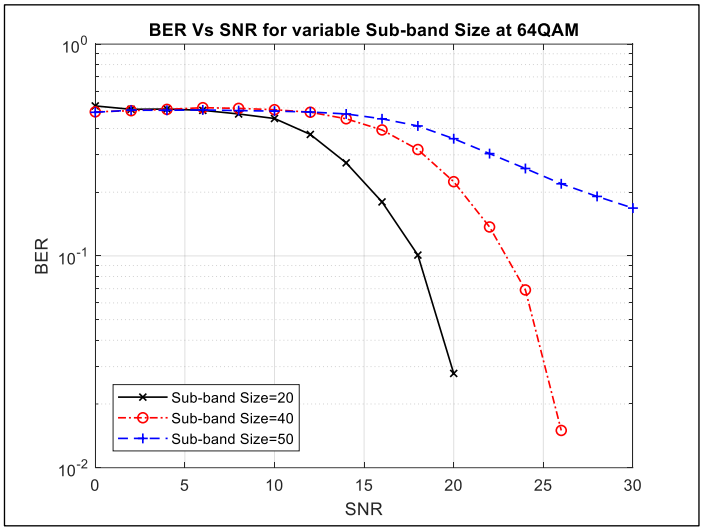

Figure 11: BER vs SNR for Polar coded UFMC Waveform with variable sub-band size.
Source: Authors, (2025).

Concerning [36], concatenation schemes of polar codes with convolutional codes result in frame error rate reduction with the frame length. This joint technique shows a significant improvement over standalone polar code. In the simulated system, convolutional codes are applied as inner and polar codes as outer codes. The 64x16 MIMO antenna array is implemented with 64QAM order. Figure 12 concludes that combining convolutional and polar coding provides an SNR gain of ~3 dB.

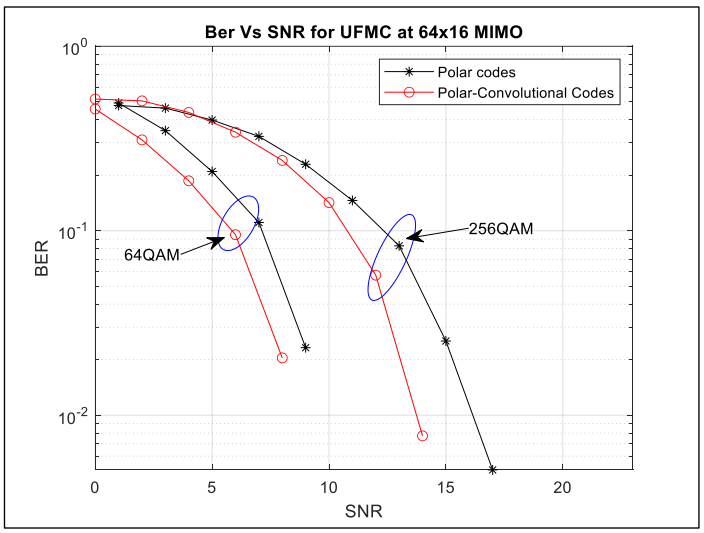

Figure 12: BER performance of joint convolutional and polar coded UFMC system with variable QAM order
Source: Authors, (2025).

VI. CONCLUSIONS

This paper analyzes the parametric performance of a massive MIMO-based system with Convolutional and Polar codes in UFMC waveform for URLLC use case with short block transmission. The system with different MIMO antenna array size and their impact on the BER is being considered for 5G systems. The Convolutional codes provide the SNR gain of 4dB as compared to the uncoded UFMC signal. Channel coding and its integration with UFMC provide flexibility in selecting the filter characteristics and sub-band size.

UFMC and Polar codes provide flexibility with better error rate performance to be compatible with mission-critical applications in 5G. Simulation results conclude that keeping CRC length to 24, the smaller sub-band size, the higher sidelobe attenuation, and the larger antenna array size will fulfill Ultra reliability. The short block provides ultra-low latency, and polar coding and UFMC are the most promising techniques compatible with short-burst communications. Additionally, the concatenation of convolutional and polar codes enhances BER performance.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Smita Prajapati, Divya Jain, and Neha Kapil.
Methodology: Smita Prajapati, Divya Jain.
Investigation: Smita Prajapati
Discussion of results: Smita Prajapati, Neha Kapil.
Writing – Original Draft: Smita Prajapati
Writing – Review and Editing: Smita Prajapati and Divya Jain.
Approval of the final text: Smita Prajapati, Divya Jain, and Neha Kapil

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A LOGISTICS 5.0 MATURITY MODEL: A HUMAN-CENTRIC AND SUSTAINABLE APPROACH FOR THE SUPPLY CHAIN OF THE FUTURE

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ABSTRACT

Logistics 5.0 represents a transformative advancement by integrating advanced technologies such as artificial intelligence, machine learning and blockchain with a human-centric and sustainability-focused approach. Unlike Logistics 4.0, which prioritized automation and digitalization, the new approach emphasizes collaboration between humans and machines to create more efficient and resilient supply chains. Maturity models specific to this emerging phase are crucial to assess technological readiness, human-machine integration capabilities and commitment to sustainable practices. The application of technologies such as autonomous vehicles, predictive algorithms and collaborative robots optimize processes, reduce errors and minimize environmental impacts, aligning with global sustainability goals. In addition, green logistics practices, such as the use of renewable energy and the circular economy, are essential to reduce companies' carbon footprint. However, the transition to Logistics 5.0 faces significant challenges, including the need for investment in infrastructure, employee training and overcoming cultural barriers. Yet companies that adopt this approach not only increase their competitiveness, but also contribute to a more sustainable and resilient economy, positioning themselves ahead in a dynamic, innovation-driven global market.

I. INTRODUCTION

Technological evolution, marked by the transition from Industry 4.0 to Industry 5.0, has promoted significant changes in the logistics sector. While Industry 4.0 focused on the automation and digitalization of processes through the Internet of Things (IoT), robotics, and artificial intelligence (AI), Logistics 5.0 introduces a more humanized approach, emphasizing collaboration between humans and machines to create more efficient and personalized processes [1].

eIn this context, [2] state that Logistics 5.0 emerges as a response to the needs of an increasingly dynamic and demanding market, promoting a deeper integration between human and technological capabilities.

Among the innovations arising from Logistics 5.0, advanced technologies such as blockchain, big data, and AI (or blockchain, big data, respectively) stand out to improve the transparency, efficiency, and sustainability of logistics operations. This new phase not only aims to improve the speed and accuracy of deliveries, but also seeks to reduce environmental impact and increase the resilience of the supply chain, especially in sectors such as electronics, where flexibility and responsiveness are essential [3]. Thus, the introduction of these technologies allows organizations to anticipate demands, optimize resources and improve customer service, creating a more efficient and adaptable value chain.

According to [4] indicate that the transition to Logistics 5.0 also brings considerable challenges, especially in terms of measuring maturity and adopting new technologies. One example pointed out by the author is that existing maturity models developed for Logistics 4.0 may not fully capture the specific nuances and needs of Logistics 5.0, such as the need for human-machine collaboration and the focus on sustainable practices.

In this sense, therefore, it is essential to develop new maturity models that can manage industries in assessing their readiness to adopt these advanced technologies and implement smarter and more sustainable logistics practices.

II. THEORETICAL REFERENCE

II.1 IMPACTS OF LOGISTICS 4.0 ON LOGISTICS 5.0

Logistics 5.0 represents a significant advance over previous approaches, integrating advanced technology with a strong emphasis on sustainability and human centrality. According to [5] explain that, unlike Logistics 4.0, which focused predominantly on the automation and digitalization of industrial processes, Logistics 5.0 places humans at the center of technological transformation, promoting a more harmonious collaboration between humans and machines. This type of approach is interpreted as a response to criticism that Logistics 4.0, by prioritizing efficiency and automation, has neglected important aspects of sustainability and human well-being. Therefore, [6] define that human centrality in Logistics 5.0 is facilitated by emerging technologies such as cyber-physical systems, collaborative artificial intelligence, and intelligent robots, which work in synergy with human operators to improve productivity and reduce physical workload. This integration of humans and machines not only increases operational efficiency, but can also improve safety and job satisfaction, creating a more inclusive and safe work environment.

It is also worth noting that sustainability is another fundamental pillar of Logistics 5.0. According to [7] explain in their study that the concept of green logistics is integrated into logistics processes to minimize environmental impact and promote more responsible business practices. Another study according to [8] also highlighted that the adoption of sustainable technologies, such as electric vehicles and the use of renewable energy in logistics operations, can significantly reduce the carbon footprint of companies and increase their long-term resilience [4].

Studying maturity models in Logistics 5.0 can be essential for several reasons, especially as organizations seek to improve their logistics operations in an environment that is becoming increasingly complex and technological Oran and Cezayirlioglu [9]. Therefore, maturity models for logistics 5.0 need to be adaptive and comprehensive, covering the various dimensions of digital and sustainable transformation. Certainly, one of their functions is to assess technological readiness, human-machine integration capacity and commitment to sustainable practices.

Namely, a recent study by [10] proposed a maturity model based on decision support systems that considers initial investments, return on investment, implementation complexity and exploitation as essential criteria for assessing the maturity level of companies in adopting logistics 5.0. This is because the transition to logistics 5.0 requires a well-defined strategic approach that incorporates big data analysis to predict trends and adjust operations in real time, thus increasing the flexibility and responsiveness of the supply chain [4]. To this end, the implementation of collaborative and human-centered practices can promote a more innovative and resilient work environment, capable of facing future challenges and adapting quickly to market changes.

II.2 INTEGRATION OF TECHNOLOGIES AND SUSTAINABILITY

Therefore, the application of advanced technologies in logistics 5.0 is not limited to automation and digitalization. Some tools play the role of a compass to provide greater transparency and security in the supply chain. According to [11] point out that the blockchain can facilitate product tracking and ensure compliance with environmental and safety standards. In addition, artificial intelligence and machine learning algorithms can also enable more effective predictive analysis, helping companies to optimize their logistics operations and reduce waste.

At the same time, other studies by [12] suggest that sustainability and logistics efficiency are greatly benefited by adopting a holistic approach that incorporates green technologies and sustainable practices from the beginning of the logistics planning process. Undoubtedly, one of the motivating factors in the implementation of green warehousing is social responsibility, while one of the biggest barriers was local laws and regulations. Therefore, [13] suggest that top management should be the main initiator of the implementation of green technologies in organizations.

Likewise, reducing waste through green management can improve the living conditions and productivity of employees, by the sustainable and human-centered standards of logistics 5.0. Strategically, [14] also state that the integration of technologies and sustainability not only adds value to the corporate image of companies, but also contributes to the creation of an adaptable logistics ecosystem, capable of responding to global crises and market fluctuations more effectively.According to [15] argue that blockchain is emerging as a disruptive technology in logistics 5.0, as it offers a new layer of transparency and security to supply chain operations. In the same sense, [16] point out that by providing an immutable and verifiable record of all transactions and movements of goods, blockchain helps to increase trust between business partners and reduce fraud and errors.

In the same vein, According to [17] state that blockchain technology enables greater administrative efficiency by eliminating the need for intermediaries and traditional auditing processes. Similarly, this can not only speed up logistics operations, but also reduce operational costs, providing a significant competitive advantage [18]. In this vein, research indicates that the interoperability of blockchain systems with other technologies, such as IoT and AI, can also expand the benefits of logistics 5.0, enabling more comprehensive automation and a faster response to unexpected events in the supply chain. However, for [4], the large-scale implementation of blockchain faces challenges, such as the need to standardize protocols and resistance to change on the part of the parties involved. This integration between possibilities can result in more resilient and adaptable operations, essential characteristics in an increasingly dynamic and unpredictable business environment, mainly adding value to Brazil.

II.3 AI AND MACHINE LEARNING (ML)

The transition to logistics 5.0 involves not only the adoption of new technologies, but also the integration of AI and machine learning (ML) to optimize processes and improve decision-making. For [19], these technologies allow logistics systems to be more responsive and adaptable, analyzing large volumes of data in real time to predict demands, optimize routes and manage inventories more effectively. In this context, maturity models become fundamental, as they help organizations identify their readiness to implement and take advantage of these advanced technologies.

Research by [20] indicates that AI and ML play roles in the transformation of logistics 5.0, providing new capabilities to automate and optimize complex logistics processes. Certainly, these technologies are fundamental to the creation of more intelligent logistics systems, which not only improve efficiency, but also the adaptability and resilience of the supply chain, for example. In the same vein, the application of AI and ML in logistics 5.0 enables a more predictive and data-driven approach,

essential for managing the growing complexity of global supply chains [21]. In this context, logistics 5.0 uses AI to analyze large volumes of data generated throughout the supply chain, helping companies identify patterns and trends that would be impossible to detect manually. For [22], for example, machine learning algorithms can accurately predict future demand based on a variety of factors, such as economic conditions, historical purchasing patterns, and even weather factors.

This predictive capability helps companies optimize their inventories and improve production planning, reducing costs and increasing customer satisfaction [23]. For [24] AI, in addition to enabling the automation of many logistics processes that traditionally required human intervention, its automated systems, such as autonomous vehicles and warehouse robots, are capable of operating 24 hours a day without rest, improving efficiency and reducing human error. For information, these systems are often integrated with AI platforms that continuously monitor their performance and make adjustments in real time to optimize operations [22].

In fact, [23] state that AI also contributes significantly to personalization and flexibility in the supply chain. In a logistics 5.0 environment, intelligent systems can quickly adapt to changes in market demands or disruptions in the supply chain, automatically adjusting production and logistics processes to minimize the impact. For [25], this flexibility is particularly important in a world where volatility and uncertainty are the norm, allowing companies to maintain business continuity amid unforeseen challenges. Another important aspect of the application of AI in logistics 5.0 highlighted by [26] is its ability to improve the sustainability of logistics operations.

Through route optimization and efficient resource management, AI algorithms can reduce fuel consumption and carbon emissions, helping companies meet sustainability goals. For example, AI-based systems can calculate the most efficient route for delivery vehicles in real time, taking into account factors such as traffic, weather, and road conditions, resulting in significant fuel savings and reduced emissions.

In addition, for [27], AI also facilitates the creation of safer and more efficient work environments. In warehouses and distribution centers, for example, AI-based computer vision systems are used to monitor activities and identify potential safety risks, such as obstructions or risky behavior by employees. These systems can automatically alert supervisors or take corrective action to prevent accidents, contributing to a safer work environment [28].

Concurrently, [29] state that machine learning, a subcategory of AI, is particularly useful in analyzing unstructured data such as product images, security camera videos, and customer feedback. Through techniques such as deep learning, companies can extract valuable information from this data to improve their logistics processes and customer experience. In this case, deep learning algorithms can be used to analyze product images to detect damage or inconsistencies before products are shipped to customers, thus reducing returns and improving customer satisfaction [30].

In addition to practical applications, [31] indicate that AI and machine learning also offer opportunities for continued innovation in Logistics 5.0, since by automating data collection and analysis, these technologies allow companies to experiment with new strategies and business models with minimized risk. In this regard, [32] explain that a company can use AI to simulate different supply chain scenarios and identify the most effective model before implementing it on a large scale. In theory, this not only saves time and resources, but also increases the company's agility and responsiveness to market changes.

According to [14] highlight that it is important to note that, although AI and machine learning offer many benefits for logistics 5.0, their successful implementation requires a significant investment in technological infrastructure and human skills. That is, companies must ensure that their employees are properly trained to work with these advanced technologies and that IT infrastructures are sufficiently robust to support the processing of large volumes of data in real time. Furthermore, [33] attest that companies must be prepared to deal with ethical and privacy issues associated with the use of AI, ensuring that customer data is protected and used responsibly. Therefore, it is essential that studying maturity models in logistics 5.0 is essential for the market to seek to evolve its logistics operations in a strategic and effective manner. It is in this sense that in [34] indicate that AI and machine learning in logistics 5.0 are intrinsic to the ways in which these technologies are shaping the future of the supply chain. By adopting these technologies, organizations can not only improve their efficiency and sustainability, but also better position themselves to face the challenges and seize the opportunities of an increasingly dynamic global market.

For [35], the application of these technologies (artificial intelligence (AI) and machine learning for lane detection and steering control in autonomous vehicles) provides greater precision and safety, crucial elements for both the development of autonomous vehicles and for Logistics 5.0.

It is also worth noting that the incorporation of computer vision techniques and high-resolution neural networks, such as HR-Net, mentioned by [35], can be applied in parallel in Logistics 5.0 to optimize processes and increase the resilience of logistics operations. HR-Net, for example, allows capturing details at different scales of resolution, which can be advantageous for real-time monitoring and optimization of complex logistics operations, such as inventory management and vehicle traffic analysis in warehouses. This level of detail improves the ability of neural networks to predict demands and dynamically adjust routes, responding to unexpected changes, such as adverse weather conditions or peaks in demand.

In addition, Logistics 5.0 can benefit from semantic segmentation techniques used for lane detection in autonomous vehicles, applying these methods to identify flows and patterns in supply chains. The ability to accurately segment and analyze logistics flows can reduce waste and optimize the use of resources, aligning with sustainability principles. These AI tools not only increase efficiency but also contribute to the personalization of logistics services, an important feature of Logistics 5.0, which seeks to integrate technological solutions focused on human well-being and sustainability.

Following the same reasoning, [36] state that by applying such technologies in a logistics context, the use of AI and machine learning for route prediction and process optimization is expected to promote a safer and more adaptable operational environment, essential to achieve higher levels of logistics maturity.

Therefore, the implementation of technologies such as HR-Net for segmentation and monitoring tasks can be a strategic differentiator, allowing logistics companies to quickly adapt to changes in the business environment, improving their responsiveness and resilience.

Therefore, the use of advanced AI techniques in logistics solutions can be a powerful tool for achieving higher logistics maturity, helping companies not only remain competitive but also

position themselves as leaders in a market that is increasingly driven by data and operational efficiency.

II.4 MATURITY MEASUREMENT TOOLS

Given the growing focus on sustainability and the adoption of green logistics practices, it is essential for companies to continually assess and monitor their progress on this journey. According to [1] explain that maturity measurement tools are essential in this context, as they allow organizations to identify their current level of adoption of sustainable and technological practices, in addition to providing a clear roadmap for continuous improvement.

By using these tools, organizations can systematically assess their processes and identify opportunities for improvement that not only drive operational efficiency but also strengthen their commitment to sustainability.

Thus, measuring logistics maturity not only helps integrate green practices into day-to-day operations, but also positions companies to become leaders in a market that is increasingly oriented towards environmental and social responsibility. In Logistics 5.0, maturity measurement tools are compasses for assessing companies' progress and readiness to adopt advanced technologies and sustainable practices. According to [37] state that these tools provide a structured framework that helps organizations understand their current level of technological integration, operational efficiency, and sustainability, and identify areas for future improvements. The use of well-defined maturity models is essential to guide digital transformation strategies and ensure that companies are prepared to face the challenges and seize the opportunities of Logistics 5.0 [38].

One of the most widely used maturity measurement tools is the digital maturity model (DMM). For [39], this model assesses a company's digital readiness in several dimensions, including the ability to integrate information and communication technologies (ICTs) into logistics processes, the effectiveness of using big data and analytics to optimize operations, and the ability to adopt artificial intelligence practices for automation and decision-making. Thus, according to [40], the DMM is structured into different levels of maturity, ranging from the initial stage of digitalization to full digital maturity, where the company uses advanced technologies in an integrated and strategic manner.

Another relevant model is the Sustainable Logistics Index (ILS). This index measures the adoption of sustainable practices in a company's supply chain and logistics operations, evaluating factors such as the use of renewable energy, resource consumption efficiency, waste management, and the implementation of green technologies, such as electric vehicles and recyclable packaging. SLI helps companies monitor and improve their environmental performance, ensuring compliance with environmental regulations and meeting the expectations of increasingly sustainability-conscious stakeholders [11].

According to [13] explain that the Industry 5.0 maturity model is a significant emerging tool focused on human-centricity. This model assesses how companies are incorporating aspects of human well-being and human-machine collaboration into their logistics operations. In addition to considering automation and digitalization, the Industry 5.0 maturity model also assesses the impact of these technologies on workers and society at large. This includes analyzing factors such as worker adaptation to new technologies, the impact of automation on employment, and initiatives to ensure safe and inclusive work environments [41].

As companies advance on their Industry 5.0 maturity journey, integrating aspects of human-centricity and human-machine collaboration, it is equally important for organizations to assess their progress against industry standards and competitors [42].

To this end, logistics benchmarking tools can be applied as an essential category in measuring maturity. These instruments allow companies to compare their logistics performance with that of other industry players, providing input to improve their operations and align them with best market practices.

Another essential aspect of logistics 5.0 is predictive simulation, which allows companies to test future scenarios and develop strategies to deal with possible dysfunctions in the supply chain. The goal is to predict challenges before they happen, as suggested by [43], who point out that these techniques use artificial intelligence and machine learning models to anticipate the impact of changes in market conditions, such as variations in demand or supply disruptions. By predicting these changes, companies can proactively adjust their operations, increasing the resilience and agility of the supply chain [44].

Thus, the ability to respond quickly to unforeseen events becomes a competitive advantage in the market in the era of logistics 5.0. Another important tool is the supply chain sustainability assessment (SCSA). According to [45] state that this tool is used to assess the environmental and social impact of the entire supply chain, from the acquisition of raw materials to final delivery to the consumer. The SCSA analyzes energy efficiency, carbon footprint, use of natural resources and waste management at all stages of the supply chain, helping companies identify critical points for improvement and develop strategies to reduce their environmental impact [46].

By considering the environmental and social impact of their operations, companies not only fulfill their sustainability responsibilities, but also identify areas for improvement that can lead to more efficient operations. However, as logistics 5.0 evolves, it is not enough to simply assess the impact; it is important to make decisions based on accurate and real-time data to quickly adapt to changes in the market and operational conditions. In this context, According to [47] share that AI-based decision support tools are becoming increasingly relevant, as they can enable managers to make more informed and effective decisions by using machine learning algorithms to analyze large volumes of data and identify patterns and trends that might not be evident through traditional methods.

In this sense, the integration of AI into decision support tools enables more accurate demand forecasting, optimization of logistics routes, and efficient allocation of resources, promoting operations that are not only sustainable, but also more economical and resilient [48].

In addition to promoting more efficient and sustainable operations, the use of AI in decision support tools highlights the importance of an integrated and collaborative approach in Logistics 5.0. However, for these technologies to reach their full potential, it is essential that all parties involved in the supply chain are aligned and connected.

In this regard, [21] point out that in this context, digital collaboration platforms play a substantial role, facilitating communication and coordination between different decision makers. These platforms not only allow the sharing of real-time information, such as demand forecasts and inventory availability, but also help to build more integrated and resilient supply chains, where collaboration becomes key to achieving common efficiency and sustainability goals [49].

This transparency and connectivity significantly improve supply chain efficiency, enabling rapid responses to market changes and contributing to more resilient and integrated chains [50]. However, for these supply chains to remain efficient and adaptable, it is equally strategic to address the risks that may arise throughout logistics operations. In this context, logistics risk management tools become indispensable. Using predictive models and big data analytics, these tools help identify, assess and mitigate potential risks, such as natural disasters, supplier failures or regulatory changes, ensuring that companies can develop effective contingency plans and reduce the impact of adverse events [51].

II.5 CHALLENGES AND OPPORTUNITIES OF LOGISTICS 5.0

The adoption of Logistics 5.0 brings significant challenges, including the need for substantial investment in technological infrastructure and the training of a skilled workforce to operate and maintain advanced technologies. Furthermore, the transition to more sustainable and human-centered practices requires a cultural shift within organizations, where innovation is seen not only as a means of increasing efficiency, but also as a path towards sustainable and inclusive development [52].

On the other hand, the opportunities offered by Logistics 5.0 are considerable. Companies that adopt this approach can not only improve their operational efficiency, but also strengthen their long-term resilience and their capacity to innovate. The integration of sustainable practices and advanced technologies can result in a significant competitive advantage, particularly in sectors where sustainability and social responsibility are increasingly valued by consumers and regulators [53].

III. MATERIALS AND METHODS

This research aimed to develop a maturity model for Logistics 5.0, based on a human-centered approach, with an emphasis on sustainability and human-technology integration. The methodology adopted included the definition of the universe and sample, the justification for the methods and procedures used, as well as the details of data processing, ensuring rigor and reproducibility.

The transition from Logistics 4.0 to 5.0 presents significant gaps, especially regarding the measurement of maturity in the context of human-machine integration and sustainable practices. Among the limitations faced, the scarcity of robust data on emerging practices and the difficulties of the participating companies in adapting to the research stand out. In addition, restricted access to financial indicators of sustainable impact limited the scope of the economic analyses.

The study universe included companies operating in strategic sectors for Logistics 5.0, such as manufacturing, technology and distribution. The sample consisted of 28 companies, selected based on criteria of sector relevance, economic size and previous experience with Logistics 4.0 technologies. Representativeness was ensured by the diversification of sectors and alignment with the research objectives. Data collection was carried out using a structured questionnaire, based on studies by [10] and [54], adjusted to the Brazilian context. The questions addressed essential dimensions such as automation, sustainable practices and human-machine integration.

Quantitative data, such as operational efficiency and use of emerging technologies, were supplemented with information extracted from reports provided by the companies. The methodological procedures were divided into three main stages: (1) Systematic review of the literature in databases such as Scopus and Web of Science to identify gaps and guide the development of the model; (2) Application of the structured questionnaire digitally via Google Forms, with validation of the responses by Cronbach's Alpha coefficient ($\alpha > 0.8$), ensuring consistency; and (3) Case study in five sample companies, with technical visits for direct observation and interviews with managers, providing an in-depth qualitative analysis.

The technical infrastructure used included statistical analysis software (SPSS 27.0), multicriteria modeling tools (DEMATEL), and videoconferencing platforms for remote interviews. Precise specifications of this equipment ensured the reliability of the data collected.

Data processing involved the development of a practical theoretical basis. The maturity model used equations derived from the DEMATEL methodology to identify causal relationships between maturity dimensions. The algorithm was implemented in Python and validated through sensitivity analysis. Standardized metrics, such as carbon footprint and delivery cycles, were used to ensure robust and comparable analysis.

Data were obtained from audited reports and reliable secondary sources, ensuring integrity. The methodology was carefully designed to be replicable, with sufficient detailing of materials and procedures. This rigor allows the application of the study in other contexts or sectors, contributing significantly to the advancement of Logistics 5.0.

IV. RESULTS AND DISCUSSIONS

The results of this research point to significant contributions to the understanding of Logistics 5.0, highlighting technological advances and practical limitations observed in the transition between logistics phases. The application of the proposed maturity model revealed that, of the 28 companies analyzed, 35% presented an intermediate level of maturity, 50% a basic level, and only 15% reached an advanced stage. These findings highlight the need for greater technological capacity and human-machine integration in the sector.

The companies that achieved the best performance stood out for adopting emerging technologies, such as artificial intelligence for demand forecasting and blockchain for supply chain traceability. In addition, green logistics practices, such as the use of electric vehicles and renewable energy, demonstrated a direct impact on reducing the carbon footprint, contributing to the achievement of environmental goals. However, most organizations still face challenges such as high implementation costs, cultural resistance, and gaps in team training.

The analyses using the DEMATEL methodology identified relevant causal relationships between dimensions of the maturity model, highlighting the central role of human-machine integration as a catalyst for advances in sustainability and operational efficiency. The validation of the algorithm in Python demonstrated accuracy in mapping interdependencies, contributing to the robustness of the model. From the perspective of the discussions, it is observed that Logistics 5.0 requires a balance between automation and human centrality.

Although technologies offer efficiency and agility, the human factor remains essential for adaptability and innovation. In addition, sustainability practices, when incorporated from the logistics planning stage, add both economic and social value to operations. Regarding limitations, the need for standardization of data provided by companies stands out, as well as challenges in measuring direct financial impacts associated with sustainability. Such issues reinforce the importance of future studies that explore

more precise metrics and complementary qualitative methods. Finally, the results obtained in this research provide practical guidelines for companies seeking to align themselves with the principles of Logistics 5.0. It is recommended that training programs be expanded and investments in technological infrastructure be made as fundamental steps for the sector's evolution. In addition, future studies could explore the impact of these practices on global supply chains, consolidating Logistics 5.0 as an essential pillar for more resilient and sustainable operations.

Table 1: Maturity Levels in Logistics 5.0 by company

Maturity Level	Key Characteristics	Percentage of Companies
Basic	Limited automation, low use of AI, little human-machine integration	50%
Intermediate	Moderate use of emerging technologies, early sustainability initiatives	35%
Advanced	High human-machine integration, consolidated sustainable practices, extensive use of AI	15%

Source: Authors, (2025).

Table 1 shows the results of this research, which show that the maturity of Logistics 5.0 in the companies analyzed still presents significant disparities, with the majority positioned at basic or intermediate levels, reflecting the need for greater investment in emerging technologies, team training, and human-machine integration. Organizations that have reached advanced levels have demonstrated that the adoption of sustainable practices, such as green logistics and the use of AI and blockchain, not only improves operational efficiency and resilience, but also contributes to reducing environmental impacts and meeting global sustainability goals. However, challenges such as high costs, cultural resistance, and lack of data standardization persist as barriers to the evolution of the sector.

This study reinforces the importance of well-structured strategies that align technological innovation with sustainability, highlighting human-machine integration as a critical factor in driving transformations in supply chains. It is therefore recommended that companies prioritize training, infrastructure and cultural change initiatives, in addition to fostering strategic partnerships that accelerate the transition to a more advanced, competitive and sustainable Logistics 5.0 model.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Nazaré Toyoda.
Methodology: Nazaré Toyoda.
Investigation: Nazaré Toyoda.
Discussion of results: Nazaré Toyoda.
Writing – Original Draft: Nazaré Toyoda.
Writing – Review and Editing: Nazaré Toyoda.
Supervision: Nazaré Toyoda.
Approval of the final text: Nazaré Toyoda.

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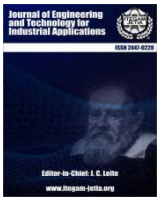

RESEARCH ARTICLE OPEN ACCESS

A MEASUREMENT MODEL OF LOGISTICS 5.0 MATURITY: AN INTEGRATIVE REVIEW AND FRAMEWORK PROPOSAL BASED ON LITERATURE

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ABSTRACT

This article explores Logistics 5.0 as an evolution of Industry 4.0, emphasizing the integration of emerging technologies such as artificial intelligence, IoT, and big data in logistics management. It proposes a specific maturity measurement model for Logistics 5.0, structured into five levels: initial, repeatable, defined, managed, and optimized, which evaluate technological readiness, process management, analytical capacity, change management, and sustainability. The analysis highlights gaps in traditional models, proposing dimensions adapted to the demands of digital transformation. The model emphasizes the harmonization between technology, people, and processes, pointing toward more efficient, adaptable, and sustainable logistics. It concludes that the practical application of the model can help companies enhance their competitiveness and sustainability in a dynamic global market.

Keywords: Logistics 5.0; Industry 4.0; logistics maturity; emerging technologies; sustainability.

I. INTRODUCTION

In recent years, Logistics 5.0 has emerged as a fundamental concept in the evolution of supply chains, incorporating significant advancements in technology and management strategies to meet the demands of an increasingly dynamic and interconnected global market. The transition from Industry 4.0 to Industry 5.0 is not merely an incremental shift but represents a qualitative leap in operational capabilities and the integration of new technologies, such as Artificial Intelligence (AI), the Internet of Things (IoT), and Big Data analytics, which are essential for fostering smarter, more resilient, and sustainable logistics operations [1].

According to [2], companies must remain competitive to ensure their long-term survival in the market and meet consumer needs. To achieve this, they must continuously adjust their operations to adapt to changes and maintain relevance in a competitive environment. These adjustments are required both in overall strategy and internal operations, focusing on how machine learning methods applied to predict atmospheric corrosion can be adapted and utilized in logistics to enhance operational efficiency and maturity.

The use of Machine Learning (ML) has shown promise in predicting complex phenomena such as atmospheric corrosion, a multifaceted problem involving various environmental factors [2]. In Logistics 5.0, this approach can be leveraged to optimize processes ranging from demand forecasting to predictive maintenance, thereby increasing the resilience and efficiency of operations.

For instance, ML techniques such as Neural Networks (NN), Support Vector Machines (SVM), and Regression Trees, which were used to predict steel mass loss due to corrosion with high accuracy (correlation coefficient $R^2 = 0.9814$ for NN) in the studies of [2], can be applied in logistics to predict equipment failures and optimize resource allocation. These techniques enable more precise asset management, which is essential for maintaining high levels of logistics maturity.

Similarly, just as in the atmospheric corrosion study, where sensors were used to collect environmental data across different stations, the use of IoT devices in logistics allows real-time monitoring of operational conditions. Sensors can be installed in vehicles, warehouses, and equipment to monitor critical variables such as temperature, humidity, and vibration. Applying ML algorithms to analyze this data makes it possible to predict undesirable events and perform preventive maintenance, reducing unexpected downtime and operational costs [2].

In the same vein, [3] suggest that the use of machine learning techniques, such as combining neural and semantic features to analyze online customer feedback, provides significant insights into the performance and quality of services delivered. In Logistics 5.0, these approaches can be employed to measure customer satisfaction in real time, identify critical areas requiring improvement, and offer actionable insights to optimize the supply chain.

Consequently, digitalization has become an inevitable factor for companies' survival, and this transformation depends on how digitalization is implemented across different sectors. Industry 4.0 is introduced as a crucial concept in this process, characterized by the integration of computing, automation, and machine-to-machine communication through the IoT and the use of real-time data.

Studies by [4] emphasize that maturity assessment is vital not only for diagnosing an organization's current level of competence but also for identifying the necessary steps to achieve higher levels of maturity and operational efficiency. Existing literature presents various maturity models, each emphasizing different aspects and dimensions of evaluation, reflecting the diversity of organizational contexts and needs [5],[6].

II. THEORETICAL REFERENCE

II.1 MATURITY MODELS IN LOGISTICS AND SUPPLY CHAIN MANAGEMENT

Maturity models are essential analytical tools for assessing an organization's digital readiness and ability to adopt new technologies and operational practices [7]. These models, often structured in progressive levels, reflect the sophistication and efficiency of organizational practices, enabling the identification of gaps and guiding development strategies.

According to [4], an effective maturity model should be tailored to sector-specific characteristics, incorporating best practices and innovative capabilities. On the other hand, [8] highlight that project-based learning can serve as a complementary methodology, fostering the development of competencies necessary for implementing and managing these technologies through real-world challenges and interdisciplinary collaboration. Thus, both maturity models and practical pedagogical approaches emphasize the importance of aligning organizational and educational processes with technological advancements to achieve sustainable competitiveness and innovation [9].

A classic example of a maturity model is the one proposed by [6], which developed a supply chain management process maturity model based on business process orientation. This model identifies five maturity levels, ranging from the initial level, where processes are ad hoc and non-standardized, to the optimized level, where processes are automated, adaptive, and fully integrated with information technology systems. The application of this model has shown that organizations with higher process maturity tend to perform better in terms of logistics efficiency and supply chain resilience [10].

Building on this definition by [5] introduced a logistics maturity model specifically designed for large industrial enterprises. This model highlights five maturity levels: initial, repeatable, defined, managed, and optimized. The research also indicates that companies at more advanced stages of logistics maturity tend to exhibit greater responsiveness to changes in the business environment, as well as higher operational efficiency and sustainability. The model underscores the importance of integrating sustainability practices into logistics processes, a factor that is becoming increasingly critical in the era of Logistics 5.0.

Moreover, models like the one proposed by [7] focus on developing supply chain management maturity through the integration of digital technologies and change management practices. This model is particularly relevant in the context of Logistics 5.0, as it addresses the need for a comprehensive digital transformation that encompasses all aspects of the supply chain, from production to distribution and customer service.

II.1.2 DIGITAL READINESS AND PERFORMANCE ASSESSMENT

Digital readiness is a critical component in assessing an organization's logistics maturity. For [1] developed a maturity model to evaluate the digital readiness of manufacturing companies, which can be adapted to the context of Logistics 5.0. This model includes dimensions such as technological infrastructure, analytical capability, change management, and organizational culture. Digital readiness is defined as an organization's ability to adopt and integrate digital technologies into its business processes, which is essential for the effective implementation of Logistics 5.0 [11].

According to [12] proposed a performance measurement framework for supply chains, which is highly relevant for assessing logistics maturity as it incorporates metrics of efficiency, effectiveness, and sustainability. This framework includes a range of key performance indicators (KPIs) that measure operational efficiency, service quality, and environmental sustainability-all critical aspects of Logistics 5.0 [12].

Performance assessment in logistics environments was also explored by [12], who developed a framework for analyzing supply chain performance evaluation models. This framework considers not only financial outcomes but also responsiveness, flexibility, and sustainability, reflecting a holistic approach to logistics performance assessment. These aspects are particularly relevant to Logistics 5.0, which emphasizes the integration of advanced technologies and adaptation to rapid changes in the business environment [13].

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II.1.4 MODELS FOR INDUSTRY 4.0 AND LOGISTICS 5.0

With the transition to Industry 5.0, new maturity models have been proposed to address the complexity and interconnection of advanced systems. According to [14] introduced SIMMI 4.0, a maturity model designed to classify the readiness of information technology and software in industrial environments. This model is particularly relevant to the context of Logistics 5.0, as it focuses on organizations' ability to integrate emerging technologies such as IoT, big data, and artificial intelligence into their logistics operations [14].

Moreover, the work of according to [15] emphasizes the impact of process maturity and uncertainty on supply chain performance. They argue that process maturity is directly linked to an organization's ability to adapt to changes and manage risks, aspects that are critical for the successful implementation of Logistics 5.0 [15].

II.2 PROPOSED MEASUREMENT MODEL FOR LOGISTICS 5.0 MATURITY

II.2.1 MODEL STRUCTURE

The proposed Logistics 5.0 maturity model is structured into five levels, capturing the evolution of technological and organizational capabilities of companies in the context of digital transformation. Each level represents a degree of sophistication in adopting advanced practices and technologies that are essential to achieving full Logistics 5.0 maturity. This model builds on traditional frameworks, such as those by [5] and [7], while incorporating new dimensions specific to contemporary logistics operations.

Initial Level

This level marks the starting point for many organizations operating with basic, often non-standardized, and non-automated logistics processes. Operations are conducted on an ad hoc basis, without the consistent use of advanced information systems. Companies at this stage face significant challenges, such as low operational efficiency and heavy reliance on manual processes, which can lead to errors and inefficiencies [4]. The lack of technological integration hinders their ability to collect and utilize data effectively, resulting in a reactive approach to logistics, where actions are primarily taken in response to emerging problems [5].

At this level, logistics is often perceived merely as a cost center rather than a strategic enabler. The absence of integration with other functional areas can result in information silos, limiting the organization’s ability to respond to customer demand changes or supply chain disruptions. To progress, companies must begin documenting processes and consider implementing basic technological solutions that enhance visibility and control over logistics operations [5].

Repeatable Level

At this second level of maturity, organizations start recognizing the importance of process standardization and documentation. Automation begins to be introduced, albeit limited to specific functions such as warehouse management or route optimization [10]. The focus is on reducing errors and improving operational accuracy through basic digital technology adoption. Logistics begins to evolve from a cost center to a more integrated function, with growing recognition of its strategic role in the supply chain.

Despite these improvements, companies at this stage often operate in silos, with minimal integration between functional areas. Investments in information systems and technology are typically reactive, addressing immediate needs. However, this level lays the foundation for broader automation and the adoption of more sophisticated logistics practices in higher maturity levels [16].

Defined Level

At this level, companies significantly expand automation to include critical logistics processes and begin exploring advanced technologies like RFID and data analytics for operations optimization. Logistics is now viewed as a strategic function focused on both efficiency and adding value to customers, thus driving competitive advantage [12]. Organizations at this stage have a clear understanding of their logistics processes and actively invest in technologies that enable greater visibility and control across the supply chain.

Emerging technologies are integrated with existing operations, enhancing flexibility and responsiveness. RFID implementation improves traceability and inventory accuracy, while data analytics supports demand forecasting and proactive operations optimization. This level marks a shift toward a proactive logistics approach, where companies anticipate changes and prepare for them [13].

Managed Level

Organizations reaching this level demonstrate a high degree of integration of emerging technologies, such as IoT and big data analytics, across the supply chain. Logistics operations are interconnected, efficient, and data-driven, enabling rapid and precise responses to market changes and disruptive events [14]. Supply chain management becomes predictive and proactive, utilizing advanced analytics to anticipate demand and adjust operations in real time.

At this stage, continuous information flow across all supply chain links facilitates more effective collaboration and informed decision-making. IoT implementation enables remote monitoring of asset conditions and performance, while big data analytics provides insights into market trends and customer behavior patterns. This predictive capability provides a significant competitive edge, particularly in highly volatile and competitive markets [15].

Optimized Level

At the highest maturity level, companies achieve fully autonomous and adaptive logistics operations, utilizing artificial intelligence and machine learning for continuous optimization and innovation. Organizations at this level can predict market changes and autonomously adjust operations, maximizing efficiency and minimizing costs. Logistics becomes seamlessly integrated with all organizational functions and external partners, creating a digitally

connected and collaborative supply chain capable of effectively responding to any market event or demand [17].

Additionally, companies at this level exhibit high resilience and adaptability to disruptive changes. Advanced technologies provide greater agility and flexibility, while predictive and prescriptive analytics form a robust foundation for strategic decision-making. Digital transformation is perceived as a strategic enabler driving continuous innovation and sustainable growth, helping companies maintain leadership positions in a competitive global market [1].

II.2.2 EVALUATION DIMENSIONS

The proposed Logistics 5.0 maturity model includes five evaluation dimensions that are fundamental in determining an organization's maturity level. Each dimension captures critical aspects of logistics transformation and the adoption of emerging technologies.

Technology and Innovation - This dimension assesses the level of adoption and integration of emerging technologies such as IoT, AI, big data, blockchain, and advanced robotics. An organization's ability to experiment with and implement new technologies is essential to achieving higher maturity levels. Technological innovation is a key driver of Logistics 5.0, enabling greater efficiency, accuracy, and adaptability in logistics operations [1]. Companies must invest in research and development to explore the potential of these technologies and tailor them to their specific needs.

Additionally, the technology and innovation dimension evaluates an organization's capability to scale its technological operations and seamlessly integrate new solutions with existing systems. This integration is crucial to avoid operational disruptions and maximize the benefits of new technologies. Continuous innovation and the adaptation of emerging technologies allow companies to enhance operational efficiency, respond swiftly to market changes, and maintain a competitive advantage [11].

Process Management - This dimension focuses on the standardization, automation, and efficiency of logistics processes. Organizations at higher maturity levels have well-defined processes that are continuously monitored to maximize efficiency and reduce costs. Effective process management is essential for Logistics 5.0, ensuring consistent and optimized operations that minimize waste and utilize resources efficiently [18].

Automation is a key component, enabling companies to shorten order cycles, improve inventory accuracy, and increase customer satisfaction. Process standardization also facilitates integration with external partners and collaboration across the supply chain, enabling faster and more coordinated responses to disruptions and changes in customer demands [19].

In the context of Logistics 5.0, process management evolves to incorporate emerging technologies that automate both repetitive and complex tasks, such as AI-based warehouse management systems for optimizing product storage and movement. Real-time data analytics enable continuous monitoring of operations, facilitating the detection of inefficiencies and the implementation of improvements. Thus, process management in Logistics 5.0 extends beyond automation to continuous data-driven optimization and rapid adaptability to business environment changes [20].

Analytical Capability - This dimension is critical in Logistics 5.0 as it involves the organization's ability to collect, analyze, and utilize data for decision-making. Organizations with high analytical maturity leverage real-time data to optimize operations, predict demands, and proactively adapt their strategies. This enhances operational efficiency and improves the organization's ability to respond swiftly to market changes and unexpected events [13].

The use of big data and advanced analytics enables Logistics 5.0 companies to identify customer behavior patterns, anticipate demand fluctuations, and adjust their operations accordingly. Predictive and prescriptive analytics empower organizations to make data-driven decisions, minimizing risks and maximizing market opportunities. In the Logistics 5.0 context, analytical capability serves as a crucial competitive differentiator, enabling greater agility and proactive operational strategies [8].

Change Management - Change management is a critical dimension for successfully implementing Logistics 5.0, as it encompasses an organization's ability to manage and adapt to technological and organizational changes. The transition to Logistics 5.0 often requires significant cultural shifts, business process adjustments, and workforce upskilling [21]. Effectively managing these changes is essential for the successful adoption of new technologies and logistics practices.

Change management also involves preparing the organization to handle uncertainties and challenges associated with new technology and process implementation. This can include training programs to develop employee competencies, clear and consistent communication about the benefits of changes, and fostering an organizational culture that values innovation and continuous improvement [22]. Organizations with strong change management capabilities are better positioned to seize opportunities offered by Logistics 5.0 while mitigating risks such as internal resistance and strategic misalignment.

Organizational Culture and Sustainability - This dimension examines the alignment of a company’s culture with sustainable practices and its readiness to innovate. In the context of Logistics 5.0, companies must foster a culture of innovation and sustainability that not only enhances efficiency but also contributes to long-term goals of social and environmental responsibility [23]. An organizational culture that promotes experimentation, collaboration, and continuous learning is essential for implementing advanced logistics practices successfully.

Companies that adopt a sustainable approach to logistics operations not only reduce their environmental impact but also improve their market reputation and strengthen stakeholder relationships. Logistics 5.0 provides numerous opportunities for implementing sustainable practices, such as optimizing routes to reduce carbon emissions, using recyclable packaging, and establishing reverse logistics processes [13]. Organizations with high maturity in this dimension integrate these sustainability principles across their logistics operations, promoting positive impacts for both the business and society.

II.2.3 APPLICATION OF THE MODEL

The proposed Logistics 5.0 maturity model can be applied through various methodologies, including internal self-assessments, external audits, and industry benchmarking. Applying the model enables companies to identify their strengths and weaknesses in logistics maturity, providing a foundation for developing targeted action plans to enhance their capabilities and achieve higher maturity levels [6].

Internal self-assessments are an effective approach for organizations to understand their current maturity state and identify priority areas for improvement. These assessments can be conducted using structured questionnaires and interviews with key stakeholders to collect data on the organization's processes, technologies, and cultural practices. On the other hand, external

audits can offer an unbiased and comparative perspective, helping companies identify gaps that may not be evident internally. These insights are crucial for developing robust improvement and transformation strategies [4].

Additionally, the use of industry benchmarks allows companies to compare their logistics maturity with that of competitors and industry leaders. This not only provides a better understanding of best practices but also motivates the organization to achieve higher performance standards. Combining these methodologies offers a comprehensive approach to applying the maturity model, ensuring that companies can assess their capabilities holistically and develop effective strategies to progress toward full Logistics 5.0 maturity [11].

In practical terms, applying the model can be accompanied by the use of both quantitative and qualitative metrics to provide a more detailed and accurate assessment of logistics maturity. Quantitative metrics, such as order cycle time, inventory accuracy, and logistics costs as a percentage of sales, provide an objective measure of logistics performance. Conversely, qualitative metrics, such as adaptability to change, efficiency of internal and external communication, and the degree of technological integration, offer a more holistic view of organizational capabilities. Together, these metrics enable a comprehensive evaluation of an organization's logistics maturity and facilitate the identification of specific areas for improvement [12].

In summary, the proposed Logistics 5.0 maturity model provides a robust tool for organizations to assess and enhance their logistics capabilities in a rapidly changing business environment. By integrating critical dimensions of technology, processes, analytical capability, change management, and organizational culture, the model delivers a comprehensive framework for achieving operational excellence and continuous innovation in the digital era.

III. MATERIALS AND METHODS

This research aims to propose a maturity model for Logistics 5.0, grounded in an integrative literature review. This methodological approach was chosen for its ability to synthesize and integrate the most relevant theoretical advancements on the subject, considering the complexity of contemporary demands related to digitalization, sustainability, and logistics innovation. By developing an updated maturity model, the study seeks to address gaps identified in traditional models and provide a practical and theoretical tool for organizations aiming to improve their logistics operations.

1. Methodological Approach and Justification

The integrative review combines evidence from various studies, offering a comprehensive and critical view of the state of the art in Logistics 5.0. According to Mendes and Silveira, this approach is particularly useful in emerging research areas, enabling the construction of conceptual models based on robust theoretical foundations. The choice of this method is also justified by the need to map and integrate dimensions still underexplored in traditional logistics maturity models, such as the integration of emerging technologies and sustainability in supply chains.

The research is exploratory and descriptive, focusing on the documental analysis of academic and technical publications. A qualitative research method was adopted to interpret the collected data and identify the critical elements that compose the proposed model. This approach was grounded in rigorous selection and analysis criteria, as detailed below.

2. Data Collection

Data collection involved searching renowned academic databases such as Scopus, Web of Science, IEEE, and ScienceDirect. Keywords such as “Logistics 5.0,” “maturity models,” “IoT,” “artificial intelligence,” “logistics sustainability,” and “supply chain” were used. To ensure the relevance and timeliness of the analyzed material, studies published between 2012 and 2023 were prioritized. Additionally, widely cited foundational works, including the models by Lockamy III and McCormack (2004) and De Bruin et al. (2005), were included to contextualize and substantiate the development of the model.

Inclusion criteria considered studies that directly addressed topics such as logistics maturity, technological integration, data analysis, and sustainability. Conversely, publications lacking a clear description of methods or limited to purely conceptual analyses without practical propositions were excluded. This selection resulted in a corpus of 45 articles subjected to detailed critical analysis.

3. Universe and Sample Definition

The research universe encompassed theoretical and applied logistics maturity models across various industrial and technological contexts. The sample comprised studies with explicit criteria for evaluating logistics processes, integrating emerging technologies, and sustainability practices. Representativeness was ensured through the inclusion of high-impact and relevant publications in the field, such as indexed journal articles, book chapters, and technical reports from reputable organizations.

Ensuring sample representativeness was central to validating the findings. Study selection was guided by a systematic process that analyzed publication impact (citation index), journal quality (impact factor), and thematic alignment with the research objectives.

4. Data Processing and Analysis

Data processing was conducted in three main steps:

1. **Systematization of Existing Models:** Critical elements of existing maturity models were organized into thematic categories such as levels of automation, technological integration, change management, and sustainability.
2. **Comparative Analysis:** A comparative analysis was conducted between traditional models and the specific requirements of Logistics 5.0, focusing on identifying gaps such as the absence of dimensions related to artificial intelligence and IoT.
3. **Proposed Model Development:** Based on the collected data, a maturity model comprising five levels (Initial, Repeatable, Defined, Managed, Optimized) was developed. These levels were structured to reflect the evolution of technological and organizational capabilities required to meet Logistics 5.0 demands.

Qualitative tools such as NVivo software were used to support data coding and pattern identification. Additionally, tables and matrices were employed to compare critical elements of the reviewed models.

5. Model Development Criteria

The proposed model was founded on dimensions considered essential for logistics maturity in the digital era:

- **Technology and Innovation:** Evaluates the adoption and integration of emerging technologies such as IoT, artificial intelligence, and blockchain.

- **Process Management:** Focuses on the standardization, automation, and efficiency of logistics processes.
- **Analytical Capability:** Measures the organization's ability to collect and interpret data for strategic decision-making.
- **Change Management:** Involves the capacity to adapt to organizational and technological transformations.
- **Organizational Culture and Sustainability:** Examines the alignment of company culture with sustainable and innovative practices.

Each dimension was detailed based on specific indicators validated through literature analysis.

The proposed model innovates by incorporating dimensions underexplored in traditional models, such as real-time analytics, advanced technology adoption, and integrating sustainable practices. Furthermore, the five-level structure allows for scalable assessment tailored to different organizational contexts, from small businesses to large corporations.

This approach aligns with contemporary challenges faced by organizations, such as meeting dynamic market demands and integrating principles of socio-environmental responsibility into operations.

6. Materials and Specifications

Technical materials include detailed specifications of the analyzed technologies and methods, such as requirements for IoT implementation, machine learning algorithms, and big data analysis tools. Quantities necessary for simulations and criteria for the model's empirical validation were also described.

The study emphasizes the importance of adapting the model to the specific conditions of each organization, considering factors such as current maturity level, existing technological infrastructure, and investment capacity in innovation.

The primary limitations include the absence of empirical validation, as the model was not applied in practical case studies due to the exploratory nature of the research. However, this limitation is addressed through recommendations for future applications in real-world settings, such as manufacturing industries and global distribution networks.

The methodology employed ensures the robustness of the proposed model, allowing it to be replicated and adapted to different organizational contexts. The methodological approach combined academic rigor and practical relevance, providing a solid foundation for companies to evaluate and improve their logistics capabilities in a rapidly transforming business environment.

IV. RESULTS AND DISCUSSIONS

The proposed Logistics 5.0 maturity model offers a significant contribution to the supply chain management and logistics literature by providing a comprehensive and integrated view of the capabilities required to achieve an advanced level of logistics maturity. Compared to traditional models, the proposed model for Logistics 5.0 emphasizes the integration of advanced technologies and the adaptability of logistics operations in a dynamic and interconnected environment.

The importance of maturity models in the context of Logistics 5.0 lies in the necessity for companies to adapt rapidly to technological and market changes. The model not only provides a framework for assessing an organization's current maturity level but also serves as a strategic guide to achieving higher levels of logistics performance and efficiency. Companies utilizing this model can identify gaps in their capabilities and develop strategies to integrate emerging technologies more effectively, fostering a more resilient and sustainable supply chain [4].

Moreover, the proposed model accounts for the growing importance of sustainability in logistics operations. As companies face increasing pressure to reduce their environmental impact and improve their social responsibility, the model includes criteria for evaluating the sustainability of logistics practices. This is particularly relevant in the era of Logistics 5.0, where digital technologies enable more efficient operations and offer new opportunities for implementing sustainable practices, such as waste reduction and resource optimization [12].

A comparative analysis of the different maturity models discussed in the literature reveals several gaps that the proposed model aims to address. For instance, while traditional models such as those by Saleh, Ghazali, and Rana [24] provide a solid foundation for assessing logistics maturity, they do not fully address the integration of emerging technologies and the need for agile supply chain management. The proposed model, on the other hand, incorporates these dimensions, offering a more holistic perspective tailored to the needs of modern logistics operations.

Finally, the proposed model also emphasizes the importance of change management and organizational culture as critical factors for the successful implementation of Logistics 5.0. As demonstrated by Casino, Dasaklis, and Patsakis [9], an organization's ability to manage change and adapt its culture to new technological demands is essential for achieving high maturity levels. The Logistics 5.0 maturity model incorporates this dimension, recognizing that digital transformation is not just about technology but also about people and processes.

Table 1: Distribution of Logistics 5.0 Maturity Levels Across Key Dimensions.

Dimension	Beginner Level	Intermediate Level	Advanced Level
Sustainability	50%	30%	20%
Automation	40%	40%	20%
Human-Machine Integration	30%	50%	20%

Source: Author, (2024).

The Table 1 illustrates the distribution of Logistics 5.0 maturity levels across three dimensions: Sustainability, Automation, and Human-Machine Integration, highlighting beginner, intermediate, and advanced adoption percentages within organizations.

V. CONCLUSIONS

In conclusion, the importance of a specific maturity model for Logistics 5.0, tailored to the new technological and organizational demands characterizing the modern logistics environment, becomes evident. By integrating dimensions such as change management, analytical capability, automation, and organizational culture, the proposed model offers a holistic and practical approach. It enables logistics organizations across different sectors to identify their current maturity level and develop clear strategies for advancement. Unlike traditional models, which primarily focus on static structures less connected to technological innovation, the Logistics 5.0 maturity model incorporates the dynamic market needs, such as the implementation of emerging technologies, data-driven optimization, and agility in responding to external changes [1]-[5].

Change management is highlighted as a crucial dimension, as the effective implementation of Logistics 5.0 practices and technologies depends on the organization's ability to adapt its processes and organizational culture. Resistance to change is one of the main challenges in digital transformation, and the model acknowledges that success in this journey requires a work environment that values innovation, continuous learning, and strategic alignment among teams [14],[21]. Preparing employees through training focused on the new competencies required and maintaining transparent internal communication about the benefits of technological transformations are fundamental elements to ensure that everyone in the organization is aligned with the objectives of change [7].

The analytical capability dimension is another key differentiator, as it emphasizes the use of data to support decision-making and adapt operations proactively. An organization's analytical maturity is reflected in its ability to collect and interpret real-time data, which optimizes resource use, predicts demand, and precisely adjusts strategies [6]. In Logistics 5.0, real-time data analysis facilitates continuous monitoring of operations, providing valuable insights for decision-making and making the supply chain more responsive and resilient [12]. Organizations that achieve high levels of analytical maturity are better positioned to respond to market changes and seize the opportunities offered by new technologies [16].

Automation, integrated into the proposed model, is also fundamental to Logistics 5.0. The use of technologies such as artificial intelligence, robotics, and the Internet of Things enables the automation of repetitive and complex tasks, improving accuracy, reducing cycle times, and minimizing errors [8],[18]. This automation helps organizations reach higher levels of operational efficiency, freeing employees for higher-value activities and enhancing market competitiveness. The standardization of processes, combined with automation, facilitates integration with external partners and strengthens the supply chain, enabling coordinated and agile responses to disruptive events [23].

Finally, the proposed model for Logistics 5.0 recognizes that success is not achieved solely by adopting new technologies but by harmonizing technology, people, and processes. Digital transformation requires an approach that values both technological development and the management of human competencies and organizational culture [11]. By incorporating these dimensions, the Logistics 5.0 maturity model proves to be a comprehensive tool for guiding companies in their journey toward logistics modernization, enabling them to develop more efficient, adaptable operations aligned with global market demands [3],[25].

In doing so, the model helps organizations maximize their competitive potential, optimize resources, and promote sustainability in an increasingly complex and interconnected business landscape. The practical application of this model can assist companies in strategically positioning themselves to seize the opportunities offered by digital transformation while minimizing risks and successfully addressing the challenges of Logistics 5.0 [21],[25].[26]

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Nazaré Toyoda.
Methodology: Nazaré Toyoda.
Investigation: Nazaré Toyoda.
Discussion of results: Nazaré Toyoda and **Carlos Manoel Taboada Rodriguez**.
Writing – Original Draft: Nazaré Toyoda.
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Supervision: Nazaré Toyoda.
Approval of the final text: Nazaré Toyoda and **Carlos Manoel Taboada Rodriguez**.

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RESEARCH ARTICLE OPEN ACCESS

PARAMETRIC STUDY OF THE THERMAL BEHAVIOR OF COLD METAL TRANSFER WELDING WITH TITANIUM

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ABSTRACT

This work focused on enhancing the efficiency of thermal behavior in the application of Cold Metal Transfer (CMT), especially for welding tough metals like titanium, has the potential to significantly impact the field of welding technology. The investigation of the thermal behavior of CMT welding, carried out by means of parametric analysis, was a crucial step in this direction. This research, carried out with the assistance of numerical simulations with COMSOL Multiphysics, particularly emphasized crucial factors such as plate thickness and welding power. The significance of this study in advancing our understanding of additive manufacturing in welding is highlighted by the findings of the study. These results, which illustrate the effects of the specified influencing parameters through temperature distribution at various time intervals, 2D and 3D graphs depicting temperature evolution along the welding path, and the 2D temperature profile at (t = 5s) across different plate thicknesses, have the potential to revolutionize the field of welding technology and bring about exciting new possibilities.

I. INTRODUCTION

The CMT manufacturing process is a complex and intricate process that significantly influences the quality of the additively made component. This involves a complex interplay of multi-physical and transdisciplinary phenomena, necessitating a comprehensive study to fully comprehend the physics and material science at the core of this technology and to achieve meticulous control over the production process.

A variety of physical processes, such as heat transfer from the arc to the electrode wire, wire electrode melting, droplet formation, droplet deposition onto the substrate, and bead cooling and solidification, are at play and influence the entire process. Each of these procedures can significantly affect the performance and dimensional accuracy of the final product. It's important to note that numerous technical factors govern these operations, and several comprehensive studies have been conducted to investigate how these technological factors impact the geometry, surface morphology, and mechanical properties of additively fabricated products. The thoroughness of these studies reassures us about the reliability of the findings.

The mechanical properties of the cladding material are significantly impacted by the heat exchange that takes place both during and after the deposit process [1–3]. Research has revealed that CMT cladding provides a substantial advantage over conventional techniques. This advantage is performed by the utilization of lower processing temperatures, which ultimately leads to less thermal impacts on the materials that are being treated [4],[5]. When it comes to cladding, it's a matter of concern that it is vulnerable to oxidation when it is exposed to high temperatures. However, it has been confirmed that CMT cladding may be utilized to clad a variety of substrates, including cobalt [6],[7], nickel [8–11], aluminum [12],[13], and steel-based alloys [14].

With advancements in welding research, computational modeling techniques have become more effective for analyzing laser welding behavior [15]. The categorization of the simulation models for laser welding allows us to understand the aspects of the welding process [16]. The first one covers thermo-mechanical and thermo-metallurgical studies, while the second one outlines studies

that combine fluid dynamics with energy transfer. Convective heat transfer is not included in this model since fluid dynamics are not a part of it. Fixing this restriction could be as simple as changing the heat source or the material's conductivity.

A volumetric heat source is mostly used since, during the material joining process, it is situated in the keyhole where the laser-material interaction transpires and the weld pool is generated. So, instead of being at the front, the two-dimensional elements are in the back, which allows us to model the laser beam's path from front to back and show the melt pool's shape.[17] provide a quick way to change heat source model parameters to mimic Cold Metal Transfer (CMT) welded joint temperatures and distortions.

The approach uses RSM and FEM. A 3D elastic-plastic FEM model represents mechanical behaviour, whereas a 3D transient FEM model with a Goldak heat flux simulates thermal behaviour. Design of Experiments (DoE) simulations alter heat source settings for FEM models. The data are utilised to create temperature and distortion polynomial regression models. RSM automates pre- and post-processes and replaces trial and error to discover the ideal settings, reducing engineering time.

Cold Metal Transfer (CMT) is a variant of Gas Metal Arc Welding (GMAW) where molten metal is transferred to the weld pool primarily during the short-circuit phase, with the wire being retracted to allow precise, spatter-free welds with lower energy input. To simulate this process, a model using the Smoothed Particle Hydrodynamics (SPH) method was developed [18], addressing mass and heat transfer. A simplified surrogate model served as the arc heat source.

The SPH-based welding simulation model, with its inclusion of surface effects, Joule heating of the wire, and electromagnetic forces, demonstrates a high level of precision and reliability, as evidenced by its good qualitative agreement with real experiments.

A thermal source model for Cold Metal Transfer (CMT) welding has been developed to simulate the dynamic temperature field of the welding pool [19]. The model’s predictions were validated by comparing the thermal cycle curve of 16Mn steel surfacing welding with experimental measurements using ANSYS finite element simulations. The results showed a significant agreement, confirming the model’s reliability and providing reassurance about its accuracy. This analysis helps simplify CMT welding experiments and optimize process parameters.

Thermo-mechanical simulations, considering phase changes and the actual weld geometry induced by the filler material, were conducted using an equivalent heat source approach [20]. A unique heat exchange coefficient, accounting for thermal losses, was identified. By incorporating these losses into thermal calculations, a good agreement was found between measured and calculated temperatures.

The thoroughness of the mechanical calculations allowed for the recovery of the horse saddle shape after actual welding, with a relative difference of less than 10% in angular distortion between calculated and measured values, instilling confidence in the model's ability to predict mechanical behavior.

In cold metal transfer welding, periodic and recurrent arcing and metal deposition are simulated using a heat source model [21]. This model will enable detailed analysis of weld pool behaviour and mechanical characteristics for this welding.

The suggested model uses a double-ellipsoidal heat source model, which depicts the heat source as two ellipsoids, one for the arc and one for the droplet, and makes geometrical and heat input parameters time-dependent. The CMT welding process was used to obtain dissimilar welded joints of a super-austenitic stainless (AL6XN) and a nickel-based super alloy (IN718) [22]. Microhardness, tensile and low cycle fatigue tests were carried out to determine the mechanical behavior of the welded joints. The main purpose of this work is to analyze the low cycle fatigue behavior of dissimilar welded joint as well as the heat input effect of the CMT welding process. A 3-D transient thermal conduction finite element model was developed to correlate the thermal history with the microstructural transformation on the HAZ. This model was experimentally validated by weld thermal cycles obtained from K-type thermocouples [20] simulate CMT welding of thin stainless-steel sheets to predict temperature fields and welding-induced deformations. Instrumented tests and numerical simulations were established to compare experiments and simulations. Butt-welding stainless-steel sheets 1 to 1.2 mm thick were proposed.

To establish an analogous heat source for each arrangement, weld seam samples were inspected. Electric current, voltage, and K-type thermocouples were also measured. Additional displacement measurements were made utilizing DIC (Digital Image Correlation). Then, thermomechanical simulations were performed using an equivalent heat source technique, taking into account element phase shifts from solid to liquid and liquid to solid. These models additionally incorporate filler-induced [23] evaluate CMT technology's history, variations, improvements, and prospects. The research begins by tracing the history of CMT welding and the introduction of many versions with different properties and uses.

Recent CMT process parameter optimization studies have improved weld quality and productivity, improving parameter control, arc stability, and wire feeding mechanisms. Research has also examined the microstructural development and mechanical characteristics of CMT welded joints for comparable and dissimilar metals, revealing material compatibility, joint design, and performance under different situations. CMT technique has been shown to be versatile in Laser-CMT hybrid welding, CMT cladding, CMT wire arc additive manufacturing, and CMT welding for repair across materials.

This study significantly enhances the understanding of the thermal processes involved in the CMT welding process on titanium for linear applications, a crucial area in the field of welding and materials science. Utilising COMSOL Multiphysics simulations, we examined the heat exchange during welding, with special emphasis on the motion and deformation of the metal droplet.

This enabled us to get significant insights into the thermal processes happening throughout the welding process. Furthermore, we analysed the influence of critical process factors, including workpiece thickness and applied electrical power, on temperature distribution and thermal dynamics. The simulations evaluated three workpiece thicknesses (2 mm and 5 mm) and three levels of applied electrical power (800W, 850W, and 900W).

The findings are displayed as temperature distribution at various time intervals, accompanied by 2D and 3D graphs that depict the temperature progression throughout the welding route. Additionally, we presented a comprehensive 2D temperature profile at a designated time (t=5s) across different plate thicknesses.

The present investigation enhances comprehension of the impact of process factors on the thermal field in linear welding, which is crucial for optimising welding parameters, mitigating faults, and improving the overall quality of the welded material.

II. NUMERICAL MODELING

II.1 WELDING OF METAL PLATE

The complete modeling of thermal processes involving electric arcs and molten pools is highly complex, requiring consideration of various factors like thermo-fluid heat transfers and electromagnetic phenomena. While extensive literature exists on modeling these aspects, our study simplifies by focusing solely on heat conduction. We replace the intricate details of the arc and molten pool with a simplified heat source. While this approach provides insights, it's important to acknowledge its limitations in accurately representing the system.

II.1.1 HYPOTHESES

To study and model heat transfers during a welding (Figure 1), hypotheses are required:

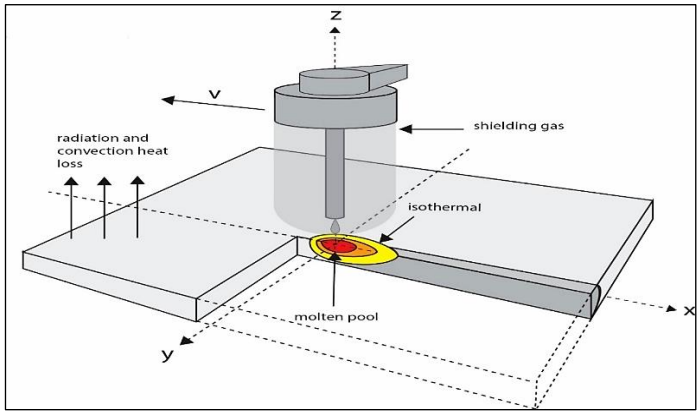

Figure 1: The welding process of two thin sheets.
Source: Authors, (2025).

1-The 3D axi-symmetric heat transfer problem (ABFE plane of symmetry),
2-Throughout the study, it is assumed that the heat source is moving. Al though complex paths of the source can be considered, we place ourselves in the case of a rectilinear translation at constant speed along an axis in Cartesian coordinates (case of plate welding).
3-The regime is considered Transitional,
4- The X axis coincides with the welding direction
5- The physical properties of the material are considered constant.
6-The flow in the weld pool and the electromagnetic phenomena (the forces of gravity (buoyancy), surface tensions (Marangoni forces), viscosity of the liquid metal, aerodynamic shear, electromagnetic forces (Lorentz forces)) are considered negligible.
7-Heat losses by convection and radiation through free surfaces and the boundaries of the room are taken into account.

II.1.2 HEAT GOVERNING EQUATION

The heat conduction equation in the domain Ω (domain defined by the two metal plates to weld) (Figure 1) is written for the three-dimensional case.

$$\rho c_p \frac{\partial(T)}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + S \qquad (1)$$

Where T is the temperature, t the time, ρ the density of the material to be welded, Cp the specific heat, K the thermal conductivity and S the heat generated or absorbed per unit of time.

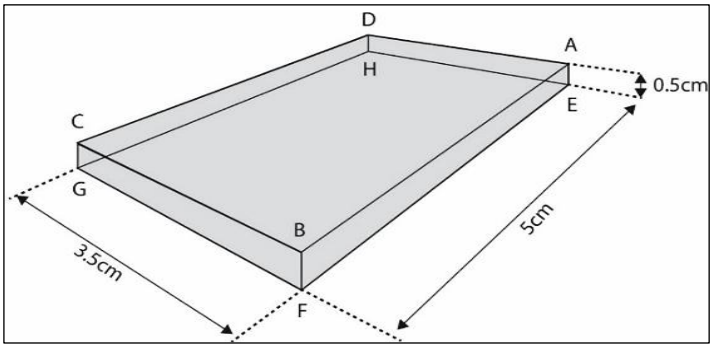

Figure 2: Ω domain and boundaries.
Source: Authors, (2025).

The general form of the equation above is:

$$\rho c_p \frac{\partial T}{\partial t} = -div\left(-K\overrightarrow{grad\,T}\right) + S \qquad (2)$$

The solution of this equation gives the temperature distribution in the domain Ω, that means the change in temperature with relative to the change in position and time.

II.1.3 BOUNDARY AND INITIAL CONDITIONS

The boundary conditions are determined from the equations of the heat flow exchanged with the surrounding environment by convection and radiation.
1) The energy given by the electric arc is modeled by a heat source S which is moves with a speed v along the x axis, this heat flux is q is transmitted to the plate through the upper face (ABCD).

$$q_n = S - [h_\infty(T - T_\infty) + \sigma\varepsilon(T^4 - T_\infty^4)] \qquad (3)$$

1) At the borders (ADHE), (DCGH), (BCGF) and (EFGH) (Figure 2), the flow qn is equal to:

$$q_n = h_\infty(T - T_\infty) + \sigma\varepsilon(T^4 - T_\infty^4) \qquad (4)$$

Were
h∞: convection coefficient.
T: temperature at the edge of the assembly (K).
T∞: ambient temperature (K).
ε: thermal emissivity.
σ: Boltzmann constant equal to $5.67.10^{-8} w/m^2K^4$.
1) In the symmetry plan (ABFE), the heat flow is zero:

$$q_n = -K\frac{\partial T}{\partial x} = 0 \qquad (5)$$

2) The initial temperature of the material is assumed equal to the ambient temperature.

II.1.4 FINAL EQUATIONS SYSTEM

We have the three following equations:

$$\rho\, c_p \frac{\partial(T)}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + S \qquad (6)$$

$$q_n = S - [h_\infty(T - T_\infty) + \sigma\varepsilon(T^4 - T_\infty^4)\,] \quad in\ (ADHE), (DCGH), (BCGF) and\ (EFGH) \qquad (7)$$

$$q_n = 0\ in\ (ABFE) \qquad (8)$$

The source term S will be modeled subsequently to close the system of equations. The equation the final differential is therefore a nonlinear partial differential equation.

II.1.5 HEAT SOURCE MODELS

In our study, the heat source model used is The Goldak Double-Ellipsoid Heat Source. Were the center point of the weld arc moves along the x axis, at a velocity v. Its current position is thus given by x0 = v.t. The heat source by Goldak is defined by two regions that join at x0, and whose shapes are ellipsoidal. The widths α and depths b of these regions are equal, but the front and rear lengths, c_f and c_r, may differ, see Figure 3. The heat source is given by:

$$q_v = \begin{cases} Q_m . e^{\left(-3\left[\frac{(x-x_0)^2}{c_f^2}+\frac{y^2}{a^2}+\frac{z^2}{b^2}\right]\right)} (x \geq x_0) \\ Q_m . e^{\left(-3\left[\frac{(x-x_0)^2}{c_r^2}+\frac{y^2}{a^2}+\frac{z^2}{b^2}\right]\right)} (x < x_0) \end{cases} \quad (9)$$

where Q_m as mentioned in chapter one is the power density of the weld, given by:

$$Q_m = \frac{6\sqrt{3}.Q_0 f_r}{c_r bc\pi\sqrt{\pi}} = \frac{6\sqrt{3}.Q_0 f_f}{c_f bc\pi\sqrt{\pi}} \quad (10)$$

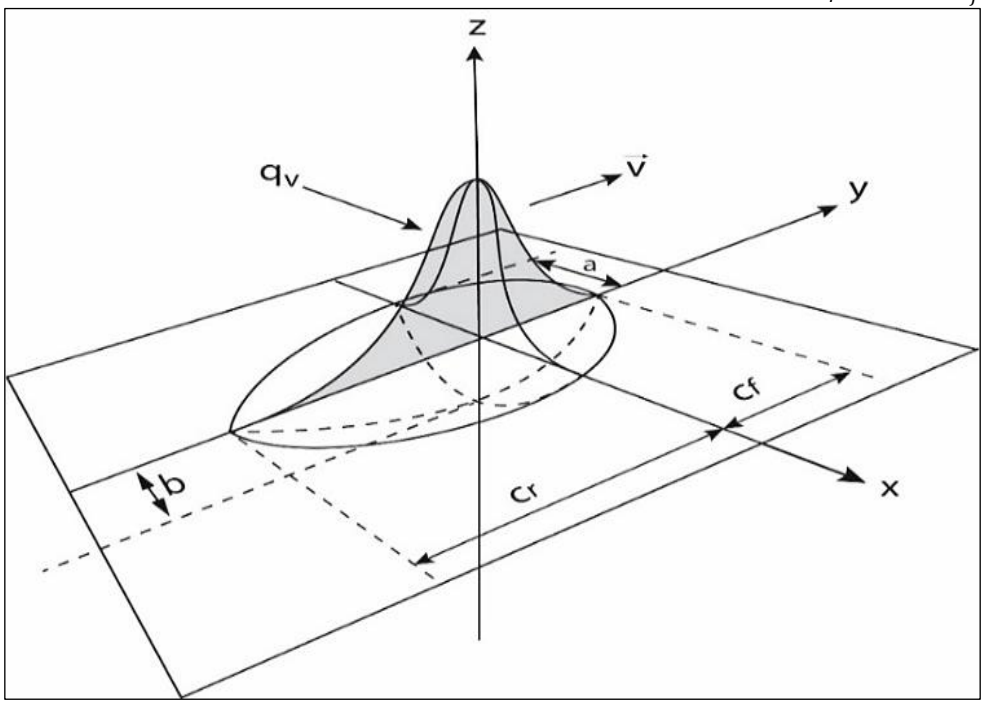

Figure 3: 3D double-ellipsoid heat sources.
Source: Authors, (2025).

II.1.6 PULSING EFFECT

The pulsing effect is the result of the automatic current cut each time a drop of melting feeding wire is in touch with the molten pool causing a short circuit, the modeling of this effect required the integration of a periodic function β into the moving heat source heat flux equation.

$$q(n)_{pulsed} = q(n).\beta \quad (11)$$

$$\text{Were} \quad \beta = rect1\left(mod\left(t[s], \frac{1}{f}\right)\right) \quad (12)$$

Were f is the frequency of the pulsing, rect1 is the COMSOL rectangular pulse function module and mod is the COMSOL command that create the repetition of the pulse every $(1/f)$ step in time t.

II.3 MATERIALS

The materials used in this simulation are the titanium grade one alloy, aluminum 1050 alloy and the ARMCO iron alloy. The thermal properties such as thermal conductivity, heat capacity, and materials density will be taken from the COMSOL material library.

II.4 PROPERTIES

All the properties needed are gathered in the Table 1.

Table 1: Simulation properties.

Symbol	Value	Description
Lx	0.05m	Plate length
L_y	0.035m	Plate width
L_z	0.005m /0.002m /0.008m	Plate thickness
Q_0	800W /850W /900W	Weld power
v	0.001m/s	Welding speed
A	0.004m	Goldak ellipsoid measurement
B	0.004m	Goldak ellipsoid depth
c_r	0.008m	Goldak ellipsoid length, rear
c_f	0.004m	Goldak ellipsoid, front
f_r	1.3333	Goldak parameter
f_f	0.66667	Goldak parameter
Ƒ	50Hz	Pulse frequency
ε	0.4	emissivity
h	10W/m².K	Convective heat transfer coefficient

Source: Authors, (2025).

III RESULTS AND DISCUSSIONS

III.1. WELDING OF METAL PLATE RESULTS

This simulation aimed to study the results of changing different parameters such as plate thickness, welding power and plate material on the temperature distribution and how its behave during CMT welding.

III.1.1 MESHING EFFECT

The more refined the mesh the more accurate the results with a smooth Gaussian curve transition of temperature value from a point to the next one indicating a mush realistic change in the temperature gradient. Based on that the extremely fine mesh is chosen with a 142669 tetrahedral element, 10312 triangular face and 360 edge elements (Figure 4).

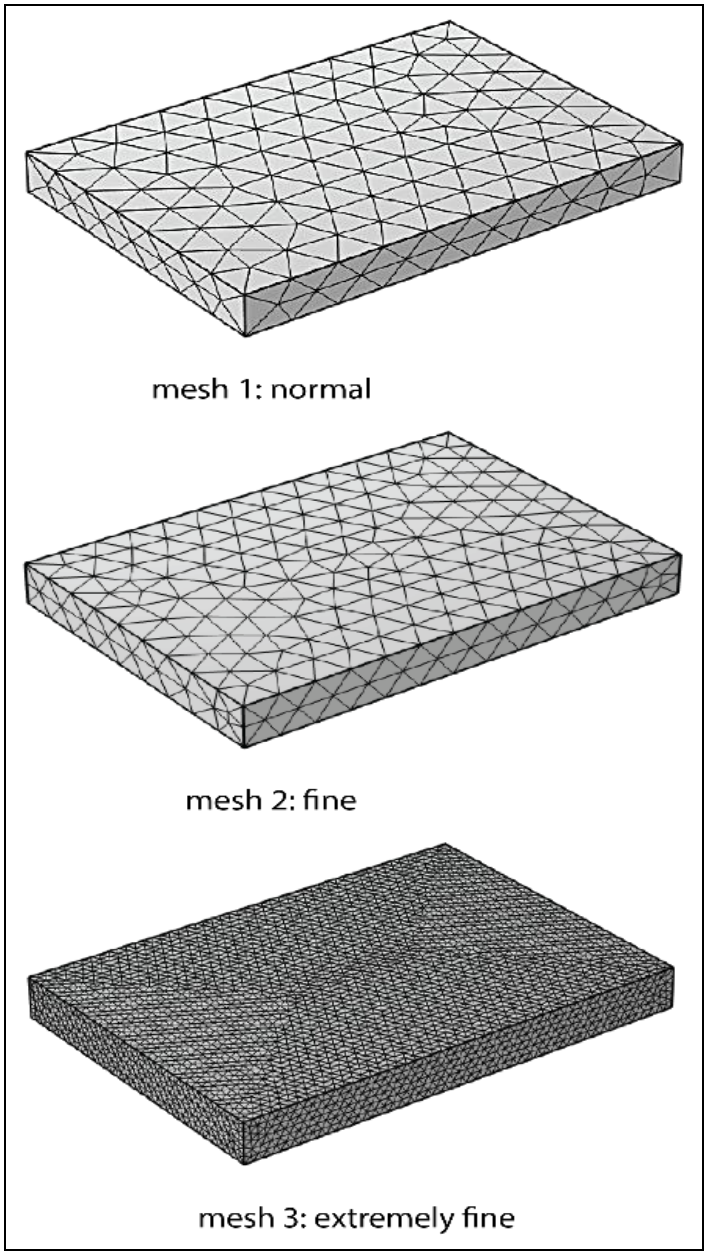

Figure 4: Different mesh types.
Source: Authors, (2025).

Figure 5 demonstrates the efficiency of more granulated meshes in temperature simulations. These meshes, while less detailed, are more cost-effective in terms of computational resources. On the other hand, finer meshes, while offering more precision, require a greater portion of computational resources.

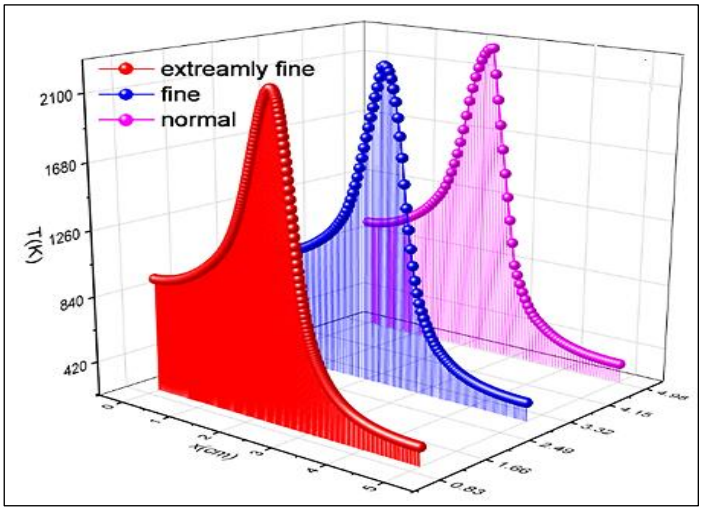

Figure 5: Temperature distribution for three mesh types.
Source: Authors, (2025).

III.1.2 INFLUENCE OF PLATE THICKNESS ON TEMPERATURE DISTRIBUTION

The temperature profile of a titanium plate subjected to a continuous 800W power input during welding is shown in Figure 6. At the beginning of the time steps, it shows the heat concentration in the welding zone, and as time goes on, it spreads, making a temperature gradient. Understanding the heat-affected zones and maintaining material integrity during welding are both aided by the dynamic variations in the temperature distribution.

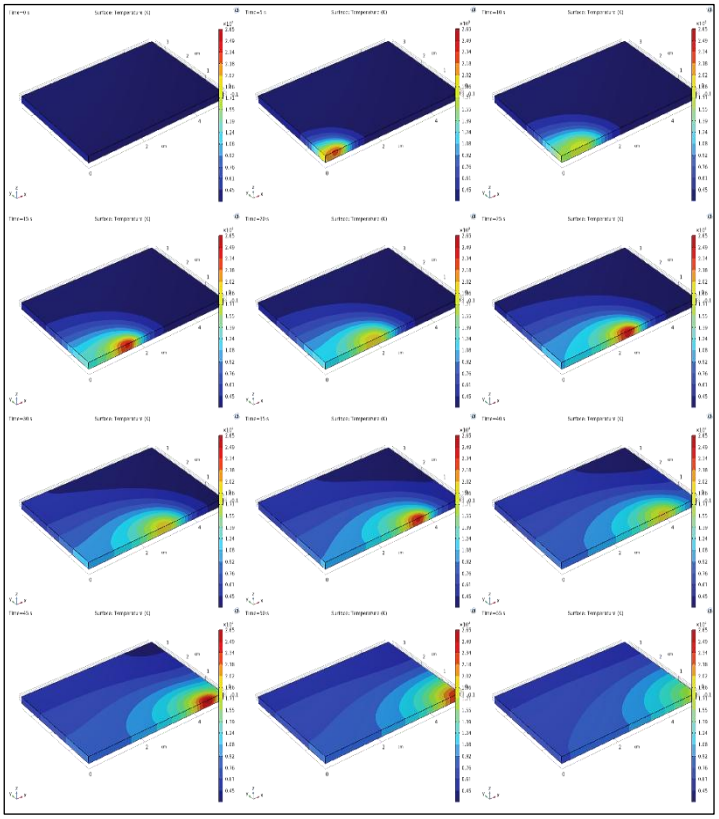

Figure 6: Temperature distribution in a 2mm height titanium plate in different time steps with 800W welding power.
Source: Authors, (2025).

Figure 7 depicts the temperature fluctuations along the titanium welding route over time. With a continuous 800W welding power, the 3D plot displays the surface and depth temperature distribution of the 2mm-thick plate. The welding process generates heat that propagates along the line, creating a shifting high-temperature zone. The x and y axes show the welding path's position on the surface and across the plate's thickness, while the z-axis displays the temperature at different time intervals. Time steps demonstrate how heat diffuses from the original weld location, forming a progressive heat-affected zone. High and low temperatures throughout the welding route are clearly visible in 3D.

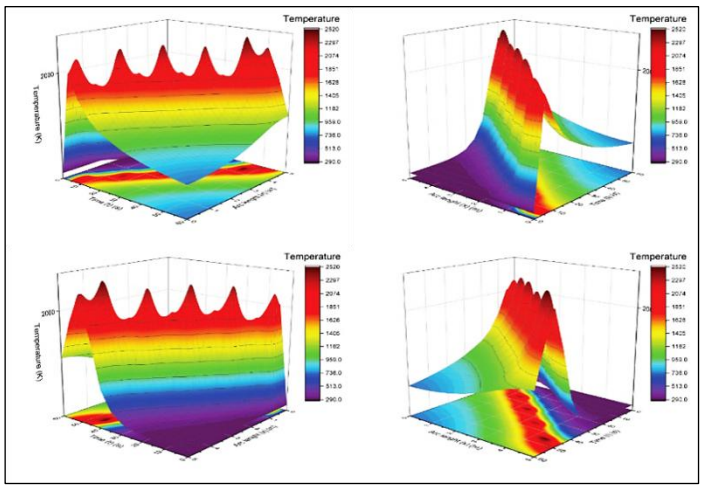

Figure 7: 3D graphic representation temperature evolution along the welding path at different time steps in a 2mm height titanium plate with 800W welding power.
Source: Authors, (2025).

Figure 8 presents a two-dimensional visualization of the temperature distribution along the welding path over time. The graph likely plots the temperature along the surface of the titanium plate at various time intervals, with the x-axis representing the position along the welding path and the y-axis showing the temperature at different points along that path. The welding power, under our precise control, is fixed at 800W, ensuring a consistent heat application. As the welding progresses, heat is applied to the plate, causing a temperature rise near the weld zone. As time progresses, the heat spreads from the centre of the weld, creating a temperature gradient that gradually decreases as the distance from the weld increases.

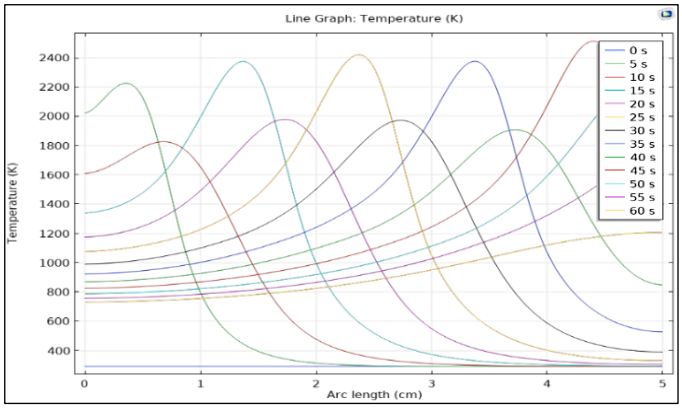

Figure 8: 2D graphic representation temperature evolution along the welding path at different time steps in a 2mm height titanium plate with 800W welding power.
Source: Authors, (2025).

The progression of temperature within a titanium plate with a thickness of 5 mm is depicted in Figure 9, which describes the welding process conducted with a constant power input of 800 watts. The temperature distribution is displayed across a number of time steps, which demonstrates how the heat that is created by the welding process travels through the material.

As a result of the focused heat that is applied by the welding arc, the temperature closest to the welding spot is at its greatest during the first step. With time, the heat will eventually travel throughout the plate, resulting in the formation of a thermal gradient that will expand away from the weld zone. Thermal conduction is the cause of this heat diffusion, which occurs when heat moves from regions with higher temperatures to areas with lower temperatures, resulting in the formation of a heat-affected zone (HAZ).

As a result of the plate's increased thickness (5mm) in comparison to thinner plates, the temperature gradient is likely to become more noticeable, with a more progressive fall in temperature further away from the weld. The titanium plate must be protected from heat deformation while still maintaining its structural integrity.

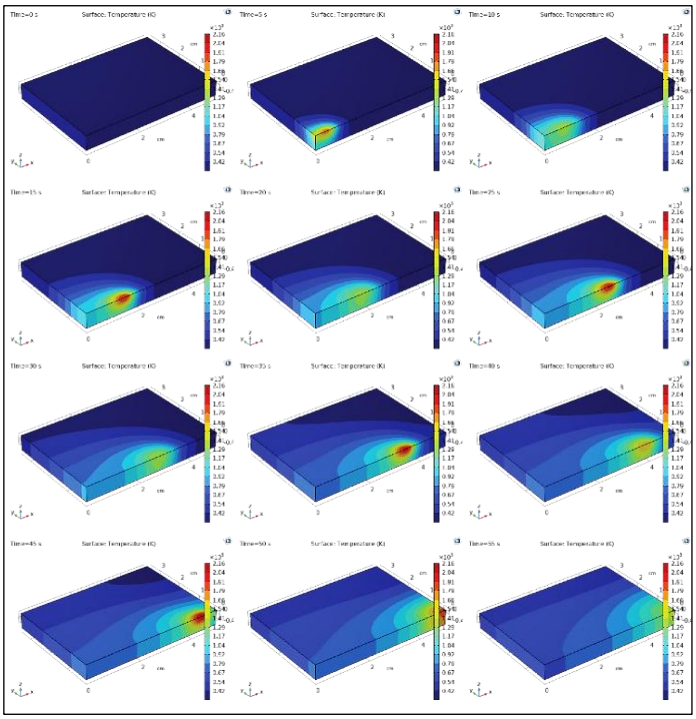

Figure 9: Temperature distribution in a 5mm height titanium plate in different time steps with 800W welding power.
Source: Authors, (2025).

Figure 10 shows the welding path temperature distribution over time in three dimensions. The z-axis shows temperature at different time steps, while the x and y axes presumably depict location along the surface and potentially across the depth of the 5mm-thick titanium plate. Since the welding power is 800W, the heat created by the welding arc first concentrates at the weld spot, raising the temperature sharply there.

Heat propagates throughout the plate's surface and thickness, forming a complicated thermal gradient over time. A growing heat-affected zone (HAZ) forms when heat diffuses through the plate, as seen in the picture. The 5mm thickness absorbs and transmits thermal energy. Thus, the vertical temperature gradient is greater, and the heat distribution is slower than with thinner plates.

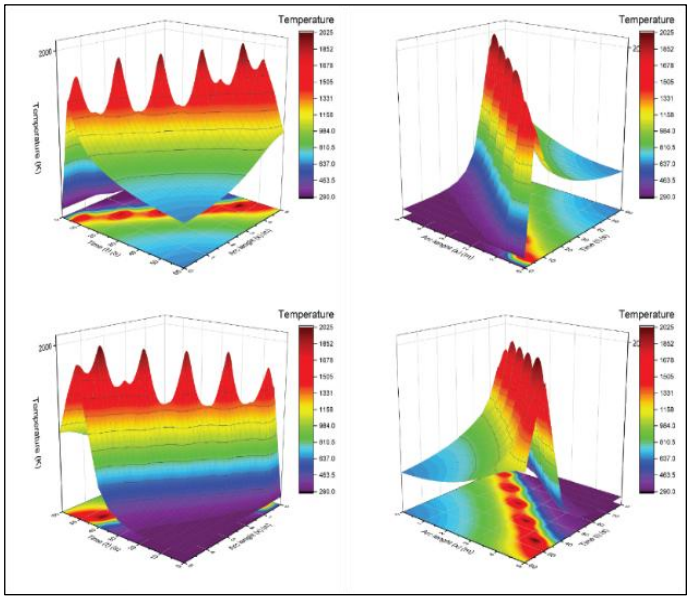

Figure 10: 3D graphic representation temperature evolution along the welding path at different time steps in a 5mm height titanium plate with 800W welding power.
Source: Authors, (2025).

Figure 11 depicts a 5mm-thick titanium plate's welding route temperature with time in two dimensions. When the welding power is 800W, the weld zone temperature is maximum due to the welding arc's focused heat. A thermal gradient, which is the rate of temperature change over a unit distance, forms when heat diffuses over the plate's surface and depth. Heat flows through the material, expanding the heat-affected zone (HAZ) and reducing the temperature as it goes away from the weld. Due to the plate's 5mm thickness, the temperature gradient would be greater and take longer to disperse.

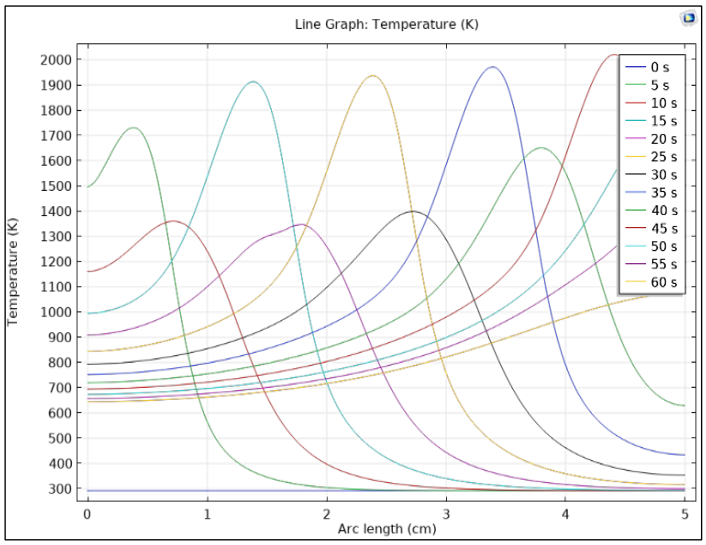

Figure 11: 2D graphic representation temperature evolution along the welding path at different time steps in a 5mm heigh titanium plate with 800W welding power.
Source: Authors, (2025).

Figure 12 illustrates how the modest temperature gradient on the 2 mm thick plate allows heat to swiftly diffuse, while the 5 mm and 8 mm thick plates present different challenges. The heat takes longer to permeate through the 5 mm thick plate, causing a greater temperature gradient and a higher heat effect. The 8 mm thick plate has a higher thermal barrier to heat diffusion, resulting in a more localized heat distribution and a deeper temperature gradient. This comparison underscores the critical role of plate thickness in heat propagation, HAZ size, and cooling rate. By adapting welding settings for various workpiece thicknesses, we can optimize material qualities, reduce overheating, and minimize plate distortions and stresses, offering a hopeful outlook for our work.

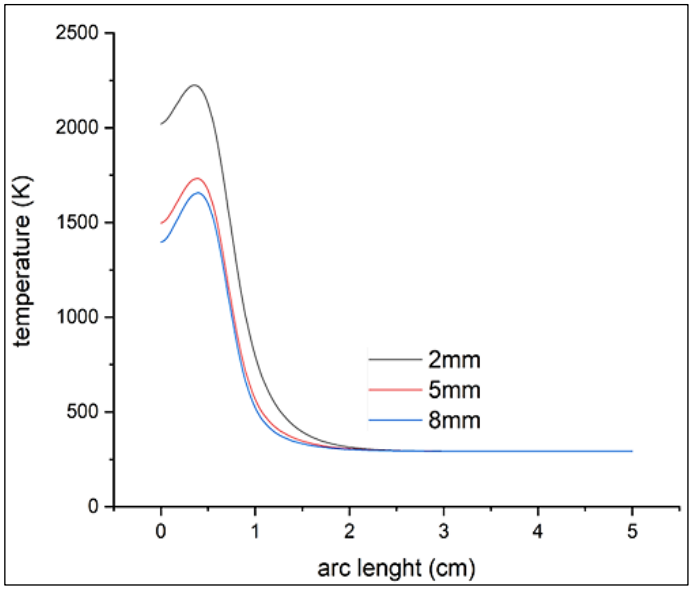

Figure 12: 2D graphic representation of temperature evolution along the welding path at t=5s in the different thickness plates.
Source: Authors, (2025).

III.1.2 INFLUENCE OF WELDING POWER ON

The simulations of temperature distribution show distinct differences at welding powers of 800 watts and 900 watts. Figure 13 illustrates the dynamic heat transfer that takes place throughout the welding process by showing the temperature distribution within the plate. First, there is a sharp concentration of heat at the weld zone, which raises the temperature quickly and locally.

There is a noticeable temperature gradient between the hot weld zone and the colder surrounding material because titanium's comparatively poor thermal conductivity prevents heat from spreading rapidly.

Due to the material's poor heat conductivity, the heat does not diffuse more uniformly throughout the plate. Therefore, this concentration of heat stays close to the weld for a long time. But as time goes on, the heat starts to permeate the material's depth as well as the plate's surface. Because titanium resists heat flow, this diffusion happens more slowly in the deeper areas of the plate, but it still occurs gradually over time.

The slow spread of heat creates a heat-affected zone (HAZ), which becomes larger as the welding process continues. The area where the material has seen a rise in temperature but has not melted is represented by the HAZ.

A larger HAZ is possible with a 5 mm thick plate because the heat is held in place longer than with thinner plates. This prolonged heat retention in thicker plates significantly impacts the welding process, as it leads to a more even and prolonged heating, potentially altering the material's hardness and microstructure in the heat-affected area.

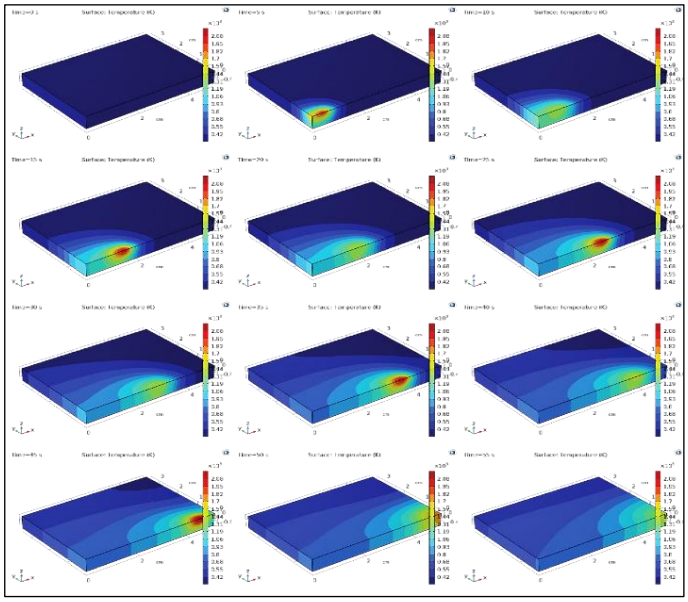

Figure 13: Temperature distribution in a 5mm height titanium plate in different time steps with 850W.
Source: Authors, (2025).

Figure 14 provides a 3D visualization of the temperature evolution along a 5mm thick titanium plate during welding with 850W power. It's a practical tool that allows us to see how heat is first concentrated in the weld zone, leading to a rapid temperature rise. The model also demonstrates how the poor thermal conductivity of titanium slows heat diffusion from the weld into the plate. As heat spreads, the HAZ expands, and the temperature drops from the weld spot. This practical visualization is crucial for optimizing welding conditions and managing material qualities, as it shows how the HAZ expands and how heat affects the plate's surface and interior.

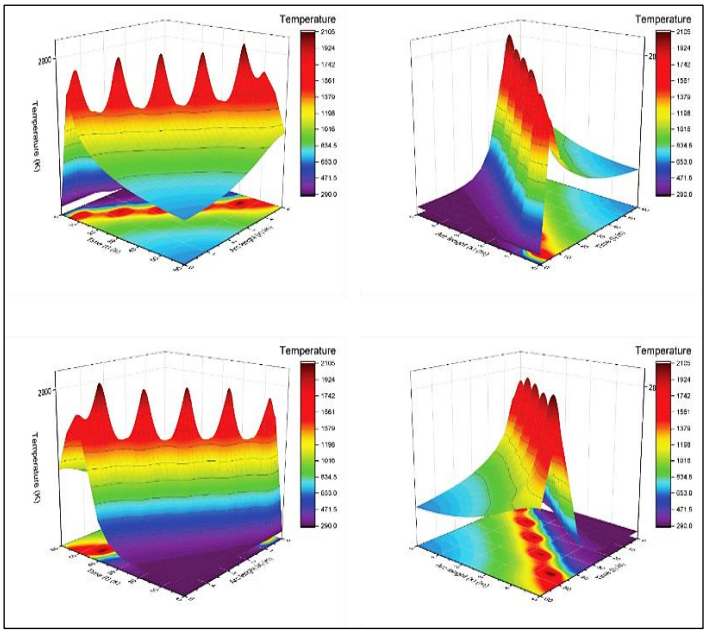

Figure 14: 3D graphic representation of temperature evolution along the welding path at different time steps in a 5mm height titanium plate with 850W welding power
Source: Authors, (2025).

Figure 15 shows the temperature distribution throughout a 5 mm-high titanium plate during welding at various time intervals. The key factor in this process is the 850W welding power, which uniformly raises the temperature. The heat from the welding source increases the temperature throughout the route, with the greatest temperatures around the weld bead centre. The graph represents the temperature gradient as heat drains from the weld zone over time. Direct heat input first raises the temperature around the welding area while the surrounding regions gradually cool. The time steps show how the thermal profile varies during welding, indicating the material's reaction to applied heat and plate conductive, convective, and radiative heat losses.

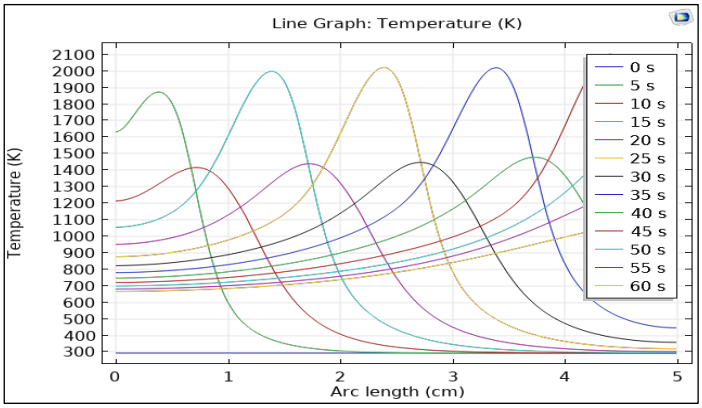

Figure 15: 2D graphic representation temperature evolution along the welding path at different time steps in a 5mm height titanium plate with 850W welding power.
Source: Authors, (2025).

Figure 16 shows the temperature distribution over a titanium plate that is 5 mm thick when welding at a power of 900W. Heat diffusion and the strength of the thermal gradient within the material are shown in the picture, which also illustrates the temperature's evolution over time.

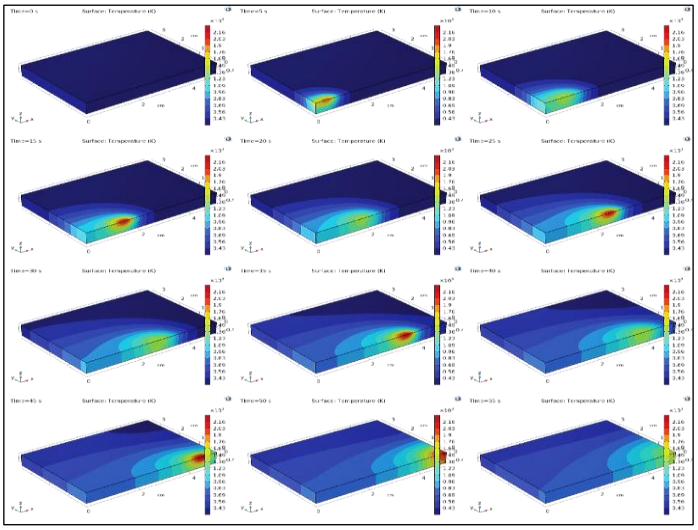

Figure 16: Temperature distribution in a 5mm height titanium plate in different time steps with 900W welding power.
Source: Authors, (2025).

In the first-time step, there is a strong temperature differential between the weld site and the colder areas outside it, and the heat is focused there. A more consistent temperature distribution is achieved as time goes on because the heat dissipates throughout the whole plate. Closer to the weld, however, the temperature stays higher, suggesting that heat is still escaping from the spot. The picture depicts many time steps, showing how the material cools down progressively as heat is transferred away

from the weld zone. An essential component in deciding the quality of the weld and avoiding thermal distortion or damage is the material's capacity to transmit and disperse heat; the overall distribution of temperatures reflects this. The 900W welding power indicates a rather high energy input.

Figure 17 shows the temperature change throughout the welding route in a 5 mm titanium plate exposed to 900W welding power at various time intervals. The highest point on the temperature curve, the welding spot, concentrates heat at the start of the welding process.

Heat diffuses down the plate's surface and depth over time, providing a thermal gradient that diminishes as it goes away from the welding path. Heat flow is dynamic, and the 3D graphic shows spatial and temporal temperature variations.

The temperature may be represented by colour intensity or surface height, with hotter areas near the weld and colder regions further away. Slowly flattening the temperature surface shows that the material is cooling and the welding operation has less thermal impact, which refers to the reduction in the heat's influence on the material.

This image shows how heat conduction, material qualities, and welding factors like power interact, making it essential for managing heat to achieve ideal weld quality without destroying the titanium plate.

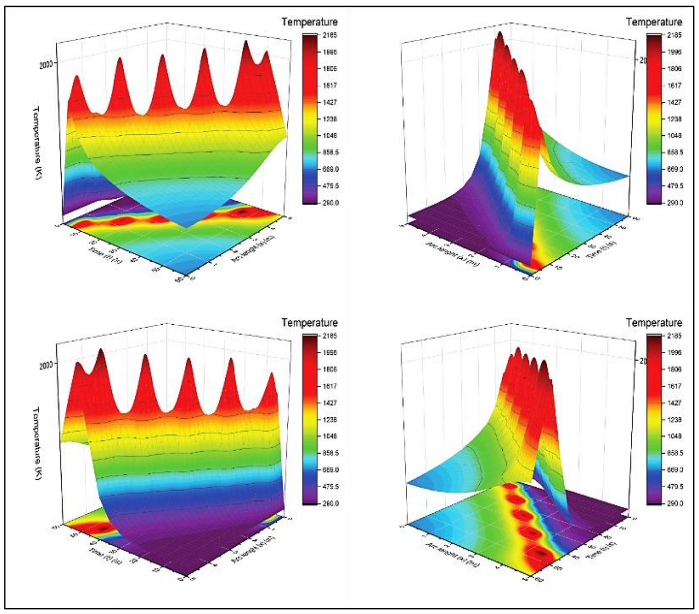

Figure 17: 3D graphic representation of temperature evolution along the welding path at different time steps in a 5mm height titanium plate with 900W welding power.
Source: Authors, (2025).

The temperature change across the welding route in a titanium plate that is 5 mm thick and exposed to 900W of welding power at different time intervals is shown in Figure 17. The greatest temperatures initially concentrated at the weld site correspond to the region where the heat is most intense, and the graph shows how the temperature fluctuates as the welding process proceeds.

Position along the welding line is probably represented by the x-axis, while the y-axis shows temperature. The weld zone is noticeably hotter than the surrounding material at early time steps, resulting in a sharp temperature gradient.

The heat, in a predictable and gradual manner, starts to disperse, and as the heat penetrates the material, the temperature profile along the welding route flattens. At subsequent time steps, the temperature is distributed more uniformly across the plate because the regions farthest from the weld zone cool more rapidly.

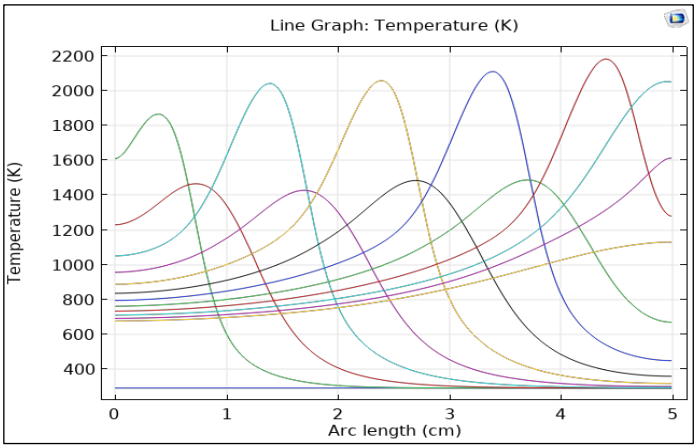

Figure 18: 2D graphic representation temperature evolution along the welding path at different time steps in a 5mm height titanium plate with 900W welding power.
Source: Authors, (2025).

Figure 19 shows volume displacement magnitude distribution within a 5 mm-thick titanium plate subjected to 800W welding power over time. During welding, the material absorbs heat and expands, as seen in the graph. In the first-time step, displacement is localized near the welding site, where the temperature is highest. Heat spreads over the plate during

welding, causing thermal expansion and displacement away from the weld zone. The material adjacent to the weld deforms more when heated and expanded, whereas colder portions further away deform less. The plate cools, reducing displacement with time. The graphic shows how the 800W welding power's temperature gradient affects the material's mechanical response, demonstrating the importance of welding power and heat dispersion in deformation.

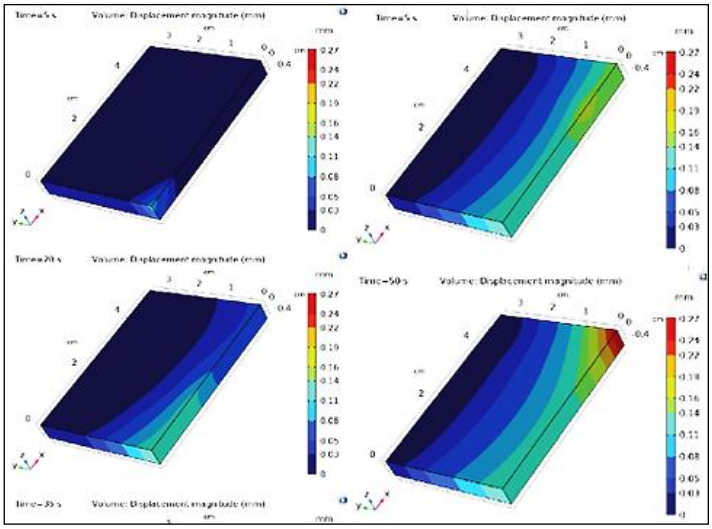

Figure 19: Volume displacement magnitude distribution in a 5mm height titanium plate in different time steps with 800W welding power
Source: Authors, (2025).

Figure 20 illustrates the distribution of volume displacement magnitude inside a 5 mm-thick titanium plate at various time intervals subjected to an 800W welding power. This research has practical implications, as it helps us understand the

material's deformation during the welding process. Titanium Grade 1, with its poor heat conductivity, exhibits significant localized deformation, especially near the welding site. Thermal accumulation in the welding area induces thermal expansion, leading to material deformation.

The maximum displacement reaches 0.26 mm, indicating considerable expansion at the weld zone. The limited heat dispersion, due to the restricted thermal conductivity of Titanium Grade 1, creates a steep temperature gradient, causing localized thermal expansion around the weld region. As time progresses and the heat dissipates, the degree of displacement diminishes.

This localized deformation is crucial for anticipating potential issues like residual strains or warping, which can impact the ultimate quality and structural integrity of the weld. The graphic effectively demonstrates the influence of welding parameters, especially the applied power, on the material's thermal and mechanical behaviour, underscoring the importance of regulating heat distribution to minimize undesirable deformations.

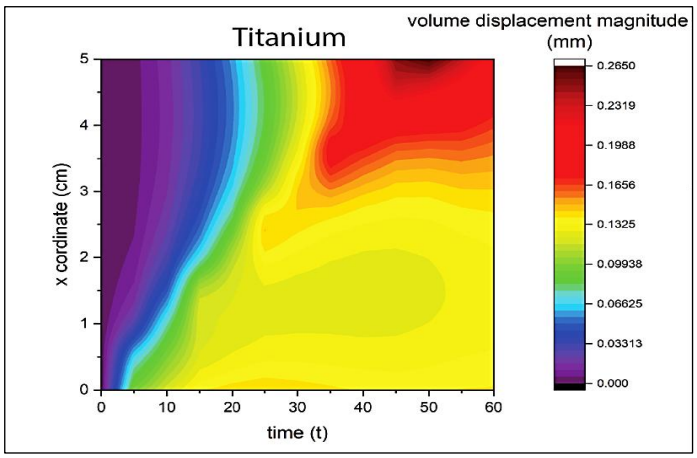

Figure 20: Volume displacement magnitude distribution in a 5mm height titanium, along the welding path in different time steps with 800W welding power.
Source: Authors, (2025).

IV. CONCLUSIONS

This study examined the thermal behaviour of Cold Metal Transfer (CMT) welding by numerical simulations using COMSOL Multiphysics. The thickness of the plate and the welding power were two critical factors on which we concentrated. The ramifications of our results, which underscore the need for meticulous control over welding conditions, might significantly impact welding practices in industrial environments.

Due to their reduced thermal mass, smaller plates (2mm) reached peak temperatures more swiftly than larger plates (5mm and 8mm), which absorbed greater amounts of heat and exhibited slower heating rates. We found that bigger plates absorbed greater amounts of heat and exhibited slower heating rates.

The maximum temperatures and heat-affected areas expanded when the welding power was raised from 800W to 900W. This was particularly evident in the 5mm thick titanium plate. Engineers may enhance weld quality by reducing thermal stresses and distortions, use these insights to adjust welding parameters for various power levels and material thicknesses.

The results underscore the industrial importance of CMT welding, especially in the automotive and aerospace sectors, due to its ability to join incompatible metals with little deformation and spatter. This competency is especially advantageous in the aviation sector. This extensive understanding of thermal behaviour in CMT welding, supported by numerical data and simulations, underscores the importance of optimizing parameters and selecting suitable materials to attain high-quality welds, thereby enhancing industrial welding practices.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Debbah Djoubeir.
Methodology: Debbah Djoubeir and Mohamed Walid Azizi.
Investigation: Debbah Djoubeir and Mohamed Walid Azizi.
Discussion of results: Debbah Djoubeir and Mohamed Walid Azizi.
Writing – Original Draft: Debbah Djoubeir, Mohamed Walid Azizi and Ibtissem Gasmi.
Writing – Review and Editing: Debbah Djoubeir, Mohamed Walid Azizi and Ibtissem Gasmi.
Resources: Debbah Djoubeir and Mohamed Walid Azizi.
Supervision: Mohamed Walid Azizi and Ibtissem Gasmi.
Approval of the final text: Debbah Djoubeir, Mohamed Walid Azizi and Ibtissem Gasmi.

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RESEARCH ARTICLE OPEN ACCESS

INTER-CLUSTER DISTANCE-BASED SMOTE MODIFICATION FOR ENHANCED DIABETES CLASSIFICATION

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ABSTRACT

Diabetes is a significant global health challenge, with early diagnosis playing an important role in preventing serious complications. However, medical datasets often exhibit class imbalance, where the number of non-diabetes cases is much larger than diabetes cases. This imbalance causes machine learning models to be biased towards the majority class, thus degrading prediction performance on the minority class. The problem with the commonly used oversampling method SMOTE (Synthetic Minority Oversampling Technique) is that the selection of new synthetic data formation points is done randomly, which often results in less representative synthetic data and reduces model performance. This research proposes a modification of SMOTE based on inter-cluster distance to overcome this problem. This approach uses the distance between cluster centroids in minority classes to form new synthetic data that is more representative. The research methodology involves data preprocessing, including missing value imputation, normalization, and data balancing using SMOTE modification, followed by classification using Random Forest algorithm. Evaluation was conducted using accuracy, precision, recall, and F1-score metrics. The results showed that the proposed approach achieved very high evaluation values, with accuracy, precision, recall, and F1-score of 99.7% each, far surpassing previous studies that used standard oversampling methods. This study proves that the inter-cluster distance-based SMOTE modification is effective in overcoming class imbalance and producing more representative synthetic data.

I. INTRODUCTION

Diabetes is one of the world's biggest health challenges, with a significant impact on millions of individuals each year [1]. Early diagnosis of the disease is crucial to prevent more serious complications. However, the medical data used to support diagnosis is often imbalanced [2], with the number of non-diabetic patients far outweighing those with diabetes. This imbalance causes machine learning models to be biased towards the majority class [3], reducing prediction accuracy in high-risk patients. Class imbalance is a major bottleneck in the development of reliable prediction systems for diabetes diagnosis [4].

Pima diabetes is one of the datasets often used in research to develop classification models [5]. This dataset has an uneven class distribution between diabetic and non-diabetic patients, which exacerbates the challenge of building effective prediction models. Previous studies have used various machine learning methods for diabetes detection, such as Random Forest, SVM, and artificial neural networks, with Random Forest often showing the best performance. Research by [6] performed neural network optimization for diabetes calcification. This study obtained good results above 80 percent. According to [7] did calcification with various machine learning. The results obtained are not optimal because the accuracy is less than 80 percent. This is because the research was conducted without overcoming unbalanced data.

Unbalanced data can be overcome by oversampling the minority class [8]. A commonly used method is SMOTE (Synthetic Minority Over-sampling Technique). Standard SMOTE often fails to produce realistic synthetic samples because it does not consider the local distribution or inter-cluster distance in the dataset. This

results in less representative synthetic data, which reduces the model's performance in recognizing patterns in minority classes.

Previous research has tried various approaches to overcome class imbalance in diabetes classification. Research [9] tried to apply SMOTE to overcome the imbalance. SMOTE gets accuracy values for C5.0, Random Forest, and SVM to 0.603, 0.727, and 0.727 respectively. this is because the leanring machine model occurs overfitting due to synthetic data generated by SMOTE. Research [10] conducted feature optimization and oversampling for diabetes prediction using machine learning. The results show that various SMOTE methods are used above 83 percent, best using KmeansSMote. Research [11] performed diabetes prediction using machine learning by utilizing PCA feature selection and SMOTE oversmpling. The results of increasing the minority class that has the ability to match the majority class, and the prediction results show f1-score 75 percent. Research [12] performed diabetes prediction with feature selection using Recursive Feature Elimination (RFE), and data augmentation using SMOTE (Synthetic Minority Oversampling Technique). This study achieved the highest accuracy of 82.5%, highlighting the importance of SMOTE in overcoming imbalance. Research [13] performed diabetes prediction using SMOTE and Deep learning. The results showed the highest accuracy of 86.29%, outperforming other algorithms such as Naive Bayes, Logistic Regression, and SVM. Research [14] predicting diabetes with machine learning and various oversmpling models. The results of the Multi-Layer Perceptron (MLP) Model with ADASYN resampling technique achieved the best performance, showing F1 Score 82.17 and AUC 89.61. While these approaches show promising results, they do not fully consider the importance of inter-cluster distribution in minority class datasets. Most of the previous studies relied on standard oversampling methods that only consider the distribution of the data. Previous research lacked attention to the inter-cluster distribution in minority data. This may cause the resulting synthetic data to not adequately represent the variation in the minority data.

In this study, we propose a new approach, which is a minority class distance-based SMOTE modification. By utilizing the inter-cluster distance as the basis for synthetic data generation, this approach aims to generate more representative data, improve classification accuracy, and reduce bias towards the majority class. By integrating the concept of inter-cluster distance into the synthetic data generation process, it is expected to overcome the limitations of traditional oversampling methods.

II. LITERATURE REVIEW

Previous research has identified various innovations in the application of technology to improve operational efficiency and risk management in various sectors. Research [15] used machine learning for diabetes prediction. The results show that the use of machine learning for diabetes prediction without smote can produce a classification accuracy of 80.79 percent. This research has not handled data imbalance. Research [16] performed diabetes prediction using SMOTE and ADASYN oversampling. The results showed that oversampling using ADASYN obtained accuracy, precision, recall, and f1-score results of 88.5, 82, 80, and 81 percent, respectively. This shows that the regular SMOTE method needs to be modified to improve performance in modeling. Research [17] proposed a framework for diabetes prediction that integrates oversampling techniques using SMOTE with various machine learning algorithms. The results show there is an increase in accuracy by using SMOTE and random forest compared to without using smote. SMOTE used is still standard and does not consider the inter-cluster distance in the minority class, so the improvement is not clearly visible only in the numbers behind the comma.

Research [9] tried to apply SMOTE to overcome the imbalance. SMOTE gets the accuracy value for C5.0, Random Forest, and SVM to 0.603, 0.727, and 0.727 respectively. this is because the leanring machine model occurs overfitting due to synthetic data generated by SMOTE. Research Jiang et al.(2024) conducted feature optimization and oversampling for diabetes prediction using machine learning. The results show that various SMOTE methods are used above 83 percent, best using KmeansSMote. Research [11] performed diabetes prediction using machine learning by utilizing PCA feature selection and SMOTE oversmpling. The results of increasing the minority class that has the ability to match the majority class, and the prediction results show f1-score 75 percent.

Research [12] performed diabetes prediction with feature selection using Recursive Feature Elimination (RFE), and data augmentation using SMOTE (Synthetic Minority Oversampling Technique). This study achieved the highest accuracy of 82.5%, highlighting the importance of SMOTE in overcoming imbalance. Research [14] performed diabetes prediction using SMOTE and Deep learning. The results showed the highest accuracy of 86.29%, outperforming other algorithms such as Naive Bayes, Logistic Regression, and SVM. Research [14] did diabetes prediction with machine learning and various oversmpling models. The results of the Multi-Layer Perceptron (MLP) Model with ADASYN resampling technique achieved the best performance, showing F1 Score 82.17 and AUC 89.61. The results with oversmpling are not optimal because the oversampling method technique used has not considered the inter-cluster distance in the minority data.

This research proposes a modification of SMOTE based on minority class inter-cluster distance. By utilizing the inter-cluster distance as the basis for synthetic data formation, this approach aims to generate more representative data, improve classification accuracy, and reduce bias towards the majority class. By integrating the concept of inter-cluster distance into the synthetic data generation process, it is expected to overcome the limitations of traditional oversampling methods.

III. MATERIALS AND METHODS

The main stages of this research are divided into 4 main stages. These stages are dataset, preprocessing, classification, and evaluation. Data preprocessing is done to fix missing values, outliers, normalization, and data balancing using SMOTE modification. Classification is done using random forest machine learning. Evaluation is used, namely accuracy, precision, recall, and f1-score. Figure 1 is the stages of this research.

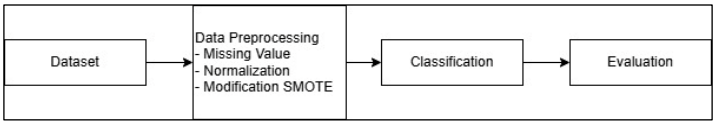

Figure 1: Stages of Research.
Source: Authors, (2025).

III.1 DATA

The data used in this study was taken from the Indian Pima Diabetes Dataset [18], which is an open dataset available in the UCI Machine Learning repository. This dataset contains medical information from 768 female individuals of Pima Indian descent who are at least 21 years old. The main focus of this dataset is to detect the presence of diabetes based on medical examination results and relevant risk factors. The dataset consists of 9 columns

that include input and output variables. The input variables include Pregnancies (number of pregnancies), Glucose (blood glucose level), BloodPressure (diastolic blood pressure in mmHg), SkinThickness (skin thickness in mm), Insulin (serum insulin level in μU/mL), BMI (Body Mass Index in kg/m²), Diabetes Pedigree Function (genetic history of diabetes), and Age (age in years). The output variable is Outcome, which is a binary indicator for diabetes, with a value of 1 indicating the individual is diagnosed with diabetes and a value of 0 indicating the individual does not have diabetes.

This dataset has zero values appearing in certain variables such as SkinThickness, Insulin, and BloodPressure. These zero values most likely reflect unrecorded or missing data, so further handling is needed. Handling was done with the median value of each class. In addition, the distribution of each variable was examined to identify potential anomalies or class imbalances in the target outcome variables. From a total of 768 samples, class imbalance was found, where 500 individuals were not diagnosed with diabetes (class 0) and 268 individuals were diagnosed with diabetes (class 1).

III.2 NORMALIZATION

Normalization is an important step in data processing that aims to equalize the scale of all features in the dataset [19]. This step is necessary so that machine learning algorithms do not give more weight to features with higher scaled values. In this research, the normalization process is performed using the Min-Max Scaling method, which is a technique that transforms feature values into the range [0,1]. This technique helps improve the stability of the model and speeds up the convergence process during training.

For example, Glucose variables that have high values tend to dominate Diabetes Pedigree Function variables that have smaller values. Without normalization, the model risks being biased towards features with larger scales. In addition, normalization also reduces the influence of extreme values or outliers, such as those found in Insulin or BMI variables, so that the model can be trained better. Thus, the application of normalization is expected to create a more stable, fair, and accurate prediction model. In this study, normalization is applied to the eight main input variables in the Indian Pima Diabetes dataset, namely Pregnancies, Glucose, BloodPressure, SkinThickness, Insulin, BMI, Diabetes Pedigree Function, and Age. The normalization process is performed using Equation 1.

$$\boldsymbol{x}_{\text{scaled}} = \frac{\boldsymbol{x}-\boldsymbol{x}_{\min}}{\boldsymbol{x}_{\max}-\boldsymbol{x}_{\min}} \quad (1)$$

This formula converts the original value (x) to a value in the range of 0 to 1 based on the minimum ($x_{\min}$) and maximum ($x_{\max}$) of each feature. With this method, the values of each feature can be compared fairly without being affected by the original scale. As an illustration, the Age variable, which ranges from 21 to 81 years old, is normalized to the same scale as the BMI variable, which has a value range from 18 to 67 kg/m².

III.3 SMOTE MODIFICATION

SMOTE (Synthetic Minority Oversampling Technique) is a method to deal with the problem of data imbalance in machine learning [20], specifically when there are very few minority classes in the dataset compared to the majority classes. This imbalance often results in models prioritizing the majority class and ignoring the minority class. SMOTE works by creating synthetic samples for minority classes instead of simply duplicating existing data. This technique helps reduce the possibility of overfitting that often occurs when using only simple repetition methods. The main stages of SMOTE are identifying minority classes, finding nearest neighbors, selecting neighbors for oversampling, and generating synthetic samples. Identify the minority class in the dataset, which is the class that has far fewer samples than the majority class. For the minority class, find the nearest neighbors using methods such as k-Nearest Neighbors (k-NN). The distance metric used is the Euclidean distance. From the list of found nearest neighbors, SMOTE randomly selects a number of neighbor samples to be used in the interpolation process. Interpolation to generate synthetic samples with equation 2. where $x_i$is the original data of the minority class, $x_j$is the selected neighbor, and δ is a random value between 0 and 1. This process creates a new data point that lies between the original data pair and its neighbor.

$$\boldsymbol{x_{new}} = \boldsymbol{x_i} + \boldsymbol{\delta} \times (\boldsymbol{x_j} - \boldsymbol{x_i}) \quad (2)$$

SMOTE modification is carried out at the stage of determining the location point for the formation of synthetic data. The main stages of the SMOTE modification are identification of minority classes and clustering, calculation of midpoints between clusters, determination of synthetic data locations, and generation of synthetic data. In the minority class identification and clustering stage, the clustering method used is K-means. Each cluster is represented by its centroid, which is the average point of the data in the cluster. The determination of the midpoint (M) between clusters uses Equation 3. where C1 and C2 are the centroids of the two clusters under consideration. Determination of the location of synthetic data based on the midpoint (M) using Equation 4. After the location of the synthetic point is determined, the generation of synthetic data is done with Equation 2. Algorithm 1 is the steps of Inter-Cluster Distance-Based SMOTE Modification.

$$\boldsymbol{M} = \frac{\boldsymbol{C_1}+\boldsymbol{C_2}}{\boldsymbol{2}} \quad (3)$$

$$\boldsymbol{X_{new}} = \boldsymbol{M} + \boldsymbol{\delta} \quad (4)$$

Algorithm 1: Inter-Cluster Distance-Based SMOTE Modification.

Input:	Unbalanced dataset (X,y), minority class C_{min}, number of clusters $K_{cluster}$, number of desired synthetic samples N
Output:	Dataset with extended minority class X_{new},y_{new}.
Process:	
1.	Identification of minority classes C_{min} in the dataset.
2.	Perform data grouping in C_{min} into $K_{cluster}$ clusters using an algorithm such as K-Means. Store the centroid of each cluster as C_1,C_2,....,$C_{kluster}$
3.	Calculate the midpoint between pairs of cluster centroids (C_i,C_j) for all i ≠ j : $M_{ij} = \frac{C\_i + C\_j}{2}$
4.	For each center point $\boldsymbol{M_{ij}}$, add a small variation δ to determine the new synthetic location: $\boldsymbol{x_{new}} = \boldsymbol{M_{ij}} + \boldsymbol{\delta}$ where δ is a small random value to introduce variation.
5.	Generate N new synthetic samples by repeating steps 3 and 4 until the number of synthetic samples is reached.
6.	Add synthetic samples X_{new} to the original dataset.
7.	Merge the original dataset with the synthetic dataset: X_{final} = X ∪ X_{new}, y_{final} = y ∪ y_{new}

Source: Authors, (2025).

III.4 CROSS-VALIDATION

The division of data in this study is done to ensure that the model built has good predictive ability and can be generalized to new data [21],[22]. The Indian Pima Diabetes dataset is divided

into two main subsets, namely training data and testing data. The data division process is carried out using the cross-validation method to maintain a proportional class distribution between the training and testing sets. Cross-validation was 10 folds. Cross-validation helps avoid bias that may arise due to class imbalance.

III.5 RANDOM FOREST CLASSIFICATION

Random Forest is an ensemble-based machine learning algorithm used for classification and regression tasks [23]. It is built on the principle of *bagging* (bootstrap aggregating) using decision trees as its base model. In classification, Random Forest generates predictions by combining decisions from many decision trees to improve accuracy and reducing the risk of overfitting. The main principles in random forest are:

1. Gini Index

The Gini Index measures the impurity of a node by calculating the probability of misclassification if the data is randomly selected based on the class distribution. The smaller the Gini value, the purer the node, so the feature that results in the largest Gini decrease is selected for splitting.

$$\boldsymbol{Gini = 1 - \sum_{i=1}^{C} p_i^2} \quad (5)$$

2. Entropy

Entropy measures the disorder in the distribution of classes in a node. A low entropy value indicates that the data in the node is more homogeneous. Features with the largest entropy decrease are prioritized to splitting the data.

$$\text{Entropy} = -\sum_{i=1}^{C} \boldsymbol{p_i \log_2(p_i)} \quad (6)$$

3. Feature Importance

Feature importance indicates the relative contribution of each feature to the model's predictions. This value is calculated based on the average impurity reduction (Gini or Entropy) across all trees caused by the feature, helping to identify the most relevant features in the dataset.

III.6 EVALUATION

The evaluation metrics used include accuracy, precision, recall, and F1-score, each of which provides a different perspective on the model's performance. Accuracy measures the overall percentage of correct predictions, while precision focuses on the model's ability to identify individuals who actually have diabetes out of all those predicted to be positive. Equation 7 is how accuracy is calculated [24],[25], and Equation 8 is how precision is calculated [26],[27]. Recall assesses the model's ability to detect individuals diagnosed with diabetes out of the total diabetes cases, and F1-score provides a balance between precision and recall. Equation 9 is calculate recall [28], and Equation 10 is calculate F1-score [26]. These metrics provide an overall picture of the model's ability to provide accurate, consistent, and fair predictions.

$$\boldsymbol{Accuracy = \frac{TP+TN}{TP+TN+FP+FN}} \quad (7)$$

$$\boldsymbol{Precision = \frac{TP}{TP+FP}} \quad (8)$$

$$\boldsymbol{Recall = \frac{TP}{TP+FN}} \quad (9)$$

$$\boldsymbol{F1-Score = 2\,x\,\frac{Precision\ x\ Recall}{Precision-Recall}} \quad (10)$$

Where TP (True Positives) is the correct prediction as positive. TN (True Negatives) is a true prediction as negative. FP (False Positives) is a false prediction as positive. FN (False Negatives) is a false prediction as negative.

IV. RESULTS AND DISCUSSIONS

This section describes the results in accordance with the research steps of Figure 1, as well as the discussion. The data used is the Indian Pima Diabetes Dataset from UCI Machine learning. The dataset contains a total of 768 samples, it is known that there is a class imbalance, where 65.1 percent are not diabetic and 34.9 percent are diabetic. The number of 65.1 percent non-diabetic individuals is 500 individuals, while the 34.9 percent who are diabetic is 268 individuals. Figure 2 is a visualization of this unbalanced (original) data distribution.

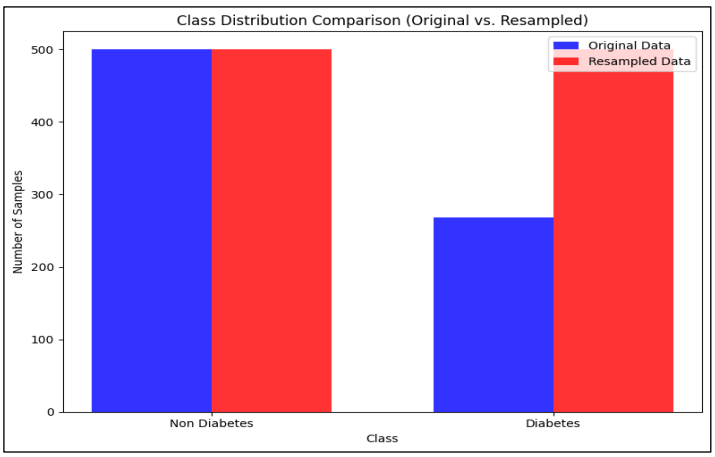

Figure 2: Class Distribution Comparision (Original vs Reampled). Source: Authors, (2025).

The original dataset has zero values in the variables Pregnancies, Glucose, BloodPressure, SkinThickness, Insulin, and BMI. This can be seen from Table 1. Pregnancies can contain zero because they have never been pregnant. While the variables Glucose, BloodPressure, SkinThickness, Insulin, and BMI cannot be zero. These zero values reflect unrecorded or missing data, so further handling is needed. Handling is done with the median value of each class. Table 2 shows the results after handling the null values.

Based on Table 2, after handling the 0 values found in some variables (which may be placeholders for missing or invalid data), the descriptive statistics for the cleaned dataset show significant changes. The handling of 0 values in the Pima Indians Diabetes dataset has resulted in a more realistic data distribution. Some variables, such as Glucose, Blood Pressure, Skin Thickness, Insulin, and BMI, which previously had a value of 0, have been corrected and replaced with more reasonable values, avoiding further distortion of the analysis. These improvements provide a more accurate picture of the distribution of the variables in the dataset, enabling more effective modeling to predict diabetes in individuals based on relevant health factors.

The preprocessing data is balanced by oversampling using SMOTE modification. Figure 2 shows the result of oversampling the minority class. The results show that between the majority class and the previous minority class, the number is now the same. Data

that has been balanced is normalized with a range of 0 to 1. After normalization, modeling is then carried out using machine learning random forest classification. In the modeling process, the data is divided into 2, namely training data and test data using cross-validation. Cross-validation is used as much as 10 kfold. The test results obtained accuracy, precision, recall, and f1-score of 99.7, 99.7, 99.7, and 99.69 percent, respectively.

Table 1: Description of the indian pima diabetes dataset.

	Pregnancies	Glucose	Blood Pressure	Skin Thickness	Insulin	Bmi	Diabetes Pedigree Function	Age
Count	768	768	768	768	768	768	768	768
Mean	3.85	120.9	69.12	20.54	79.8	31.99	0.47	33.24
Std	3.37	31.97	19.36	16.95	115.24	7.88	0.33	11.76
Min	0	0	0	0	0	0	0.08	21
25%	1	99	62	0	0	27.3	0.24	24
50%	3	117	72	23	30.5	32	0.37	29
75%	6	140.25	80	32	127.25	36.6	0.63	41
Max	15	199	122	99	846	67.1	2.42	81

Source: Authors, (2025).

Table 2: Description of the indian pima diabetes dataset after null value handler.

	Pregnancies	Glucose	Blood Pressure	Skin Thickness	Insulin	Bmi	Diabetes Pedigree Function	Age
Count	768	768	768	768	768	768	768	768
Mean	3.85	121.67	72.39	29.09	141.75	32.43	0.47	33.24
Std	3.37	30.46	12.11	8.89	89.1	6.88	0.33	11.76
Min	0	44	24	7	14	18.2	0.08	21
25%	1	99.7	64	24	102.5	27.5	0.24	24
50%	3	117	72	28	102.5	32.05	0.37	29
75%	6	140.25	80	32	169.5	36.6	0.63	41
Max	15	199	122	99	846	67.1	2.42	81

Source: Authors, (2025).

Table 3. Comparison of evaluation results with previous research.

Reference	Accuracy	Precision	Recall	F1-Score
[15]	80.79	73.68	75	-
[16]	88.5	82	80	81
[17]	89.6	86	84	85.2
[9]	72.7	-	-	-
[10]	88.56	-	-	86.66
[11]	-	89	65	75
[12]	82.5	-	-	-
[13]	86.29	81.9	84.2	-
[14]	-	-	-	82.18
Proposed	**99.7**	**99.7**	**99.7**	**99.69**

Source: Authors, (2025)

A comparison of the evaluation results in Table 3 shows the significant achievements of our proposed method, compared to previous studies. These studies used various machine learning techniques and oversampling methods to overcome class imbalance in diabetes prediction. Research [15] achieved an accuracy of 80.79% with a machine learning approach without using SMOTE, which shows the limitations of an imbalanced dataset. Research [16],[17] integrated oversampling techniques such as SMOTE and ADASYN, resulting in accuracies of 88.5% and 89.6%, respectively, with moderate improvements in precision, recall, and F1-score metrics. Research [10] used KMeans-SMOTE, achieving 88.56% accuracy with further feature optimization. Reseach [11],[12] utilized PCA and Recursive Feature Elimination (RFE) for feature selection, combined with SMOTE, resulting in F1-score of 75% and 82.5% respectively. However, the performance is still below that of the proposed method. Deep learning approaches also show potential, such as by [13] who achieved 86.29% accuracy using SMOTE and deep convolutional neural network, while [14] reported an F1-score of 82.18% with ADASYN and MLP models.

Our proposed method achieves significantly superior performance on all metrics, with accuracy, precision, recall, and F1-score of 99.7% each. By modifying SMOTE using inter-cluster distance analysis, the method effectively addresses class imbalance while preserving the underlying data structure, ensuring balanced learning between classes. This achievement confirms the importance of developing oversampling techniques and integrating a robust classification framework for diabetes prediction. The proposed methodology not only overcomes class imbalance, but also achieves unprecedented prediction performance, setting a new standard for research in this field.

V. CONCLUSIONS

This study proposes a modification of the inter-cluster distance-based SMOTE method to address data imbalance in

diabetes prediction using the Indian Pima Diabetes dataset. This approach is designed to generate more representative synthetic data by considering the inter-cluster distribution of minority classes, thus improving the quality of the classification model. The results showed that the proposed method achieved significantly higher evaluation performance than previous studies, with accuracy, precision, recall, and F1-score of 99.7% each. Moreover, this modification significantly reduces the bias towards the majority class while preserving the underlying data structure. Based on these results, it can be concluded that the proposed method successfully improves classification accuracy, and reduces bias towards the minority class. This success opens up opportunities for further application in other disease diagnosis, especially on datasets with high class imbalance.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Intan Nurzari, Ermita Sari, and David Ibnu Harris.
Methodology: Intan Nurzari, Arif Mudi Priyatno and Hidayati Rusnedy.
Investigation: Hidayati Rusnedy.
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Resources: David Ibnu Harris.
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Approval of the final text: Intan Nurzari, Ermita Sari, David Ibnu Harris, Arif Mudi Priyatno and Hidayati Rusnedy

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RESEARCH ARTICLE OPEN ACCESS

ARTIFICIAL NEURAL NETWORK-BASED DEADBEAT PREDICTIVE CURRENT CONTROL WITH DEAD-TIME COMPENSATION FOR PMSMs

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ABSTRACT

In the velocity control of Permanent Magnet Synchronous Motors (PMSMs), Deadbeat Predictive Current Controllers (DPCCs) are renowned for their excellent dynamic performance and constant switching frequency. However, achieving precise velocity regulation remains challenging due to the nonlinearities introduced by two-level voltage source inverter (2L-VSI). Specifically, the dead time inherent in 2L-VSI results in voltage distortion, which generates parasitic harmonics in the system. These harmonics degrade control accuracy, cause a current ripple, and can lead to performance degradation or even system instability, compromising reliable operation. This article proposes an innovative solution: Artificial Neural Network-Based Deadbeat Predictive Current Control (ANN-DPCC) integrated with dead-time compensation to address these issues. This approach effectively suppresses the current ripple and significantly reduces total harmonic distortion (THD). Simulation results validate that ANN-DPCC with dead-time compensation outperforms traditional DPCC by improving response times, enhancing steady-state accuracy, and minimizing current distortions. This novel strategy significantly advances PMSM control, offering precise velocity regulation, improved reliability, and superior system performance for demanding applications

I. INTRODUCTION

PMSMs have gained widespread attention due to their remarkable characteristics, including compact design, high efficiency, and exceptional power density [1],[2]. These advantages have led to their extensive application in various fields, such as robotics, intelligent manufacturing, and automotive drive systems, where they play a vital role in advancing technological progress in the manufacturing industry [3].

As motor design and manufacturing evolve, the need for more efficient and reliable control strategies for PMSMs has become increasingly important. Conventional control strategies have been widely implemented, including Direct Torque Control (DTC) and Field-oriented Control (FOC). However, in recent years, predictive control techniques have emerged as a promising alternative, offering enhanced performance in motor drive systems and power electronics [4-6].

Predictive control has gained popularity in motor control applications due to its ability to effectively manage multi-objective optimization and constraint problems without requiring parameter adjustments [7],[8]. This approach forecasts state variables' future behavior using the mathematical model of the system. Analyzing cost functions helps the controller choose the best voltage vector and implement it in the system. Commonly employed among the several predictive control strategies in motor drive systems are Deadbeat Predictive Control (DPC) and Finite Control Set Model Predictive Control (FCS-MPC) [9],[10].

Among the various predictive control techniques, DPC has gained popularity due to its ability to deliver superior steady-state

performance, including smoother current waveforms and reduced torque ripple, which significantly improve system stability [11], [12]. We can further categorize the deadbeat control method into Deadbeat Predictive Current Control and Deadbeat Direct Flux and Torque Control (DB-DTFC) [13]. While DB-DTFC requires complex flux and torque observers, DPCC simplifies the process by directly predicting and controlling the current, making it ideal for applications where current regulation is the primary focus [14]. The DPCC technique computes the voltage command for current tracking based on a discrete motor model. Then, it applies Space Vector Pulse Width Modulation (SVPWM) to convert the voltage command into the corresponding switching states [15],[16].

However, performance degradation in the DPCC of PMSM systems can be caused by two main issues. Traditional proportional-integral (PI) speed controllers in DPCC typically exhibit positive steady-state performance. Still, they are vulnerable to parameter variations like load changes and speed fluctuation. Another significant problem arises in two-level voltage source inverters (2L-VSI) fed PMSM systems because of the dead time created by SVPWM switching operations [17]. Although this dead time is brief (typically in the microsecond range), it causes voltage distortion, leading to current ripple and torque pulsations that degrade overall motor control performance [18]. Nonlinearities in the 2L-VSI, such as switching delays and voltage drops in the inverter components, cause these distortions. These distortions contribute to harmonic distortion in the motor currents, reducing the effectiveness of traditional vector control algorithms. Without adequate compensation for dead time, the DPCC control performance can further deteriorate, leading to increased losses and reduced PMSM efficiency. To mitigate these adverse effects. One practical approach leverages Fourier series analysis to model the distorted voltage components in a stationary reference frame. These methods improve the quality of the inverter's output and the accuracy of tracking reference control signals by finding and canceling out the harmonic components caused by dead time [19].

Furthermore, DPCC ability to dynamically predict and adjust inverter output voltages has led to its widespread adoption. By integrating dead-time compensation into the DPCC framework, the system can correct real-time voltage errors, significantly reducing current ripple and total harmonic distortion. This improves the precision of control signals and ensures smoother torque output, making the method highly effective for applications requiring high performance and robustness.

The primary contribution of this paper lies in developing a DPCC strategy enhanced with an ANN-based speed controller to significantly improve the dynamic performance of the speed outer loop in PMSMs. This work also integrates dead-time compensation to address the challenges associated with voltage distortions and torque pulsations in VSI-fed systems. The key contributions are summarized as follows:

1-A neural network replaces the conventional PI controller in the speed control loop. This substitution enhances reference speed tracking, improves adaptation to load variations and speed fluctuations, and results in a superior dynamic response.

2-The proposed DPCC method enables precise current tracking and rapid response by predicting the system's behavior and minimizing tracking errors in both speed and current. This enhances dynamic performance and improves overall system efficiency.

3- The integration of dead-time compensation effectively mitigates the adverse effects of switching delays in VSI-fed PMSM systems. This approach reduces voltage distortions, minimizes current ripple, and improves torque smoothness, enhancing the motor's control accuracy and efficiency. The rest of the paper is organized as follows: Section II presents the mathematical model, including the inverter and PMSM models. Section III details the proposed control method. It consists of two main steps: the current inner loop, which includes deadbeat predictive current control and the proposed dead-time compensation method, and the speed outer cloop, which incorporates artificial neural networks. Section IV demonstrates the simulation results, verifying the effectiveness of the proposed method. Section V concludes the entire paper.

II. MATHEMATICAL MODEL

The ANN-DPCC strategy with dead-time compensation is implemented for a PMSM powered by a 2L-VSI, as illustrated in Figure. 1(a). This section presents the mathematical models for the power converter and the PMSM, forming the foundation for the proposed control approach.

II.1 INVERTER MODEL

The switching state S_x for the 2L-VSI is given by the following relations [20]:

$$S_x = \begin{cases} 1 & if\ G_x\ turn-on\ \ and\ \ \bar{G}_x\ turn-off \\ 0 & if\ G_x\ turn-off\ \ and\ \ \bar{G}_x\ turn-on \end{cases} \quad (1)$$

For $x \in (a,b,c)$, G_x and $\bar{G}_x$ denotes the gate signals of the upper and lower IGBTs, respectively. The voltage combinations at the inverter's output terminals can be expressed using vector representation:

$$V = V_{dc}.\frac{2}{3}(S_a + aS_b + a^2S_c) \quad (2)$$

Where: V is the voltage combinations, V_{dc} is the dc-link voltage, and $a = e^{j\frac{2\pi}{3}}$

The inverter has eight possible switching state combinations, as described in Equation (3), resulting in eight distinct voltage vectors as shown in Fig. 1(b) [1].

$$S_{abc} = (S_a, S_b, S_c) \in V_i = \{000, 001, \ldots\ldots, 111\} \quad (3)$$

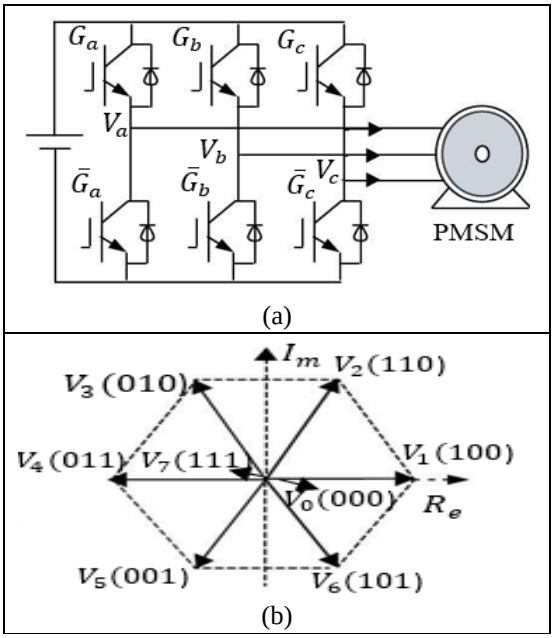


Figure 1: Two-Level Voltage Source Inverter (2L-VSI) .(a) Power Circuit Diagram, and (b) Voltage Vector Representation.
Source: Authors, (2025).

II.2 PMSM MODEL

The mathematical representation of a PMSM voltage equation in the rotating $(d-q)$ reference frame can be represented as [21], [10]:

$$\begin{cases} U_{sd} = R_s I_{sd} + L_d \frac{dI_{sd}}{dt} - L_q \omega_e I_{sq} \\ U_{sq} = R_s I_{sq} + L_d \frac{dI_{sq}}{dt} + -L_q \omega_e I_{sd} + \varphi_f \omega_e \end{cases} \quad (4)$$

Where U_{sd} and U_{sq} are the stator input voltage, R_s is the stator resistance, I_{sd} and I_{sq} are the stator currents, φ_f is the flux linkages, L_d and L_q are the stator inductances, respectively, (L_d=L_q=L_s) for the surface-mounted permanent magnet synchronous moto.

Additionally, ω_e is the rotor electrical angular speed, calculated as $(\omega_e = \mathrm{p} * \omega_m)$, where ω_m represents the rotor's mechanical rotational speed, and p is the number of poles.

III. PROPOSED CONTROL METHOD

The control strategy framework, depicted in figure 2 comprises two main stages: the current inner loop and the speed outer loop. The current inner loop precisely manages the stator currents in the electrical subsystem for accurate current control. The DPCC strategy is made better by dead-time compensation in the 2L-VSI.

Meanwhile, the speed outer loop manages the machine's mechanical subsystem using an ANN instead of traditional PI controllers. This loop tracks the speed reference accurately by employing the mechanical model to determine an appropriate electromagnetic torque reference (T_e^*).

III.1 DEADBEAT PREDICTIVE CURRENT CONTROL

The primary forward-order Euler discretization obtains the subsequent instantaneous stator currents. At the (k) th moment, the stator currents on the d-q axis, $I_{sd}(k)$, and $I_{sq}(k)$, are sampled to predict the currents at the $(k+1)$th moment [22],[23].

$$\begin{cases} I_{sd}(k+1) = \left(1 - \frac{R_s T_s}{L_d}\right) I_{sd}(k) + T_s \omega_e(k) I_{sq}(k) + \frac{T_s}{L_d} U_{sd}(k) \\ I_{sd}(k+1) = \left(1 - \frac{R_s T_s}{L_d}\right) I_{sq}(k) - T_s \omega_e(k) I_{sd}(k) - \frac{T_s \varphi_f}{L_d} \\ \omega_e(k) + \frac{T_s}{L_d} U_{sq}(k) \end{cases} \quad (5)$$

Where: $U_{sd}(k)$, and $U_{sq}(k)$ signify the d-q axis stator voltages at the (k)th moment, while $I_{sd}(k)$, and $I_{sq}(k)$ denote the d-q axis stator currents at the same instant. $I_{sd}(k+1)$ and $I_{sq}(k+1)$ denote the expected stator currents at the $(k+1)$th instant, $\omega_e(k)$ represents the electrical angular velocity at the (k) th instant, and T_s refers to the sampling time.

The reference currents $I_{sd}^*(k)$ and $I_{sq}^*(k)$ in the d-q rotating coordinate system can exhibit slight variation between two consecutive time intervals, provided the sampling duration is sufficiently small. This attribute of reference currents is denoted as:

$$\begin{aligned} I_{sd}^*(k+1) &\approx I_{sd}^*(k) \\ I_{sq}^*(k+1) &\approx I_{sq}^*(k) \end{aligned} \quad (6)$$

The second step aims to calculate the specified voltage at the (k +1) th instant, which can be expressed as:

$$\begin{cases} U_{sd}(k+1) = R_s I_{sd}(k+1) + \frac{L_s}{T_c}[I_{sd}^*(k) - I_{sd}(k+1)] - L_s \\ \omega_e I_{sq}(k) \\ U_{sq}(k+1) = R_s I_{sq}(k+1) + \frac{L_s}{T_c}\left[I_{sd}^*(k) - I_{sq}(k+1)\right] - L_s \omega_e \\ I_{sd}(k) + \varphi_f \omega_e \end{cases} \quad (7)$$

III.2 PROPOSED DEAD-TIME COMPENSATION METHOD

Figure 3. a illustrates the ideal and actual gate signal patterns, accounting for dead time. Figure 3. b displays the ideal and actual a-phase voltages according to the phase current direction. Over one SVPWM period T_s , the voltage distortion error in the a-phase due to dead time can be represented as follows [24].

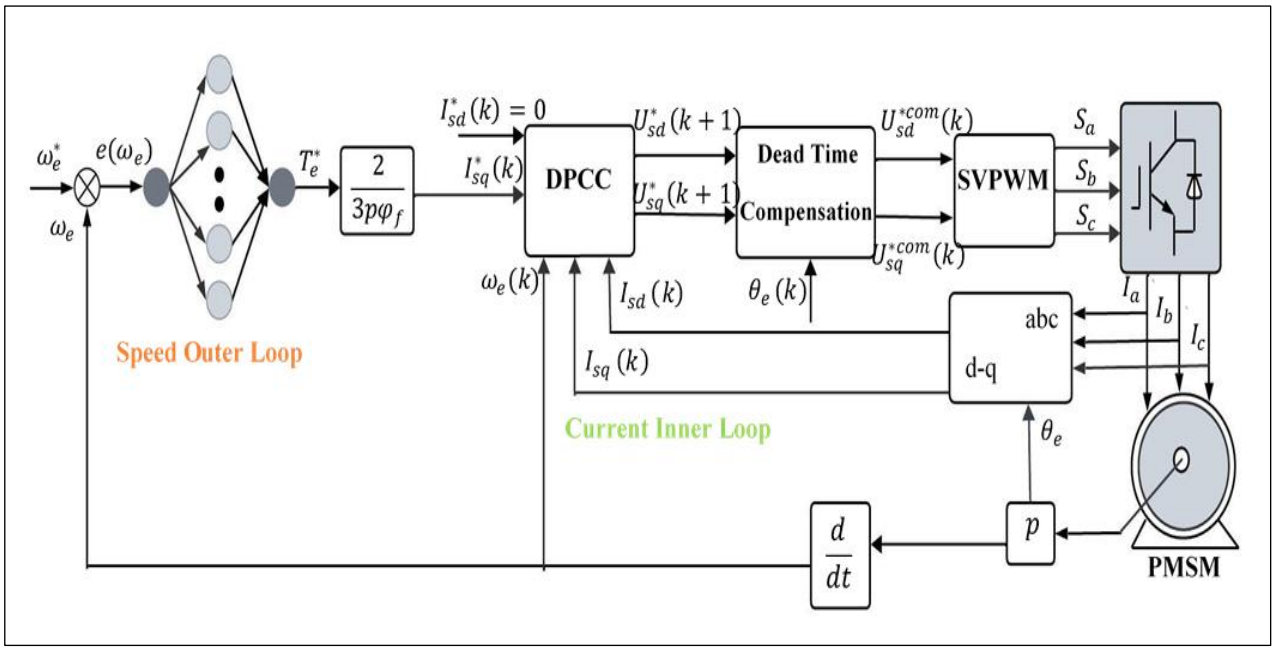


Figure 2: schematic Representation of ANN-DPCC with Dead-Time Compensation in PMSM Drives.
Source: Authors, (2025).

$$\Delta V_{ap} = V_{DT} sign(I_a) \qquad sign(I_a) = \begin{cases} 1 & I_a > 0 \\ -1 & I_a < 0 \end{cases} \quad (8)$$

Where: sign (.) is sign function. In equation (9), V_{DT} is the magnitude of the voltage error due to dead-time,which can be given as follows:

$$V_{DT} = \frac{V_{DT} + T_{on} - T_{off}}{T_s}.(V_{dc} - V_{ce} + V_D) + \frac{V_{ce} + V_D}{T_s} \quad (9)$$

Where T_{DT} denotes the dead time, T_{on} represents the switching turn-on time., T_{off} is the switching turn-off time, V_{ce} is the forward voltage drop of the switching device, and V_d represents the forward voltage drop of the diode. In this case, the voltage drops across the switching and diodes are neglected, simplifying equation (10) to:

$$V_{DT} = \frac{V_{DT} + T_{on} - T_{off}}{T_s} \quad (10)$$

The voltage error can be converted into an $\alpha - \beta$ reference frame using equation (11), as illustrated in Figure 3.b.

$$\begin{bmatrix} \Delta U_{s\alpha} \\ \Delta U_{s\beta} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} V_{DT}.sign(I_a) \\ V_{DT}.sign(I_b) \\ V_{DT}.sign(I_c) \end{bmatrix} \quad (11)$$

The voltage error $\Delta U_{s\alpha\beta}$ you can obtain an estimate by converting it into a Fourier series [25]:

$$\begin{cases} \Delta U_{s\alpha} = \frac{4\,V_{DT}}{\pi}[\sin(\theta_e + \varphi) + \sum_{n=1}^{\infty} \frac{\sin\left((6n-1)(\theta_e+\varphi)\right)}{6n-1} + \\ \qquad \frac{\sin\left((6n+1)(\theta_e+\varphi)\right)}{6n+1}] \\ \Delta U_{\beta} = \frac{4\,V_{DT}}{\pi}[\cos(\theta_e + \varphi) + \sum_{n=1}^{\infty} \frac{\cos\left((6n-1)(\theta_e+\varphi)\right)}{6n-1} + \\ \qquad \frac{\cos\left((6n+1)(\theta_e+\varphi)\right)}{6n+1} \end{cases} \quad (12)$$

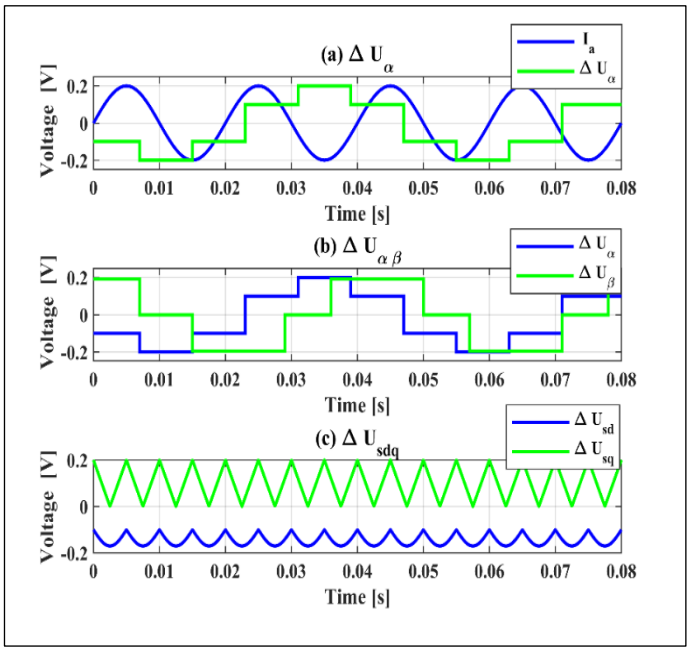


Figure 3. Illustration of voltage distortions.
Source: Authors, (2025).

In this context, φ denotes the angular difference between the current vector in the $(d-q)$ reference frame and the q -axis. Due to dead-time effects, the appearance of 5th and 7th harmonic components in the voltages becomes evident, as shown by the harmonic analysis in Equation (12). As demonstrated in equation (13), these harmonics are mapped to multiples of the 6 th harmonic in the $(d-q)$ reference frame. The resulting disturbance voltages $\Delta U_{s,dq}$ are illustrated in Figure 3.c

$$\begin{cases} \Delta U_{sd} = \frac{4\,V_{DT}}{\pi}[\sin(\varphi) + \sum_{n=1}^{\infty} \frac{\sin(6n(\theta_e+\varphi)-\varphi)}{6n-1} + \\ \qquad \frac{\sin(6n(\theta_e+\varphi)+\varphi)}{6n+1}] \\ \Delta U_{sd} = \frac{4\,V_{DT}}{\pi}[-\cos(\varphi) + \sum_{n=1}^{\infty} \frac{\cos(6n(\theta_e+\varphi)-\varphi)}{6n-1} + \\ \qquad \frac{\cos(6n(\theta_e+\varphi)\mp\varphi)}{6n+1}] \end{cases} \quad (13)$$

The harmonic ripple of the current $I_{s,\alpha\beta}$ and current $I_{s,dq}$ at the same frequencies is caused by these harmonic components in the voltage. We can mitigate the undesirable effects of the dead time and the other VSI nonlinearities by adequately compensating. The dead-time compensation method adjusts the reference voltage $U_{s,dq}^{*com}(k)$ by adding or subtracting the dead-time-induced voltage ΔU_{sdq}, depending on the direction of the q-axis reference current $I_{sq}^{*}(k)$ and the rotor speed ω_e, can be represented as:

$$\begin{cases} U_{s,dq}^{*com}(k) = U_{s,dq}(k+1) - \Delta U_{s,dq} & if\ \ I_{sq}^{*}(k) \geq 0 \\ U_{s,dq}^{*com}(k) = U_{s,dq}(k+1) + \Delta U_{s,dq} & if\ \ I_{sq}^{*}(k) < 0 \\ \qquad and\ \omega_e(k) < 0 & \\ U_{s,dq}^{*com}(k) = U_{s,dq}(k+1) - \Delta U_{s,dq} & if\ \ I_{sq}^{*}(k) > 0 \\ \qquad and\ \omega_e(k) > 0 & \end{cases} \quad (14)$$

Where : $U_{s,dq}^{*com}(k)$ are the reference compensation voltages on the $d-q$ axis q that are generated by the DPCC controllers, ,calculated for the $k+1$ period. This equation (15) scales the adjusted d-q voltage components if their amplitude exceeds a certain threshold (specifically (V_{dc}/3)) .This scaling helps ensure that the voltage commands remain within the allowable limits of the inverter.

$$\begin{cases} U_{sd}^{*com}(k) = U_{sd}^{*com}(k) V_{dc}/\sqrt{3} \sqrt{\left(U_{sd}^{*com}(k)\right)^2 + U_{sq}^{*com}(k)^2)} \\ U_{sq}^{*com}(k) = U_{sq}^{*com}(k) V_{dc}/\sqrt{3} \sqrt{\left(U_{sd}^{*com}(k)\right)^2 + U_{sq}^{*com}(k)^2)} \end{cases} \quad (15)$$

III.3 THE PRINCIPLE IDEA OF ARTIFICIAL NEURAL NETWORK

ANN technique is a computational model inspired by biological neural systems, designed to emulate human cognitive abilities in machine and control systems. ANNs consist of interconnected nonlinear processing units, or neurons, linked by synapses represented as numerical weights. This structure enables ANNs to overcome the limitations of traditional control methods through adaptive learning and processing. Typically organized into three layers - input, hidden, and output - the ANN framework allows for efficient transmission and transformation of information throughout the network. One of the model's key strengths is its adaptability to internal and external data, enabling it to respond to changing conditions dynamically [26]. The fundamental structure

of a neuron within this model is conceptually represented by the following equation:

$$y_i = F_1(s)(\sum_{i=1}^{N}(x_i w_i + b)) \quad (16)$$

$$O_i = F_2(s)(\sum_{i=1}^{N}(y_i w_i + b)) \quad (17)$$

Where y_i the output signals of the neuron, O_i is the actual response by network, x_i input signals , w_i represents the synaptic weight of the signal, b is the bias parameter, and $F_1(s)$ represents the activation function of the nonlinear hyperbolic tangent, which is calculated using the following formula.

$$F_1(s) = \frac{e^{\alpha s} - e^{-\alpha s}}{e^{\alpha s} + e^{-\alpha s}} \quad (18)$$

The function of linear activation is represented by $F_2(s)$, which can be calculated using equation (19):

$$F_2(s) = s\beta \quad (19)$$

Where the activation functions gains denote α and β, the feedforward backpropagation method trains the neural network in this study until the MSE between the intended output and the network's output is minimal [27]. The following equation is employed to determine the MSE:

$$MSE = \frac{1}{N}(\sum_{i=1}^{N}(d_i(k) + O_i(k))^2 \quad (20)$$

Where $d_i(k)$ denotes the desired response, N denotes the input-output training data and k denotes the number of iterations. The ANN structure implemented in this study is illustrated in Figure 4.

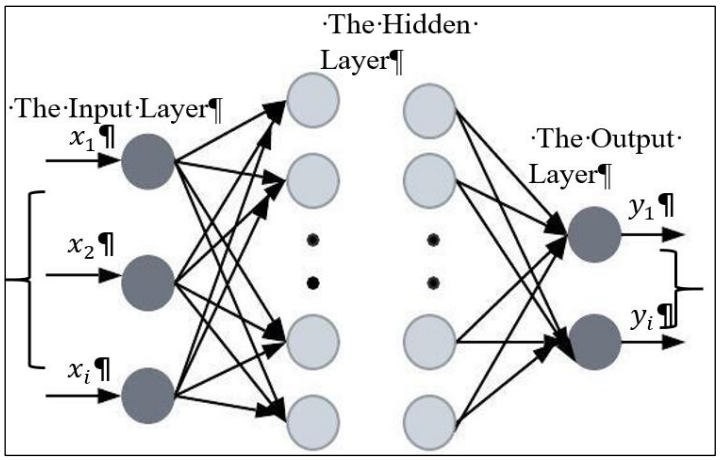


Figure 4. illustrates the structure of the ANN model.
Source: Authors, (2025)

III.3.1 PREPARATION OF INPUT-OUTPUT DATA FOR LEARNING

The first step in this process involves gathering datasets. The dataset includes input and output values from the speed regulator PI, specifically e(w), and T_e^* .We then randomly divide these data into three subsets for training, validation, and testing.

- We designate 70% of the dataset for training.
- We designate 15% of the dataset for testing.
- We reserve 15% of the dataset for validation.

III.3.2 SELECTION OF THE NEURAL NETWORK ARCHITECTURE

Configured the neural network controllers using MATLAB's "nntool" interface. The performance depends on factors such as the number of hidden layer neurons, activation functions, and the training algorithm. A Multi-Layer Perceptron Feedforward architecture, comprising input, hidden layers, and output layers, was selected for this study. Additionally, no standardized methodology exists for selecting the number of hidden layers or neurons. We initially tested single hidden-layer architectures with a small number of neurons, gradually increasing the number of neurons until we achieved the desired performance. After extensive testing, the speed controller's optimal configuration was ten neurons. We applied tangent-sigmoid activation functions (tansig) to the hidden layer and linear activation functions (purelin) to the output layer.

III.3.3 SELECTION OF THE LEARNING ALGORITHM

The final step is selecting the learning algorithm, with the Backpropagation Error Learning Method chosen for this study. MATLAB provides various algorithms, including gradient descent (traingd), gradient descent with momentum (traingdm), and the Levenberg-Marquardt algorithm (trainlm). This study utilized the Levenberg-Marquardt algorithm (trainlm). The Mean Square Error (MSE) and the regression value V are crucial performance indicators. The regression value V measures the correlation between outputs and targets; 1 means a perfect correlation. The errors become acceptable results with weights adjusted iteratively using the Levenberg-Marquardt algorithm.

III.3.4 THE NEURAL NETWORK RESULTS

The MSE as a function of the number of epochs for speed prediction is illustrated in Figure 5. The results suggest a substantial decrease in the error between the objective and predicted output during the training process. The error decreases significantly within the first 1000 epochs, following which it stabilizes, achieving a final RMSE value of approximately 4.44e-5. The optimal specifications of the proposed ANN models are summarized in Table 1.

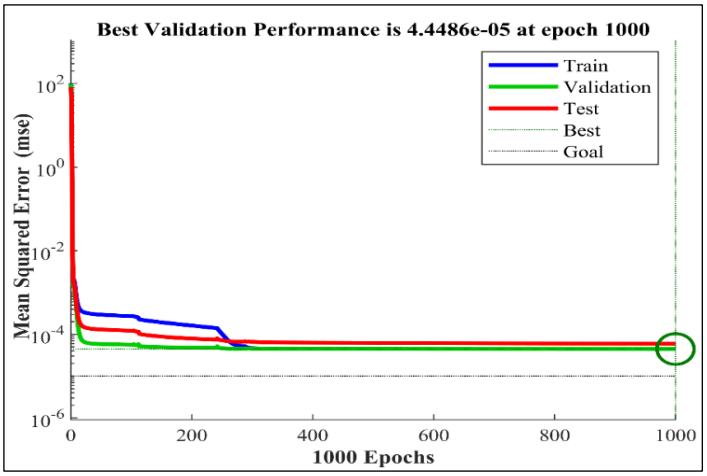


Figure 5. Performance of MSE (Testing, Validation, Training).
Source: Authors, (2025).

Table 1: illustrates the architecture and training parameters of the ANN.

ANN of Parameter	ANN Controller Speed
Neural network	Multi-Layer Perceptron Feedforward
The input layer number of neurons	1
Number of neurons in the hidden layer	10
The output layer number of neurons	1
Learning rate	0.1
Epochs number	1000
ANN training algorithm	Backpropagation
Adaption learning function	Trainlm
Activation function	Tansig
Performance function	MSE 4.44e-5

Source: Authors, (2025).

IV. RESULTS AND DISCUSSIONS

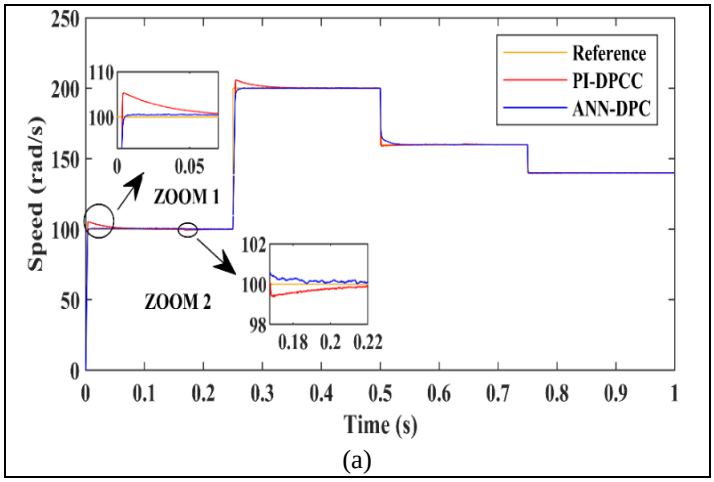
The simulation results were generated using MATLAB/Simulink. The characteristics of the PMSM are detailed in Table 2, which outlines the nominal parameters for a 3 kW power rating. The results are divided into two sections: the first provides a comparative analysis of ANN-DPCC and PI-DPCC performance under sudden load changes in the PMSM. In contrast, the second focuses on the Dead-Time Compensation Strategy applied to PI-DPCC and ANN-DPCC methods.

Table 2: PMSM nominal parameters used in numerical simulation.

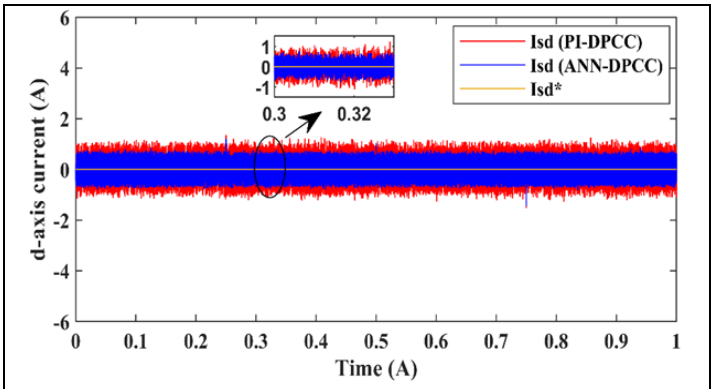
Parameters	Values
Stator Inductance *Ls (H)*	0.0076
Stator resistance *Rs* (Ω)	2.3
Friction coefficient *B (N.m.s)*	0.000169
Moment of inertia *J* ($kg.\ m^2$)	0.0032
flux linkages $\varphi_f(wb)$	0.4
Number of pole pairs *p*	4

Source: Authors, (2025).

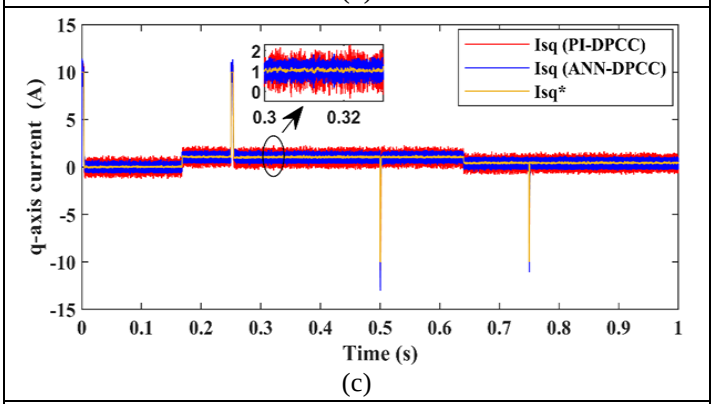
IV.1 DYNAMIC PERFORMANCE OF ANN-DPCC AND PI-DPCC UNDER SUDDEN LOAD CHANGES IN PMSM



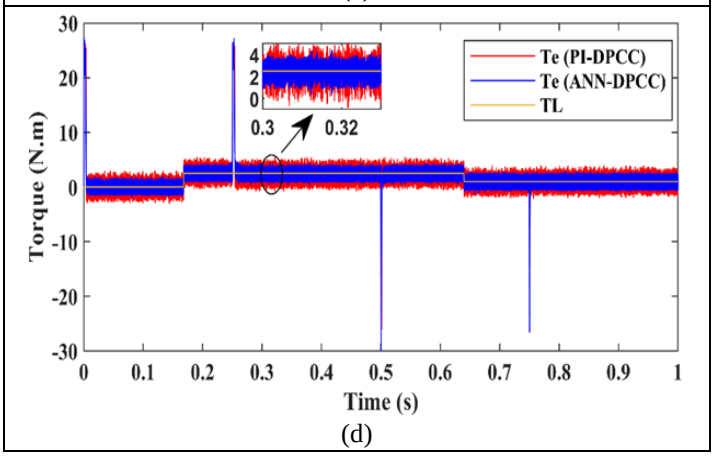
(a)



(b)



(c)



(d)

Figure 6. Performances of the PI-DPCC and ANN-DPCC applied on PMSM drive system : (a) Speed (ω_e), (b) direct current (I_{sd}), (c) quadratic current (I_{sq}), and (d) electromagnetic torque(T_e)
Source: Authors, (2025).

Figure 6.a shows the motor speed profile. According to this figure, the speed starts at 100 rpm, then increases to 200 rpm at 0.25 s, decreases to 160 rpm at 0.5 s, and reduces to 140 rpm at 0.75 s. The measured rotational speed fluctuates based on the reference, with good tracking dynamics observed under no-load and load conditions. Zoom (1) in Figure 6.a reveals that initially, the motor runs at a rated speed of 100 rad/s without load using classical PI-DPCC control, which shows an overshoot of 5.959%. In contrast, there is no overshoot when using the ANN-DPCC control.

The motor's speed regulation response time is 88.87 ms for classical PI-DPCC and ANN-DPCC controller is 5.56 ms, resulting in an improvement of 93.74%. A sudden change in load torque (2.5 Nm) is applied at t = 0.168 s, as shown in Zoom 2. Applying the load, both strategies show an undershoot in speed. The undershoot for PI-DPCC is 0.637 rad/s, while ANN-DTC is 0.2111 rad/s, demonstrating an improvement of 66.87%. The rejection times for classical PI-DPCC and ANN-DPCC are 82 ms and 19.39 ms, respectively. Consequently, ANN-DPCC more effectively preserves the system's speed stability than PI-DPCC, significantly improving the PMSM system's Variation load performance.

Figures 6. b and 6. c display the waveforms of the I_{sd} and I_{sq} current components for the PI-DPCC and ANN-DPCC control strategies. These show how the control method affects the system differently, especially during steady-state and transient conditions. The ANN-DPCC strategy achieves a significant ripple reduction in the I_{sq} current, with values decreasing from 1.164 A in PI-DPCC to 0.455 A, corresponding to an improvement of 60.91%. Similarly, ANN-DPCC minimizes the I_{sd} current ripple by 59.69%, reducing it from 1.310 A for PI-DPCC to 0.528 A.

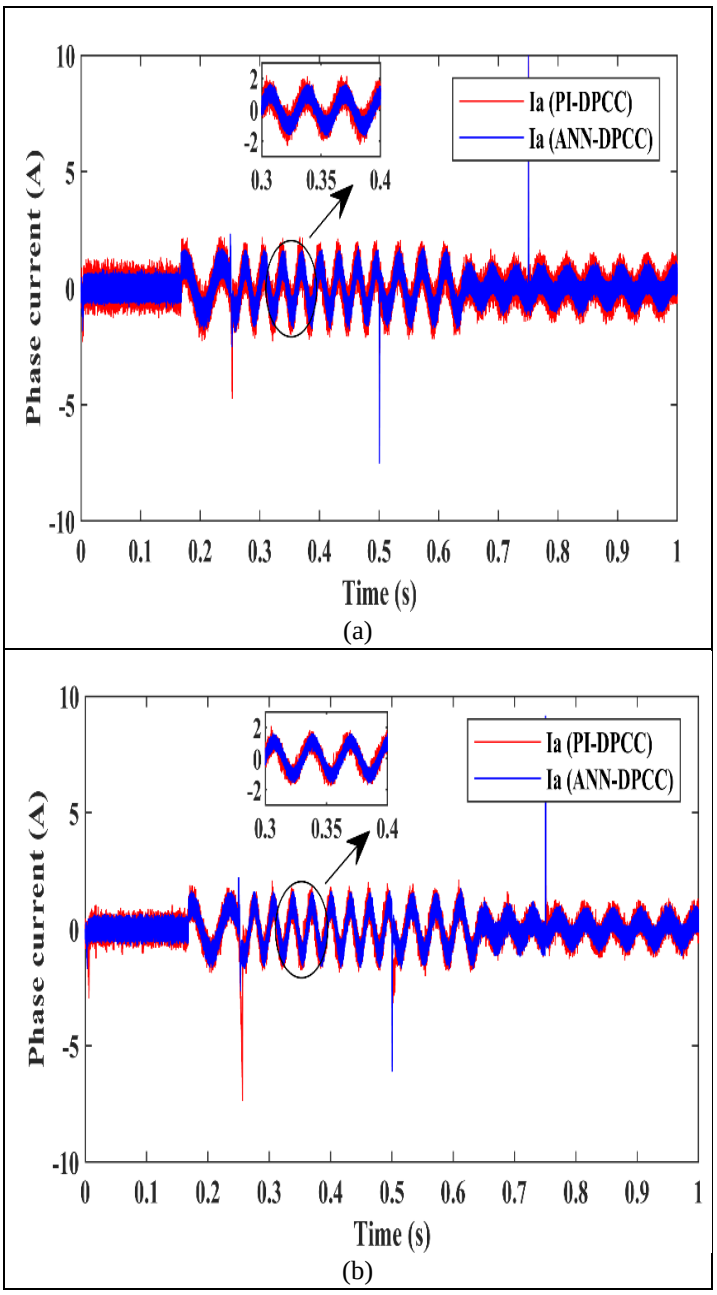
This enhancement is credited to the neural network integration, which effectively mitigates oscillations and improves control efficiency. Figure 6.d illustrates the electromagnetic torque waveforms for the PI-DPCC and ANN-DPCC techniques. Since the flux remains constant, the behaviour of the electromagnetic torque closely aligns with that of the current. The torque ripple observed with the conventional PI-DPCC is significantly higher, measuring 2.452 Nm, compared to 1.084 Nm with ANN-DPCC, indicating a substantial improvement of 55.79%. The results shown in Table 3 showed that in terms of general performance (dynamics, stability, speed and precision), the ANN-DPCC control outperformed the PI-DPCC control.

Table 3: Evaluating the Characteristics of PI-DPCC and ANN-DPCC

Parameters	Characterstics	PI-DPCC	ANN-DPCC	Improvement (%)
ω_e (rad/s)	**Response time (ms)**	88.87	5.56	93.74
	Overshoot (%)	5.959	0	100
	Rejection time (ms)	82	19.39	76.35
	Undershoot (rad/s)	0.637	0.2111	66.87
$I_{sd}(A)$	**Ripple (A)**	1.310	0.528	59.69
I_{sq} (A)	**Ripple (A)**	1.164	0.455	60.91
$T_e(N.m)$	**Ripple (N.m)**	2.452	1.084	55.79

Source: Authors, (2025).

IV.1 DEAD-TIME COMPENSATION STRATEGY FOR PI-DPCC AND ANN-DPCC METHODS



Source: Authors, (2025).

Figure 7: phase current of the PMSM in steady-state. (a) Without dead-time compensation, (b) With dead-time compensation Figures 7.a, and 7.b show the motor operation results with and without the dead-time compensation method. The phase-A current has apparent harmonic distortion when the PI-DPCC method is used for the PMSM system, as shown in Figure 8a. This distortion can negatively affect the operational performance and efficiency of the PMSM system. On the other hand, the ANN-DPCC method significantly reduces the harmonic distortion in the phase-A current. The phase-a current I_a experiences substantial distortion due to dead-time effects in the PI-DPCC system, but this is less pronounced in the ANN-DPCC system. Also, the suggested dead-time compensation method Figure 7.b reduces these problems when the ANN-DPCC control strategy is used. Therefore, dead-time compensation using the ANN-DPCC controller significantly improves the current quality of the PMSM system.

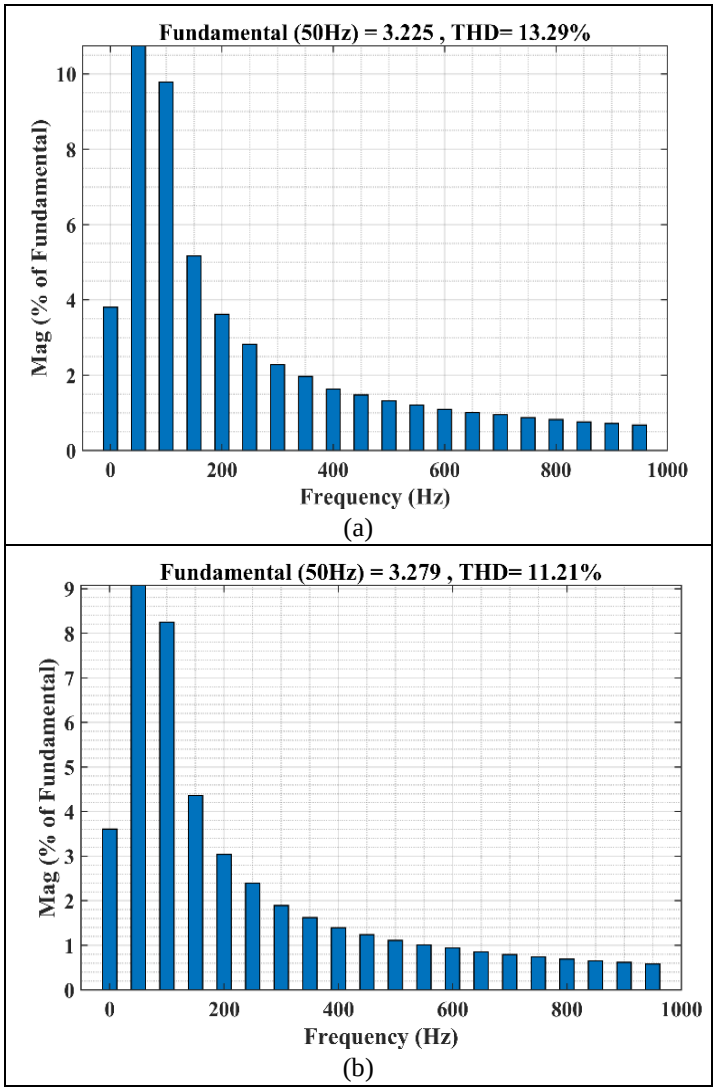


Figure 8: FFT analysis stator current of the PMSM at given state. (a) PI-DPCC. (b) ANN-DPCC
Source: Authors, (2025).

The fast Fourier transform (FFT) harmonic spectrums for both scenarios, with a fundamental frequency of 50 Hz, are shown in Figure 8. The phase-A currents of each system are subjected to a FFT analysis to assess further the impact of the per cent distortion on current quality. Table 4 and Figure 9 present the detailed results. The proposed approach significantly improves performance when comparing PI-DPCC and ANN-DPCC control techniques with and without dead-time compensation. The phase current's THD without dead-time compensation is 11.21% for ANN-DPCC and 13.29% for PI-DPCC. However, when dead-time compensation is included, the THD significantly drops to 9.42% for PI-DPCC and 8.08% for ANN-DPCC. This illustrates how well ANN-DPCC reduces current distortion, with 28.99% and 27.91% reductions, respectively.

Table 4: THD of phase current without dead time compensation and with compensation.

Switching frequency	Methods	THD without compensation	THD with compensation	Improvement (%)
20 kHz	PI-DPCC	13.29	9.42	28.99
	ANN-DPCC	11.21	8.08	27.91

Source: Authors, (2025).

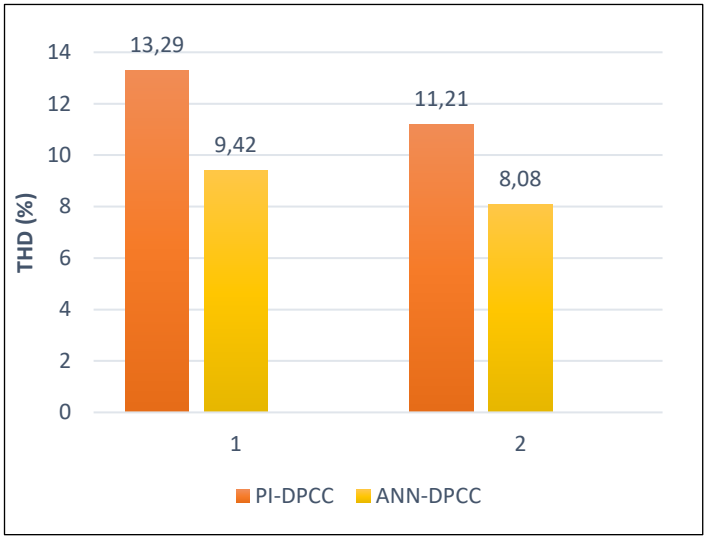


Figure 9. Total harmonic distortion comparison.
Source: Authors, (2025).

V. AUTHOR'S CONTRIBUTION

Conceptualization: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Methodology: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Investigation: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Discussion of results: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Writing – Original Draft: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Writing – Review and Editing: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Resources: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Supervision: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.
Approval of the final text: Amira Slimani, Amor Bourek, Abdelkarim Ammar, Khoudir Kakouche, Wassila Hattab and Marah Bacha.

VI. CONCLUSIONS

The proposed Deadbeat Predictive Current Control strategy, enhanced with an ANN-based speed controller and integrated dead-time compensation, demonstrates significant advancements in the control of PMSMs. The system achieves superior dynamic performance, adaptability to load variations, and improved reference speed tracking by replacing traditional PI controllers with ANN in the speed outer loop. The integration of dead-time compensation effectively mitigates the voltage distortions and current ripples caused by switching delays in the inverter, reducing harmonic distortion and enhancing overall efficiency. The simulation results validate the effectiveness of this approach, highlighting its potential for improving the reliability and performance of PMSM drives in modern applications.

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DEEP TRANSFER LEARNING FOR AUTOMATIC PLANT SPECIES RECOGNITION

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ABSTRACT

Image processing has emerged as a promising tool for plant species recognition, allowing individuals to capture images with their mobile phones in the field and identify plant species or a list of closely related plants. Deep learning, particularly Convolutional Neural Networks (CNNs), has become the leading approach in image recognition tasks. This study explores the use of transfer learning, a deep learning technique, for automatic plant species recognition. Transfer learning involves using pre-trained CNN models, originally trained on large datasets like ImageNet, and fine-tuning them for specific tasks with smaller datasets. In this research, six pre-trained CNN models—VGG16, VGG19, DenseNet121, InceptionResNetV2, MobileNet, and MobileNetV2—were evaluated on a dataset comprising 30 plant species. The goal is to determine which transfer learning model performs best for plant species recognition.

I.INTRODUCTION

Image processing is considered a promising tool for plant species recognition, enabling individuals to take pictures with their mobile phone cameras in the field and identify the plant species or a list of closely related plants [1]. When a computer application assists people in accurately identifying plants, it not only helps in recognizing various species but also raises awareness among the public about the importance of protecting them [2]. In manual recognition system, scientists use different characteristics of the plant such as seeds, fruits, flower, stem and leaf [3].

A key aspect of plant identification presents a significant scientific and technical challenges. These challenges arise not only because of the vast diversity of plant species but also because of their highly varied taxonomic characteristics [4]. For this reason, using manual approaches for plant recognition is a time consuming and demanding [5].

Therefore, it became necessary to develop an automated system for plant identification.This system involves capturing images with a smartphone, which can then be analyzed using image processing software or applications to identify the specific plant species. The analysis includes several steps such as preprocessing to enhance image quality, feature extraction to isolate important parts of the image like leaf shape and texture, and classification using machine learning or deep learning algorithms to match the extracted features with a database of known plant species [1]. Currently, deep learning is widely used in various artificial intelligence applications, especially in image recognition and classification tasks [6],[7]. Different models of Convolutional neural networks (CNNs) are generally used in this tasks [8]. Transfer learning is a technique of deep learning that uses a pre-trained CNNs model on various problems. Transfer learning is a valuable technique when there is a shortage of datasets or limited computational resources. It allows models pre-trained on large datasets like ImageNet to be fine-tuned for specific tasks with smaller datasets. In this paper, we present an approach that uses transfer learning for plant species recognition. Six pre-trained models of CNNs such as VGG16, VGG19, Mobile Net and DenseNet have been tested on a dataset of 30 classes. Our goal is to decide which transfer leaning model is more appropriate for plant species recognition.

II.RELATED WORKS

This section discusses different methods that have been used for species plant recognition using image processing and deep learning.In [9], the authors proposed research that uses deep learning for recognize local fruits. They used transfer learning models such VGG19, Inception-V3, ResNet-50, and MobileNet on

a dataset of eight classes and 3240 samples. The best results are obtained by MobileNet with an accuracy of 99.21%. In [10], the authors used AlexNet model for fruits freshness classification. This model gives an accuracy of 99,3%, 98.2% and 99.8% on three datasets. In [11], the authors suggested a CNN model using data augmentation for plant classification to overcome the problem of insufficient dataset. This work used four dataset which are Fruits-360, PlantVillage, PlantDoc and Plants.

This method showed higher performance comparted to other methods when the experiments were tested on the same datasets. In [12], the authors used VGG16 CNN model for fruits classification. Six classes of the most known fruits were used for the experiments. The results showed the classification accuracy of 94.16%. In [13], the authors used a plant dataset that have 30000 images and contains 100 ornamental species. These images were collected from Beijing Forestry University campus. The proposed ResNet-based model suggested in this work achieved a classification accuracy of 91.78. In [5], the authors proposed a hybrid approach that uses the histogram of oriented gradients vector to extract features. Then, they used those features to make classification using SVM. Secondly, they used CNN for plant species recognition. They achieved an accuracy of 98.22 on Swidish dataset when data is augmented.

III.THE PROPOSED APROACH

Transfer learning is one of the powerful techniques that has been extensively utilized for image recognition applications because of their hierarchical structure and their features extraction capabilities[14]. Transfer learning is a machine learning technique where a pre-trained model, is developed for one task and is repurposed for a different related task. In the context of Convolutional Neural Networks (CNNs), it involves using the learned features from a model trained on a large dataset to improve performance and reduce training time on a smaller, target dataset. It is proved that CNNs can achieve better performance than the classical methods [15].The proposed approach uses transfer leaning for automatic species plant identification. To achieve this goal, four CNN models were applied on a dataset of 30 classes. The flowchart of the proposed approach is shown in Figure 1.

IV.1.PRE-TRAINED CNN MODELS

Six CNN models were utilized in this work which are DenseNet, MobileNet, MobileNetV2, InceptionResNetV2. VGG16 is a CNN model developed by the visual Geometry Group at the University of Oxford. VGG16 modified AlexNet by using 3x3 kernels with 1 stride instead of 1x1 and 5x5 which allows for obtaining complicated features with short time computation. VGG16 is composed of 5 convolutional blocks. Each block have 2 to 3 convolutional layers [16]. All convolutional layers have Relu activation.

VGG19 is a convolutional neural network architecture that was proposed by the Visual Geometry Group (VGG) at the University of Oxford. It is similar to VGG16 but differ in the depth of the layers. It has 6 convolutional layers, 3 fully connected layers, 5 max-pooling layers and total of 19 weight layers. It gave a classification accuracy rate of 88% on the ImageNet dataset [17].

MobileNet is a deep CNN network was proposed by Howard to overcame the problem of using high computational resources. It is suitable for devices with limited resource such as IoT and smartphones devices [18]. MobileNet uses a single filter in the input layer which reduces the computation and uses a 1x1 convolution to join the outputs of the depthwise convolution [19].

Residual Network or ResNet was developed by [20]. ResNet is composed of the residual blocks. Each block a small number of convolutional layers. ResNet have shortcut connection that join directly the input of block by its output. RetNet50 that was used in this work is a specific type of the ResNet. It has 50 layers and is one of the most widely and known model of the ResNet types because of its tradeoff between computational efficiency, performance and the depth [21].

InceptionResNetV2 was introduced by Christian Szegedy [22]. It integrates the power of the residual networks and InceptionNetworks. It is composed of 164 layers and it can classify 1000 objects. It have a good balance between performance and resource requirements [23]. DenseNet is a deep Neural network in which the input of each layer is the concatenation of the outputs of all preceding layers within the same block in a feed-forward fashion to guarantee the maximum information stream between layers [24].

IV.2.DATASET:

To develop our automatic plan species recognition method, we downloaded various plant images from Kaggle. The used dataset is composed of 26970 plant images of 30 classes. Each class have 790 images for training and 100 images for test of different sizes. The 30 plant species are Aloevera, banana, bilimbi, cantaloupe, cassava, coconut, corn, cucumber, curcuma, eggplant, galangal, ginger, guava, kale, longbeans, mango, melon, orange, paddy, papaya, peper chili, pineapple, pomelo, shallot, soybeans, spinach, sweet potatoes, tobacco, waterapple and watermelon.

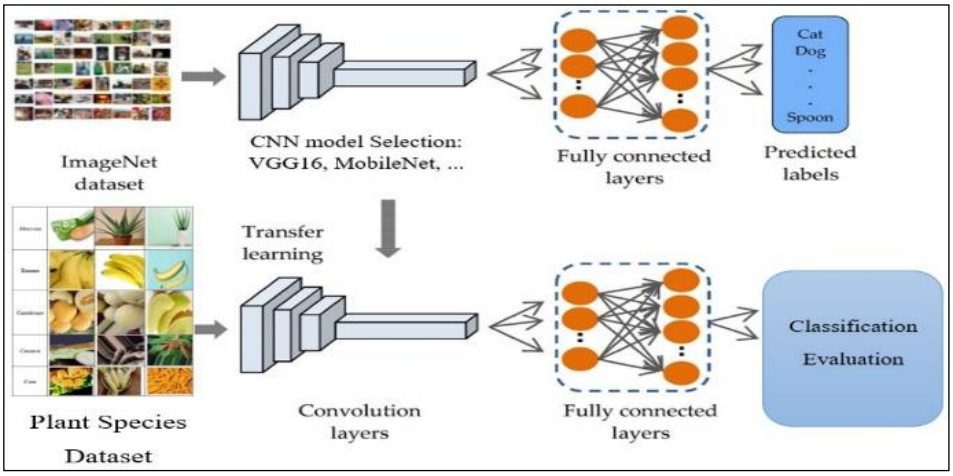

Figure 1: Flowchart of the proposed transfer learning methodology.
Source: Authors, (2025).

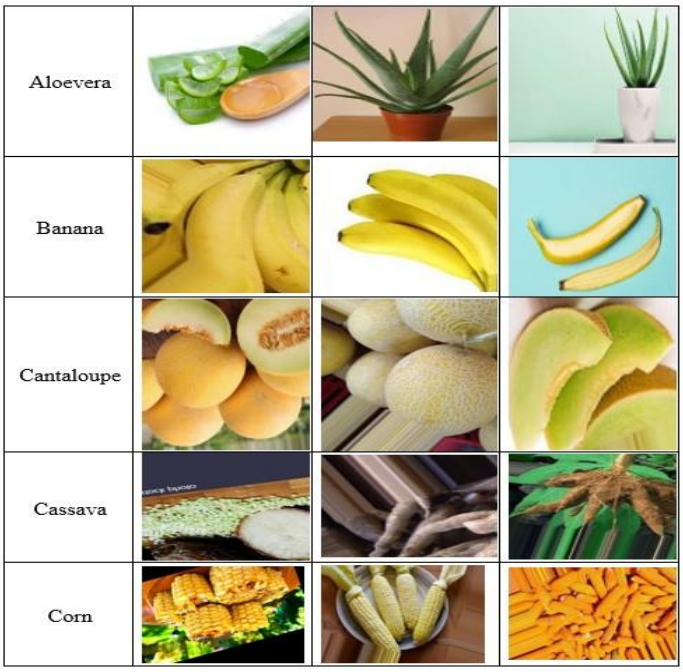

Figure 2: Samples of the different plant species of the used dataset.
Source: Authors, (2025).

IV.EXPERIMENT AND DISCUSSION

IV.1.EXPERIMENT SETTINGS

The six deep learning models were applied on machine using python 2.6 with Keras and Tensorflow. Each model is run on Windows 10 (64 bits) with Intel® Core™ i5-7200U CPU @ 2.50GHz 2.71GHz and 16 Go of RAM. The Adam optimizer with 50 epochs, 32 batch and a learning rate of 0.001 is used to train each model. The sparse categorical cross-entropy was utilized as a loss function. The models used weights pre-trained on ImageNet dataset for transfer learning. The evaluation of deep learning models for plant species recognition is done using the following measurements criteria: The Accuracy is ratio of the number of samples correctly predicted to the overall data. The accuracy is calculated using the following expression [16]:

$$\text{Accuracy} = \frac{TP+TN}{TP+TN++FN+FP} \quad (1)$$

Where TP and FP represent the number of positive samples classified as true and false respectively and TN and FN represent the number of negative samples classified as true and false respectively. The Precision is the ratio of the number of positive samples correctly classified to the overall of samples positive classified. The precision is computed as:

$$\text{Precison} = \frac{TP}{TP+FP} \quad (2)$$

The Recall is the ratio of the number of positive samples correctly classified to the overall of positive samples.

The recall is calculated as:

$$\text{Recall} = \frac{TP}{TP+FN} \quad (3)$$

Where FN represents the count of false negatives

The F1Score combine between precision and recall into a single metric. It is calculated using the following equation:

$$F_1\text{Score} = \frac{2*Precision*Recall}{Precision+Recall} \quad (4)$$

The values of accuracy, precision, recall and F1-score of each model are shown in Table .1.

IV.2.DISCUSSION:

It can be seen from table 1 that Cucumber, Kale, Longbeans, and Sweet Potatoes have high metrics across all four parameters, indicating strong VGG16 performance in identifying these classes. Cantaloupe and Melon show significantly lower scores, particularly in Recall and F1-score, suggesting that VGG16 struggles with these classes. It can be seen from table 2 that Papaya, Peper Chili, Sweet Potatoes, and Spinach demonstrate high performance across all metrics, indicating that the VGG19 model effectively recognizes these classes. Cantaloupe has the lowest performance metrics, particularly in Recall and F1-score, indicating significant difficulty for the model in correctly identifying this class. Curcuma and Galangal also show relatively lower performance, suggesting the need for improvement. The VGG16 shows higher mean values across all metrics compared to VGG19, indicating generally better performance with the former model. From table 3, it can be seen that Longbeans, Corn, Paddy, and Aloevera demonstrate exceptionally high performance across all metrics, indicating MobileNet effectively recognizes these classes. Melon and Cantaloupe show the lowest performance metrics, particularly in Precision, Recall, and F1-score, suggesting significant difficulty for the model in correctly identifying these classes. MobileNet shows the highest mean values across all metrics compared to VGG19 and VGG16, indicating superior overall performance.

Table 1: Different evaluation metrics obtained by using VGG16.

Class	Accuracy	Precision	Recall	F1-score
Aloevera	0.829	0.843	0.860	0.851
banana	0.885	0.855	0.812	0.833
bilimbi	0.872	0.818	0.775	0.796
cantaloupe	0.694	0.585	0.475	0.523
cassava	0.888	0.856	0.885	0.870
coconut	0.818	0.779	0.779	0.779
corn	0.855	0.859	0.875	0.867
cucumber	0.903	0.895	0.949	0.921
curcuma	0.779	0.759	0.737	0.748
eggplant	0.852	0.842	0.800	0.821
galangal	0.797	0.812	0.675	0.737
ginger	0.828	0.829	0.831	0.830
guava	0.803	0.789	0.833	0.810
kale	0.907	0.892	0.923	0.907
longbeans	0.928	0.901	0.912	0.906
mango	0.806	0.723	0.747	0.735
melon	0.721	0.742	0.659	0.698
orange	0.858	0.875	0.820	0.846
paddy	0.833	0.839	0.791	0.814
papaya	0.834	0.857	0.939	0.896
peper chili	0.906	0.851	0.957	0.901
pineapple	0.900	0.861	0.882	0.872
pomelo	0.886	0.855	0.812	0.833
shallot	0.840	0.844	0.852	0.848
soybeans	0.868	0.844	0.802	0.822
spinach	0.862	0.874	0.889	0.881
sweet potatoes	0.905	0.884	0.889	0.886
tobacco	0.853	0.829	0.778	0.803
waterapple	0.871	0.830	0.843	0.836
watermelon	0.846	0.802	0.766	0.784
Mean	**0.847**	**0.829**	**0.823**	**0.825**

Source: Authors, (2025).

Table 4 shows that Waterapple, Sweet Potatoes, Melon, Cucumber, and Peper Chili demonstrate exceptionally high performance across all metrics, indicating MobileNetV2 effectively recognizes these classes. Spinach, Coconut, Ginger, and Tobacco show the lowest performance metrics, particularly in Precision, Recall, and F1-score, suggesting significant difficulty for the model in correctly identifying these classes. MobileNetV2 shows slightly higher mean values for Precision and Recall compared to MobileNet. However, the F1-score is almost identical, showing consistent performance between the two models.

Table 2: Different evaluation metrics obtained by using VGG19.

Class	Accuracy	Precision	Recall	F1-score
Aloevera	0.770	0.845	0.770	0.794
banana	0.853	0.870	0.800	0.833
bilimbi	0.724	0.707	0.820	0.759
cantaloupe	0.533	0.595	0.440	0.506
cassava	0.828	0.763	0.780	0.771
coconut	0.790	0.790	0.820	0.805
corn	0.777	0.724	0.875	0.792
cucumber	0.824	0.752	0.760	0.756
curcuma	0.686	0.666	0.700	0.682
eggplant	0.724	0.779	0.760	0.765
galangal	0.704	0.670	0.690	0.678
ginger	0.805	0.821	0.790	0.800
guava	0.795	0.780	0.790	0.785
kale	0.821	0.831	0.840	0.835
longbeans	0.851	0.844	0.860	0.851
mango	0.763	0.787	0.760	0.770
melon	0.698	0.708	0.650	0.675
orange	0.834	0.839	0.820	0.829
paddy	0.770	0.740	0.820	0.778
papaya	0.876	0.868	0.890	0.878
peper chili	0.899	0.875	0.945	0.909
pineapple	0.845	0.828	0.820	0.823
pomelo	0.865	0.818	0.820	0.819
shallot	0.826	0.810	0.840	0.823
soybeans	0.774	0.740	0.815	0.773
spinach	0.845	0.862	0.860	0.861
sweet potatoes	0.858	0.834	0.890	0.861
tobacco	0.804	0.781	0.770	0.775
waterapple	0.841	0.812	0.850	0.829
watermelon	0.841	0.860	0.780	0.807
Mean	**0.796**	**0.783**	**0.791**	**0.785**

Source: Authors, (2025).

Table 5 shows that Banana, Watermelon, Tobacco, Paddy, Eggplant, Galangal, Orange, Pepper Chili, and Waterapple demonstrate exceptionally high performance across all metrics, indicating that DenseNet effectively recognizes these classes. Cantaloupe shows the lowest performance metrics, particularly in Accuracy, Recall, and F1-score, suggesting significant difficulty for the model in correctly identifying this class. Coconut, Curcuma, Shallot, and Bilimbi also show relatively lower performance compared to other classes, though better than Cantaloupe.

DenseNet shows strong overall performance, with mean Precision and F1-score similar to MobileNetV2 and slightly better than MobileNet. However, its mean Accuracy is slightly lower than MobileNetV2 and MobileNet.

Table 3: Different evaluation metrics obtained by using MobileNet

Class	Accuracy	Precision	Recall	F1-score
Aloevera	0.925	0.902	0.950	0.925
banana	0.906	0.880	0.880	0.880
bilimbi	0.900	0.900	0.900	0.900
cantaloupe	0.850	0.745	0.850	0.794
cassava	0.905	0.950	0.950	0.927
coconut	0.870	0.825	0.870	0.847
corn	0.945	0.935	0.945	0.940
cucumber	0.870	0.780	0.840	0.809
curcuma	0.900	0.850	0.850	0.850
eggplant	0.885	0.850	0.850	0.850
galangal	0.890	0.860	0.860	0.860
ginger	0.820	0.820	0.820	0.820
guava	0.885	0.825	0.870	0.847
kale	0.890	0.890	0.980	0.933
longbeans	0.980	0.980	0.980	0.980
mango	0.900	0.870	0.870	0.870
melon	0.860	0.370	0.370	0.370
orange	0.935	0.830	0.830	0.830
paddy	0.925	0.950	0.950	0.950
papaya	0.900	0.845	0.900	0.872
peper chili	0.890	0.890	0.890	0.890
pineapple	0.900	0.830	0.900	0.864
pomelo	0.905	0.905	0.905	0.905
shallot	0.855	0.820	0.855	0.837
soybeans	0.880	0.840	0.840	0.840
spinach	0.895	0.845	0.845	0.845
sweet potatoes	0.900	0.850	0.850	0.850
tobacco	0.900	0.900	0.900	0.900
waterapple	0.870	0.865	0.865	0.865
watermelon	0.910	0.905	0.910	0.907
Mean	0.893	0.859	0.887	0.863

Source: Authors, (2025).

Table 6 shows that Banana, Cantaloupe, Corn, Melon, and Watermelon demonstrate relatively high performance across all metrics, indicating InceptionResNetV2 effectively recognizes these classes. Coconut shows the lowest performance metrics, particularly in Recall and F1-score, suggesting significant difficulty for the model in correctly identifying this class. Mango and Curcuma also show relatively lower performance compared to

other classes, with Mango showing particularly poor Precision and F1-score. InceptionResNetV2 shows the lowest overall performance metrics compared to DenseNet, MobileNetV2, and MobileNet. Its mean Accuracy, Precision, Recall, and F1-score are all lower than the other models, indicating that InceptionResNetV2 is less effective for this particular classification task.

Table 4: Different evaluation metrics obtained by using MobileNetV2.

Class	Precision	Recall	F1-Score
Aloevera	0,91	0,91	0,91
Banana	0,97	0,88	0,92
Bilimbi	0,77	0,91	0,84
Cantaloupe	0,89	0,85	0,87
Cassava	0,9	0,94	0,92
Coconut	0,86	0,82	0,84
Corn	0,93	0,92	0,92
Cucumber	0,95	0,91	0,93
Curcuma	0,94	0,88	0,91
Eggplant	0,94	0,88	0,91
Galangal	0,85	0,94	0,89
Ginger	0,84	0,88	0,86
Guava	0,89	0,89	0,89
Kale	0,95	0,91	0,93
Longbeans	0,85	0,93	0,89
Mango	0,89	0,87	0,88
Melon	0,91	0,96	0,93
Orange	0,86	0,9	0,88
Paddy	0,87	0,96	0,91
Papaya	0,91	0,88	0,89
Peper Chili	0,95	0,92	0,93
Pineapple	0,85	0,85	0,85
Pomelo	0,9	0,85	0,87
Shallot	0,88	0,85	0,86
Soybeans	0,91	0,86	0,88
Spinach	0,84	0,83	0,83
Sweet Potatoes	0,93	0,95	0,94
Tobacco	0,89	0,84	0,86
Waterapple	0,97	0,95	0,96
Watermelon	0,94	0,95	0,94
Mean	0,90	0,90	0,89

Source: Authors, (2025).

Overalll from table 7, it can be see.

is the first choice for this classification task given its top performance across all metrics. MobileNet and DenseNet121 are also alternative Options with robust performance.

The confusion matrix of each model is shown in Fig. 5. Considering the confusion matrix of MobleNetV2, it can be seen that there are clear confusions between Melon and Cantaloupe, Pomelo and Coconut, Curcuma and Ginger and Orange and Pomelo.

Table 5: Different evaluation metrics obtained by using DenseNet.

Class	Accuracy	Precision	Recall	F1-Score
Aloevera	0.87	0.89	0.88	0.88
Banana	0.97	0.98	0.97	0.97
Bilimbi	0.84	0.86	0.85	0.85
Cantaloupe	0.75	0.78	0.75	0.76
Cassava	0.84	0.87	0.84	0.85
Coconut	0.81	0.83	0.81	0.81
Corn	0.91	0.92	0.91	0.91
Cucumber	0.90	0.91	0.90	0.90
Curcuma	0.83	0.86	0.83	0.84
Eggplant	0.92	0.94	0.92	0.92
Galangal	0.92	0.94	0.92	0.92
Ginger	0.87	0.89	0.87	0.87
Guava	0.88	0.89	0.88	0.88
Kale	0.86	0.89	0.86	0.87
Longbeans	0.87	0.89	0.87	0.88
Mango	0.88	0.90	0.88	0.88
Melon	0.84	0.86	0.84	0.84
Orange	0.92	0.93	0.92	0.92
Paddy	0.95	0.95	0.95	0.95
Papaya	0.89	0.90	0.89	0.89
Pepper Chili	0.92	0.94	0.92	0.92
Pineapple	0.90	0.91	0.90	0.90
Pomelo	0.87	0.89	0.87	0.87
Shallot	0.84	0.86	0.84	0.84
Soybeans	0.90	0.91	0.90	0.90
Spinach	0.88	0.90	0.88	0.88
Sweet Potatoes	0.88	0.90	0.88	0.88
Tobacco	0.95	0.96	0.95	0.95
Waterapple	0.92	0.94	0.92	0.92
Watermelon	0.96	0.97	0.96	0.96
Mean	**0.88**	**0.90**	**0.88**	**0.89**

Source: Authors, (2025).

Table 6: Different evaluation metrics obtained by using InceptionResNetV2.

Class	Accuracy	Precision	Recall	F1-Score
Aloevera	0.75	0.75	0.75	0.75
banana	0.89	0.98	0.83	0.90
bilimbi	0.83	0.68	0.82	0.74
cantaloupe	0.85	0.87	0.83	0.85
cassava	0.70	0.91	0.68	0.78

coconut	0.55	0.64	0.46	0.53
corn	0.85	0.87	0.82	0.85
cucumber	0.71	0.63	0.71	0.67
curcuma	0.59	0.85	0.58	0.69
eggplant	0.72	0.86	0.69	0.77
galangal	0.73	0.63	0.62	0.63
ginger	0.73	0.69	0.57	0.62
guava	0.75	0.77	0.61	0.68
kale	0.76	0.78	0.65	0.71
longbeans	0.84	0.82	0.86	0.84
mango	0.55	0.33	0.57	0.42
melon	0.80	0.77	0.80	0.79
orange	0.80	0.64	0.83	0.72
paddy	0.71	0.72	0.70	0.71
papaya	0.75	0.89	0.70	0.78
peper chili	0.75	0.65	0.79	0.71
pineapple	0.77	0.69	0.65	0.67
pomelo	0.71	0.55	0.65	0.60
shallot	0.76	0.67	0.69	0.68
soybeans	0.76	0.59	0.82	0.69
spinach	0.83	0.69	0.82	0.75
sweet potatoes	0.81	0.70	0.83	0.76
tobacco	0.80	0.58	0.68	0.63
waterapple	0.76	0.79	0.68	0.73
watermelon	0.82	0.88	0.79	0.83
Mean	**0.75**	**0.73**	**0.71**	**0.71**

Source: Authors, (2025).

Table 7: Mean values of each metric for each model.

Class	Accuracy	Precision	Recall	F1-Score
VGG16	0.84	0.829	0.823	0.82
VGG19	0.79	0.783	0.791	0.78
MobileNet	0.8	0.859	0.887	0.86
MobileNetV2	**0,90**	**0,90**	**0,89**	**0,90**
DenseNet121	0.88	**0.90**	0.88	0.89
InceptionResNetV2	0.75	0.73	0.71	0.71

Source: Authors, (2025).

V.CONCLUSION

The study presented an approach for automatic plant species recognition using transfer learning with six pre-trained CNN models: VGG16, VGG19, DenseNet121, InceptionResNetV2 MobileNet, and MobileNetV2. These models were tested on a dataset of 30 plant species. The experimental results demonstrated that transfer learning is highly effective for plant species recognition, with MobileNetV2 showing the best overall performance across all evaluation metrics. The MobileNetV2 model achieved the highest accuracy, precision, recall, and F1-score, making it the most suitable model for this task. MobileNet and DenseNet also showed strong performance and can be considered as alternativ .

VI. AUTHOR'S CONTRIBUTION

Conceptualization: OUAHAB Abdelwhab.
Methodology: OUAHAB Abdelwhab.
Investigation: OUAHAB Abdelwhab.
Discussion of results: OUAHAB Abdelwhab.
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Writing – Review and Editing: OUAHAB Abdelwhab.
Resources: OUAHAB Abdelwhab.
Supervision: OUAHAB Abdelwhab..
Approval of the final text: OUAHAB Abdelwhab.

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OPTIMIZING ARTIFICIAL NEURAL NETWORKS WITH PARTICLE SWARM OPTIMIZATION FOR ACCURATE PREDICTION OF INSULATOR FLASHOVER VOLTAGE UNDER DRY AND RAINY CONDITIONS

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ABSTRACT

Outdoor insulators are highly susceptible to environmental factors, such as moisture, rain, and contaminants, which significantly degrade their efficiency and durability. These factors contribute to surface flashovers, leading to insulation failures in outdoor power systems. This study presents a novel application of advanced machine learning techniques to predict the flashover performance of glass insulators under diverse environmental conditions, focusing on dry and rainy scenarios. The research emphasizes the critical role of raindrops in reducing flashover voltage. A hybrid model combining Artificial Neural Networks (ANN) with Particle Swarm Optimization (PSO) is developed to address these challenges. The PSO algorithm optimizes the ANN's hyperparameters, enabling the model to establish a nonlinear relationship between key insulator characteristics, including standard and anti-pollution profiles and their critical flashover voltage. Rigorous testing demonstrated exceptional accuracy, with a mean absolute percentage error (MAPE) of 0.2458 and a near-perfect coefficient of determination (R^2) of 0.999. These findings highlight the robustness and reliability of the proposed hybrid model in predicting flashover voltage under varying environmental conditions. This work provides a powerful tool for enhancing the design, maintenance, and operational reliability of outdoor insulators, particularly in regions prone to high levels of pollution and moisture, contributing significantly to the advancement of sustainable power transmission systems.

I. INTRODUCTION

insulators are critical components of power transmission and distribution systems, ensuring electrical insulation between conductors and grounded towers while supporting overhead lines. However, their performance is significantly affected by environmental conditions, material properties, and surface contamination [1].

Contaminants such as dust and industrial emissions significantly threaten outdoor insulators. They cause problems with performance and decrease the life of an insulator faster. This accumulation of arcing and corona discharges erodes the insulator surface finish, leaving flashover paths and accelerating the aging process. These pollutants lead to surface cracking and erosion, increasing the leakage current path over the insulator's surfaces and aggravating this fault by the conduction flow along its surface. Therefore, researchers must study the long-term behavior of insulators in outdoor environments [2],[3].

To cope with different environmental conditions, insulators are designed with varying profiles. Standard profile insulators are widely used in areas with low pollution, as they are more economical. In contrast, anti-pollution profile insulators are specifically designed for regions with moderate to high pollution levels, where they provide better performance under challenging conditions [4]. The behavior of these two insulator types differs significantly when exposed to pollutants, particularly under dry and wet conditions. The situation becomes even more complex

when multiple insulators are connected in chains, which is common in modern high-voltage transmission systems [5].

Many studies have focused on assessing insulator performance under pollution stress, employing various physical and mathematical models [6]. Experimental research has developed much over the years, as evidenced by the early analyses of this topic [7],[8]. Better characterization of the physical environment through simulation tools, which represent the complexity of environmental conditions that insulators are subjected to, has dramatically helped to understand the mechanism of pollution-induced performance degradation. Such development helps in a better characterization of insulator behavior under a broad range of stresses, as well as for the development of improved predictive models, which aim to reduce the risk of flashover.

The literature includes several advanced predictive models, such as time-series simulations, regression techniques, and artificial intelligence methods like artificial neural networks (ANN) [9], adaptive neuro-fuzzy inference systems (ANFIS), [10] and least squares support vector machines (LS-SVM) [11]. These models have been applied extensively to forecast the behavior and performance of insulators in polluted environments.

Among neural network architectures, the Multi-Layer Perceptron (MLP) is one of the most widely recognized and applied models, typically utilizing the backpropagation (BP) algorithm or one of its derivatives, known as the Backpropagation Neural Network (BPNN). However, the BP algorithm's reliance on the steepest descent search technique makes it prone to convergence issues, such as getting stuck in local optima, or in some cases, even leading to computational overflow or oscillation. These limitations have driven researchers to explore more powerful optimization techniques to enhance the effectiveness of neural networks [9].

A breakthrough in this regard is the application of evolutionary algorithms (EA) to optimize neural networks. One of the most effective of these techniques is Particle Swarm Optimization (PSO), introduced by Eberhart and Kennedy, inspired by the social behavior of birds and fish flocks [12]. Initially developed to graphically simulate the graceful, yet unpredictable, movements of flocks, the PSO algorithm was later refined to improve its performance by removing unnecessary parameters, resulting in the basic PSO algorithm.

Recent research has focused on training Artificial Neural Networks (ANNs) using the Particle Swarm Optimization (PSO) technique to predict the flashover voltage of outdoor insulators. This approach leverages data from real-world experiments conducted on high-voltage insulators to build a comprehensive database for applying artificial intelligence methodologies. These experiments involve varying levels of artificial contamination using distilled brine, with each contamination level quantified by the amount of brine applied per unit area of the insulator [13]

In this study, we propose a PSO-trained ANN model to predict the flashover voltage of standard and anti-pollution profile glass insulators under dry and rainy conditions. These insulators, extensively deployed by SONELGAZ in Algeria, are critical for reliable power delivery in diverse environmental settings. By addressing key limitations of traditional methods, our approach aims to provide a robust predictive tool for optimizing insulator performance, with implications for power utilities globally.

II. PARTICLE SWARM OPTIMIZATION (PSO)

The PSO algorithm was first developed by Kennedy and Eberhart in 1995 [12], inspired by the collective behavior observed in animal groups, such as flocks of birds and schools of fish. A semi-evolutionary swarm intelligence algorithm is one way to describe this particular method.

The process is driven by randomly picking and testing solutions and then using the results to find, step by step, a better one [14]. Every solution scanned in this process is attached to a search strategy that works at the speed and with the memory of the best condition it was ever exposed to.

There are three critical elements that play a crucial role: position, velocity, and fitness. To address an optimization issue using PSO, the steps are as follows:

- Generate an initial population of particles with random positions and velocities within the problem space.
- Calculate the fitness value for each particle.
- Update the particle positions and velocities based on equations (1) and (2)[15].

The PSO method employs equation 1 to do the update on velocity.

$$v_{ij}(t+1) = wv_{ij}(t) + c_1 r_1\left(pB_{ij}(t) - x_{ij}(t)\right) + c_2 r_2\left(gB_{ij}(t)\, x_{ij}(t)\right) \quad (1)$$

Where pij(t) represents the best personal memory, gi (t) represents the best collective memory, W represents the factor of inertia weight of particle, c1, and c2 represent the coefficients of individual learning, and r1 and r2 rep3resent the coefficients of collaborative learning [13].

To determine the positions of any newly introduced particles, this method relies on Equation 2 [14].

$$x_{ij}^{t} = x_{ij}^{t-1} + v_{ij}^{t} \quad (2)$$

III. NEURAL NETWORK MODEL

In principle, ANNs are similar to the biological systems that humans and other animals have, so they have become an excellent tool for analyzing complex data sets [9]. They excel at revealing less apparent relations between the inputs and the output, even if the data set is pretty noisy but complicated. The most widely used neural network architecture is the multilayer perceptron (MLP). However, prior research indicates that the brute force design of these networks is important, as only some formula works in every case [16].

In addition to its essential function, the ANN model created and trained in this paper predicts the flashover voltage of polluted glass insulators in extreme environments (both dry and rainy) and for different designs (standard and anti-pollution) as a function of time. The main objective of this study is to reach the topmost performance for the model by carefully refining the model architecture, determining the best fitting of activation functions thirdly, and tuning the training algorithms to gain exact prediction so that it can be highly reliable and robust for flashover voltage prediction in different surrounding such as high voltage power system dependability domain.

IV. ANN ARCHITECTURE AND OPTIMIZATION APPROACH

Our ANN model follows a multilayer perceptron (MLP) architecture known for its robustness in learning and predictive power. The MLP architecture consists of:

- **Input Layer**: Incorporates features related to the insulators, humidity, rainfall intensity, and insulator profile (standard vs. anti-pollution). These input variables provide the data needed for predicting flashover voltage across different scenarios.

• **Hidden Layers**: Hidden layers allow the ANN to process and interpret complex interactions between input variables. By applying nonlinear activation functions like the sigmoid or tangent-sigmoid (Logsig), the model is able to capture subtle relationships within the data.

• **Output Layer**: Provides the flashover voltage prediction based on the input variables and learned relationships. The output is a continuous value that represents the expected flashover voltage for each insulator configuration.

The mathematical formulation behind the MLP can be described as follows [9]:

$$S_j = F\left(\sum_{j=1}^{n} w_{kj} E_j + B_j\right) \quad (3)$$

Where:

• Sj is the neuron output in the current layer,
• F is the activation function,
• wkj and Bj are the weights and biases, respectively,
• Ej represents the node values from the preceding layer.

As depicted in figure 1, once the structure of the ANN is established, the subsequent step involves training the network.

IV.1 MODEL DEVELOPMENT

In this study, we employed a hybrid approach that combines Particle Swarm Optimization (PSO) and Artificial Neural Networks (ANN) to accurately forecast flashover voltage. The PSO algorithm optimizes the neural network's weights and biases, improving the model's performance in terms of both speed and accuracy.

Given its powerful capability for data-driven simulations and optimization, MATLAB was used to build the PSO-ANN model. The methodology started with collecting a data set that comprised numerous influencing factors as input variables such as insulator geometrical features (the spacing between the two consecutive insulator threads, S; in mm), diameter Dm (in mm), leakage length of one-piece and the number elements in the chain of insulator NE. The model's output is flashover voltage prediction (Vc, in kV) concerning two kinds of conditions: dry and rainy.

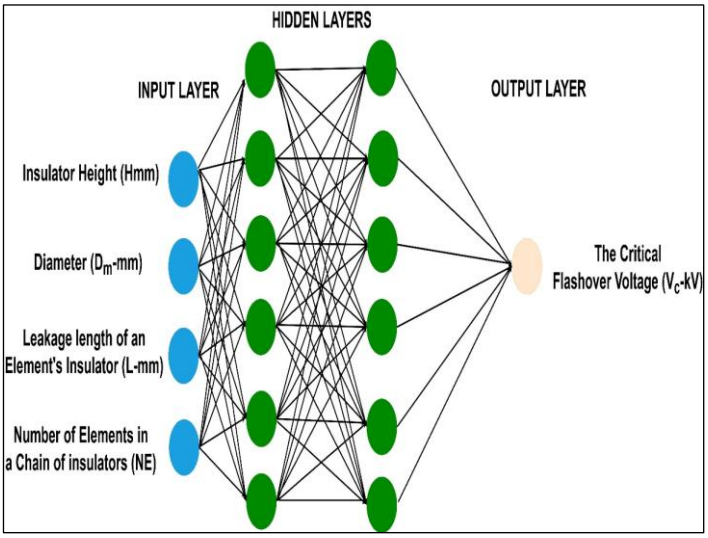

Figure 1: A standard representation of an artificial neural network (ANN).
Source: Authors, (2025).

The first step was to structure the dataset, ensuring that the input features (insulator spacing (S, in mm), diameter (Dm, in mm), leakage length of the insulator element (L, in mm), and the number of elements in the insulator chain (NE) were properly normalized. Then, the PSO algorithm was configured to optimize the initial weights and biases of the neural network.

After the ANN structure was defined consisting of input, hidden, and output layers the PSO algorithm iteratively adjusted the network's parameters, seeking the configuration that minimized the mean squared error (MSE) between predicted and actual flashover voltages. The optimization process continued until convergence, with the best particle's position representing the optimal set of network weights.

$$MSE = \left(\frac{1}{N}\right) \sum_i |t_i - o_i|^2 \quad (4)$$

Once training was complete, the model was validated using test data that were not part of the training process.

The process of training the ANN using PSO involved seven key steps:

1.Collecting the necessary data.
2.Creating the neural network.
3.Configuring the network.
4.Initializing the weights and biases of the network.
5.Training the neural network using the PSO algorithm.
6.Validating the network to assess its performance.
7.Applying the trained network for predictions.

The optimal configuration for the ANN-PSO model was established as follows: (a) The hidden layer comprised 10 neurons. (b) The training process was run for 6000 iterations. (c) The particle swarm consisted of 100 particles. (d) The acceleration constants were set at c1 = 1 and c2 = 2.

A three-layer neural network predicts insulator flashovers (Figure 2). The network architecture includes four six neurons, a hidden layer with 10 neurons, and a single output neuron. The parameters c1 and c2 are kept constant; for each config file, multiple test metrics are run to determine the better network configuration. We calculate the average deviation to find a network trained for up to 6000 iterations with minimal error. Iteratively undergoing this process ensures the model's capability to generalize in any situation and reduce predictive error.

IV.2 DATA SELECTION

In the testing process for insulators, including those featured in this study, a comprehensive evaluation of both electrical and mechanical parameters is conducted to ensure their performance and reliability under various operational conditions. A critical aspect of this evaluation is the flashover voltage test, which assesses the insulator's ability to withstand high voltages without experiencing flashover, a disruptive electrical discharge across its surface. The flashover voltage is measured under both dry and wet conditions, simulating real-world environmental factors such as rain or humidity that could impact the insulator's performance.

Each insulator model is subjected to stringent mechanical and electrical rating tests as per international standards, such as IEC 60305, ANSI, and BS [17]. These tests are essential for ensuring the insulator's capability to endure stresses encountered across different voltage ranges and environmental pollution levels. Additionally, insulators are categorized into various profiles standard and anti-pollution profile to optimize performance in specific environments, such as low-pollution areas or regions exposed to heavy pollution or desert conditions. This rigorous testing protocol ensures the reliability and operational safety of insulators used in high-voltage transmission systems worldwide.

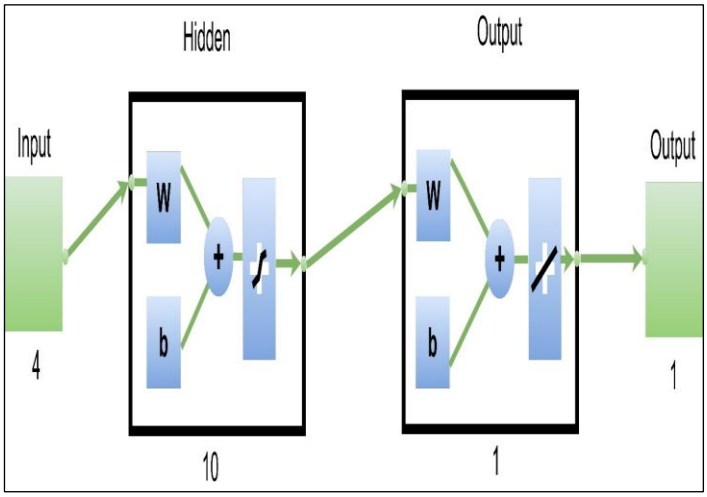

Figure 2: The network training model in MATLAB.
Source: Authors, (2025).

In this study, we focused on data derived from experimental results for the prediction of flashover voltage on two types of insulators: the standard profile insulator and the anti-pollution profile insulator, both tested under dry and rainy conditions. Our objective was to investigate the impact of rain on the flashover voltage. To achieve this, several key parameters were selected as input vectors for the predictive model, including insulator spacing (S, mm), diameter (Dm, mm), leakage length of the insulator element (L, mm), and the number of elements in a chain of insulators (NE). The predicted output is the flashover voltage (Vc, kV) under both dry and rainy conditions. In our investigations, the number of insulator elements in the chain varied, ranging from a minimum of two to a maximum of thirty, allowing us to comprehensively study the effects of different configurations and environmental conditions on the flashover voltage. This approach provides valuable insights into how rain affects the electrical performance of insulators, particularly in polluted and extreme environmental settings [17] .

Table 1 presents the characteristics and specifications of various types of insulators.

IV.3 CASE STUDIES

To effectively evaluate the predictive accuracy of the ANN -PSO model, it is necessary to use a dataset of diverse species in the testing phase that was not used in the training phase. This approach allows the creation of a representative and unbiased test set.

Splitting the data correctly can be particularly important when creating machine learning models, especially during training and testing. According to available research, 70-80 % of the data (for training) and 20-30% (for testing) can yield optimal performance. [18],[19]. For our model, 75 % of the data is reserved for training, and 25 % is reserved for testing, with the split being consistent on whether the data belongs to type 1 or type 2 insulators.

The test set data is then used to test the models' predictive accuracy. This allows the model to be trained on the given data with as slight bias and training error as possible but still retain the ability to be generalized to new data with as slight variance and test error as possible.

Table 2 presents various case studies, detailing the number of elements in the insulator chain for each type of insulator. Additionally, it includes the number of training data points and testing data points for each of the three types of insulators.

Table 1: Key features of the insulators examined in the study [17].

Insulator Type (Model)		S (mm)	D(mm)	L(mm)
Standard profile insulators	NB-70-146	146	255	320
	NB-100-146	146	255	320
	NJ-120-146	146	255	320
	NK-180-146	146	280	320
	NK-220-156	156	280	380
Anti-pollution profile insulators	NB-100PPZ-146	146	*280*	445
	NJ-120PPZ-146	146	280	445
	NJ-140PPZ-146	146	280	445
	NK-160PZ-171	171	330	545
	NK-222PZ-171	160	330	545

Source: Authors, (2025).

Table 2:The different cases studied.

	Standard profile insulators	Anti-pollution insulators
NE in train Case	22	22
NE in test case	7	7
Training data	110	110
Testing data	35	35

Source: Authors, (2025).

IV.4 PERFORMANCE EVALUATION METRICS

This study selected various performance metrics were selected to evaluate the proposed models and identify the most accurate one for predicting the Flashover output voltage. These metrics included the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute percentage error (MAPE). The following formulas were applied to compute these indices: [10]

$$R^2 = 1 - \frac{\sum_{k=1}^{n} (y_{tes,k} - y_{pre,k})^2}{\sum_{k=1}^{n} (y_{tess,k} - \overline{y_{tes,k}})^2} \quad (5)$$

$$RMSE = \left\{ \frac{\sum_{k=1}^{n} (y_{tes,k} - y_{pre,k})}{n} \right\}^{1/2} \quad (6)$$

$$MAPE = 100\%. \frac{\sum_{k=1}^{n} |y_{tes,k} - y_{pre,k}| / y_{tes,k}}{n} \quad (7)$$

V. RESULTS AND DISCUSSION

The assessment of insulator performance in different environmental conditions is crucial for comprehending the mechanisms underlying arc initiation and flashover incidents. This research focuses on examining insulator behavior in both dry and rainy settings, with a particular emphasis on how these conditions affect their electrical characteristics.

The findings shed light on the way environmental elements impact key parameters like flashover voltage, underscoring the necessity for customized predictive models tailored to diverse insulator types and weather circumstances.

The study was conducted in two distinct phases: the first phase focused on determining the critical flashover voltage under dry conditions, while the second phase examined the same under wet conditions, utilizing experimental test data from previous research [17].

The performance of the model developed using the ANN-PSO approach was thoroughly evaluated, yielding superior results compared to existing methodologies. These findings are presented in Figures 3 to 6. Figures 3 and 4 present the performance of the ANN-PSO model in predicting the flashover voltage using the testing dataset for the standard profile insulator under dry and rainy

condition. The model demonstrates a remarkable ability to closely replicate the trend of the experimental data, indicating that it has been effectively trained to capture the complex, nonlinear relationships governing flashover voltage behavior. The significant overlap between the experimental results and the ANN-PSO predictions during the testing phase underscores the model's high degree of accuracy and its capability to generalize the intricate characteristics of flashover voltage for both insulator profiles.

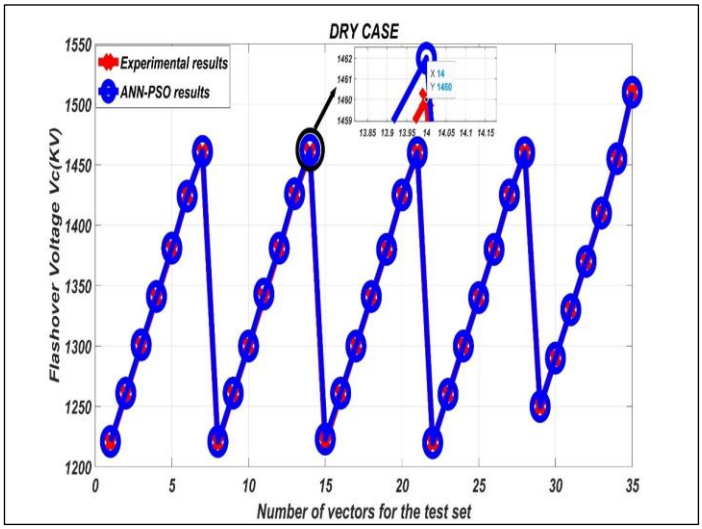

Figure 3: ANN-PSO model performance for testing (standard profile under dry conditions)
Source: Authors, (2025).

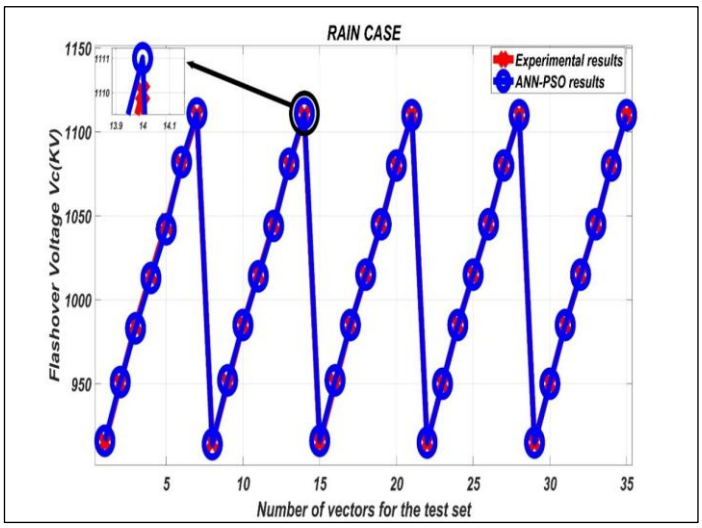

Figure 4: ANN-PSO model performance for testing (standard profile under Rain conditions)
Source: Authors, (2025).

Figures 5 and 6 evaluate the model's performance using an independent testing dataset for the anti-pollution profile insulator, offering additional confirmation of its predictive accuracy.

Even when faced with data points not previously encountered during training, the ANN-PSO model consistently produces predictions that closely match the experimental results. This reliability under
unfamiliar conditions underscore the model's robustness and its strong ability to generalize beyond the training dataset.

The results highlight the model's potential as an effective tool for predicting critical flashover voltage, with implications for optimizing insulator design and improving the reliability of high-voltage systems under diverse operating conditions.

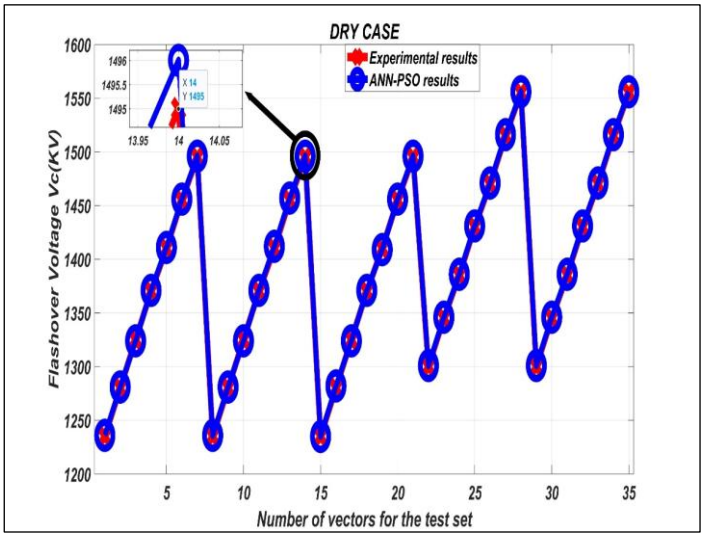

Figure 5: ANN-PSO model performance for testing (Anti-pollution profile under dry conditions)
Source: Authors, (2025).

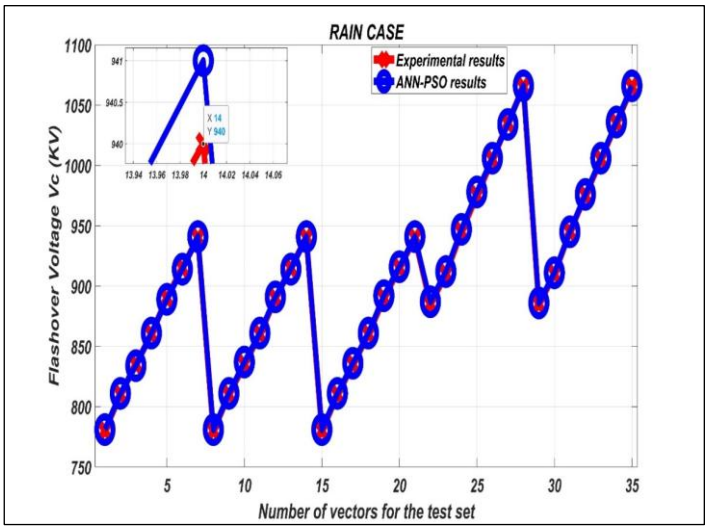

Figure 6: ANFIS-PSO model performance for testing (Anti-pollution profile under Rain conditions).
Source: Authors, (2025).

According to the results presented in Figures 3 through 6, the flashover voltage of insulators under rainy conditions is significantly lower compared to dry conditions. This explains how the deposition of water droplets on the surface of insulators alters the resistance Rp. Rain introduces water on the insulator's surface, which can significantly reduce the surface resistance, especially if the water contains dissolved salts or other contaminants.

The presence of water promotes the formation of a conductive path along the insulator's surface, leading to a substantial decrease in flashover voltage. This means that under wet conditions, the insulator is more prone to flashover at lower voltages compared to dry conditions. By comparing the values of flashover voltage in dry and rainy conditions, we can calculate the mean percentage as follows:

For standard profile : $\frac{\text{V Dry}}{\text{V Rain}} = 1.3423,$

For anti-pollution profile: $\frac{\text{V Dry}}{\text{V Rain}} = 1.4600,$

Anti-pollution profile insulators exhibit clear superiority over standard profile insulators due to their enhanced design

features tailored for polluted and challenging environments. With increased leakage distances and optimized profiles, they effectively reduce surface electric field intensity and mitigate the risk of flashovers caused by contamination and moisture.

Unlike standard insulators, which are more susceptible to flashovers under polluted or wet conditions, anti-pollution insulators demonstrate higher flashover voltage and better performance, even in regions with heavy industrial emissions, salt deposits, or extreme weather. Their self-cleaning capability allows rain and wind to remove contaminants more efficiently, maintaining their insulating properties and reducing maintenance requirements.

Additionally, anti-pollution insulators are more resistant to surface erosion and material degradation, ensuring longer operational life and greater reliability in high-voltage applications. These attributes make them the preferred choice for ensuring the safety and efficiency of power transmission systems in harsh environmental conditions.

To evaluate the precision of the ANN-PSO model, one approach is to analyse the correlation between the actual critical flashover voltage (V_c) and the estimated values produced by the ANN-PSO. With the maximum possible correlation being one, a correlation value closer to 1 indicates a higher performance level of the model. Figures 7 and 8 display the correlation for the estimated versus actual values of V_c for the Anti-pollution profile insulator under both dry and rainy conditions, which were used to assess the model.

The data points almost perfectly align with the line of best fit, demonstrating the model's strong ability to accurately predict the duty ratio for the test dataset. Specifically, the correlation for the test set under dry conditions reached 0.99812, while under rainy conditions, it was 0.999, showcasing the model's high accuracy in both scenarios. Evaluating the ANN-PSO model's performance involves comparing it with other models, a key step in assessing its effectiveness.

To do this, validation indices such as RMSE, MAPE, and R^2 were measured against results previously reported in literature for two specific scenarios, as detailed in Table 3. From the comparison outlined in Table 3 with other intelligent methods, it is evident that the model we propose stands out by securing a higher coefficient of determination (R^2=0.999) and exhibiting a remarkably low root mean square error (RMSE=0.00288), clearly surpassing other modelling approaches in effectiveness.

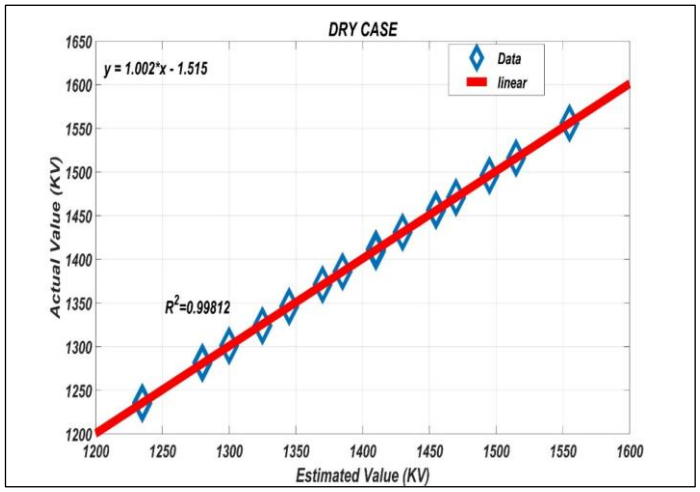

Figure 7: Correlation between predicted and actual Critical Flashover Voltage values for Anti-pollution profile insulators tested under dry conditions.
Source: Authors, (2025).

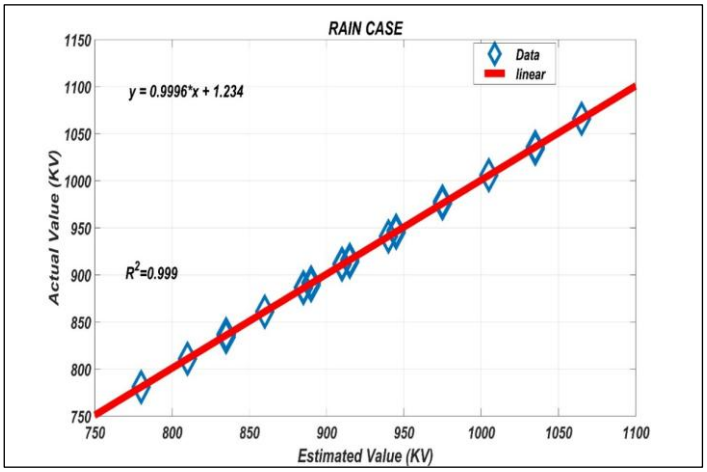

Figure 8: Correlation between predicted and actual Critical Flashover Voltage values for Anti-pollution profile insulators tested under Rainy conditions.
Source: Authors, (2025).

Table 3: Evaluating the suggested ANN-PSO models against other modelling approaches.

Methods	(RMSE)	(R^2)	(MAPE)
GMDL Dry [17]	-	0.9929	-
GMDL Rain [17]	-	0.998	-
LS-SVM Dry [17]	0.0389	0.997	-
LS-SVM Rain [17]	0.371	0.9983	-
ANN-PSO Dry	0.00288	0.999	0.2458
ANN -PSO Rain	0.00295	0.99812	0.3546

Source: Authors, (2025).

The findings indicate that an ANN trained with PSO not only offers more accurate predictions, but also requires fewer computational resources. This approach is particularly robust, as it avoids becoming trapped in local optima. Moreover, it benefits from straightforward logic, ease of implementation, and built-in intelligence. When compared to results from practical experiments, the PSO-ANN technique proves to be highly effective in forecasting flashover in high-voltage polluted insulators.

VI. CONCLUSIONS

This study introduces an advanced Artificial Neural Network (ANN) model optimized using the Particle Swarm Optimization (PSO) algorithm to predict the flashover voltage of glass insulators with standard and anti-pollution profiles under dry and rainy conditions. The research highlights the significant influence of raindrops on reducing flashover voltage, emphasizing the critical implications for the reliability of high-voltage insulation systems.

The ANN's parameters were meticulously fine-tuned by leveraging the PSO algorithm, enabling the model to effectively capture the complex interactions between insulator characteristics, environmental conditions, and flashover performance. The findings indicate that this model excels at forecasting flashover voltages for contaminated high-voltage insulators in various weather conditions.

To evaluate the effectiveness of the suggested model, several statistical measures were utilized, including the Root Mean Square Error (RMSE), the Mean Absolute Percentage Error (MAPE), and the coefficient of determination (R^2). The analyses and outcomes of this study, including comparisons with other methodologies such as GMDL, ANFIS, and LSSVM models,

distinctly highlight the proficiency of the proposed ANN-PSO modelling approach. It effectively predicts the critical flashover voltage for various insulator types across different regions, by providing comprehensive data on the electrical transmission system.

To construct a more comprehensive and adaptive predictive framework, future research could enhance this study by integrating additional environmental and climatic variables, such as temperature, humidity, wind speed, and varying pollution levels. Incorporating real-time monitoring data from power systems would enhance the model's precision and applicability in dynamic operational settings. Moreover, exploring hybrid optimization techniques or ensemble learning approaches could augment the model's performance, improving its predictive accuracy and robustness under complex scenarios.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Lazreg Taibaoui, Abdelhalim Mahdjoubi and Boubakeur Zegnini.
Methodology: Lazreg Taibaoui, Boubakeur Zegnini and Abdelhalim Mahdjoubi.
Investigation: Lazreg Taibaoui and Abdelhalim Mahdjoubi.
Discussion of results: Lazreg Taibaoui, Abdelhalim Mahdjoubi and Boubakeur Zegnini.
Writing – Original Draft: Lazreg Taibaoui.
Writing – Review and Editing: Lazreg Taibaoui and Abdelhalim Mahdjoubi.
Resources: Lazreg Taibaoui.
Supervision: Abdelhalim Mahdjoubi and Boubakeur Zegnini.
Approval of the final text: Lazreg Taibaoui, Abdelhalim Mahdjoubi and Boubakeur Zegnini.

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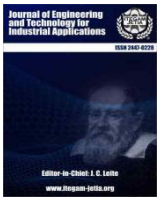

RESEARCH ARTICLE OPEN ACCESS

THE IMPLEMENTATION OF ENHANCED MICROGRID USING MAYFLY ALGORITHM BASED PID CONTROLLER

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ABSTRACT

Micro grids, comprised of distributed generation units, are designed to function independently of the main grid. To ensure stable operation in isolated mode, precise control of system is essential. Common challenges faced by standalone microgrids include maintaining stability of the system with balancing the load and generation from renewable energy sources and preventing fluctuations. Primary objective of paper to develop and execute an auxiliary controller capable of regulating system within a networked microgrid environment. Intermittent nature of renewable energy sources can lead to fluctuations in system frequency and power flow variations in tie line. To mitigate these challenges and balance the nonlinear output from renewable sources, Mayfly Algorithm (MA)-optimized Proportional-Integral-Derivative (PID) controller is proposed and implemented. Validation results demonstrate that the proposed MA-PID controller effectively regulates system in response to varying load demands and renewable energy sources.

I. INTRODUCTION

Generation of renewable energy through distributed energy resources (DERs) of solar panels (PV) and wind turbines (WT) is crucial for environmental sustainability. Micro grids (MGs), powered by these alternative energy sources, have emerged as efficient, controllable, and easily integrable energy systems. Small community networks, or MGs, have gained a lot of interest recently because of their benefits, which include lowering transmission line power losses, optimizing RES utilization, and giving customers dependable electricity.

PV arrays, WTs, DC/AC inverters, in power systems may function in independent or grid-connected modes are examples of typical MGs. Energy Storage Systems (ESSs) are crucial for addressing fluctuations in wind energy and solar power, maintaining power and energy balance, and enhancing power quality. To handle rapid power variations and provide micro grid autonomy, ESSs require high power and energy density. Therefore, combining multiple storage technologies into Hybrid Energy Storage Systems is essential.

The ideal dimensions of the ESS for a specific application are crucial for ensuring the dependable, effective, and cost-efficient functioning of a microgrid. After determining the battery size, it is crucial to manage its energy levels effectively to guarantee the stable and safe functioning of the microgrid. [1] introduces an innovative expert fuzzy system that utilizes grey wolf optimization (GWO) to develop an effective meta-heuristic approach for battery pack design and control of energy. The operation and control of energy under consideration is executed using GWO, which assists in establishing membership functions and generating the rules for expert system.

The smooth and efficient operation of the current network, frequency and voltage regulation, and the management of the energy sources currently in use all depend on MGs. Depending on the weather and surrounding circumstances, MGs—which may function both independently of the grid and in connection with the main grid-have shown effective in mitigating the negative consequences of intermittent energy generation [2].

A comprehensive overview of the literature on control features in AC, DC and hybrid micro grids is included [3]. Numerous studies have been conducted on different micro grids. Using a coefficient diagram technique (CDM) for proportional integral derivative acceleration (PIDA)controller design built for load frequency control (LFC) of an isolated microgrid (IMG) system's frequency stability was investigated [4]. Accelerator PID

controller was used, and its achievement was correlated with 2DoF-PID controllers.

Micro grids are tiny power networks that combine dispersed generation with local loads. These devices are often linked to the global network but can be disconnected during major disruptions. They may feed delicate loads. Uncertainties in real power systems include changes in load Micro-grid inverters are being developed to ensure steady voltage and frequency even when there are drastically fluctuating demands. Stability and power quality are maintained by microgrid's freestanding operation, which guarantees steady functioning even during network outages.

Research is being done on how distributed generators (DGs) that are connected to distribution networks behave [5], flaws in system modelling and changes in the structure. The Load Frequency Control problem cannot be resolved using classical controllers with continuous interest. The dependability and frequency stability of the electric power system of the future depend heavily on demand response (DR). To maximize the coefficients proposed cascade fractional order two-degree-of-freedom controller, a quasi-oppositional Harris Hawks Optimization is developed [6].

To overcome these limitations, a versatile controller is necessary. PID controllers have been widely adopted, for first time, a proportional-integral-derivative-filter controller based on colliding bodies optimization algorithm is designed for load frequency control (LFC) of hybrid power systems [7]. The controller's performance is evaluated at its nominal operating points. Traditional methods are used to determine these operating points. While numerous studies have explored various micro grid configurations with hybrid energy sources, the integration of DFIG's within microgrids has received less attention.

This paper introduces a novel micro grid topology powered by wind turbines using doubly fed induction generators and photovoltaic (PV) sources. The key advantage of this design simplified connection to both alternating current (AC) and direct current (DC) grids, eliminating the need for AC/DC and DC/DC converters. This configuration optimizes power control, enhances power quality of both AC and DC grids, regulates voltage and frequency, ensures uninterrupted power supply, and provides local reactive power compensation.

Moreover, a multi-source microgrid offers greater flexibility in power management between the microgrid and the main grid. The paper presents simulation results demonstrating effectiveness of proposed control algorithm under various challenging scenarios, including changes in power demand, random fluctuations, and sudden weather events. This article is structured as follows. Section 2 Micro grid Modelling. Methodology of design of PID controller and May fly algorithm are explained in Section 3. Description of proposed system is section 4 and simulation results is given in 5 Section and finally conclusion is provided.

II. MICRO GRID MODELLING

Although expanding transmission and distribution networks can enhance grid reliability and stability, it can also have drawbacks. These include inefficient electricity transmission to remote and inaccessible locations, higher energy losses during transmission and distribution and increased complexity in safeguarding network due to its wider reach. In response to these issues, distributed generation (DG) has become increasingly popular. DG involves generating electricity at the point of consumption, reducing the need for long-distance transmission. Microgrids are self-contained power systems that incorporate distributed generation (DG) and local loads [8]. These grids can function autonomously or be connected to the larger electrical grid. Figure 1 depicts the overall configuration of a micro grid.

Micro grids can incorporate a variety of renewable and conventional energy sources, including photovoltaic generators, wind turbine generators and battery energy storage systems. These micro resources are interconnected with main grid at point of common coupling (PCC) and communicate using electronic devices. Microgrids often utilize both AC and DC components for power conversion and control [9].

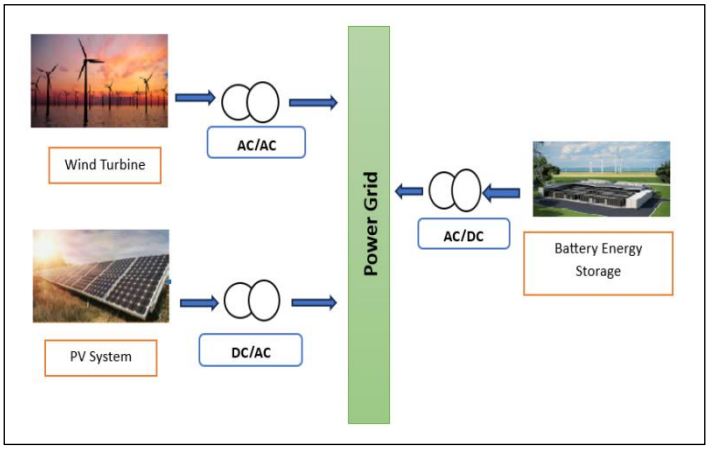

Figure 1: Micro grid structure.
Source: Authors, (2025).

III. METHODOLOGY

III. 1. PID CONTROLLER DESIGN

Effectiveness of proportional integral derivative (PID) controller is determined with its proportional gain (K_p), integral gain (K_i) and derivative gain (K_d). These gains affect controller's response to errors. Figure 2 illustrates a closed-loop control system for regulating DC microgrid voltage using a PID controller. The error signal, which is difference between voltage measured (V_o) and desired voltage (V_d), is amplified by controller. Controller then generates a PWM signal that adjusts power sharing among AC-DC converters in DC micro grid to minimize error [10]. Magnitude and direction of error signal directly correlate discrepancy between V_o and V_d.

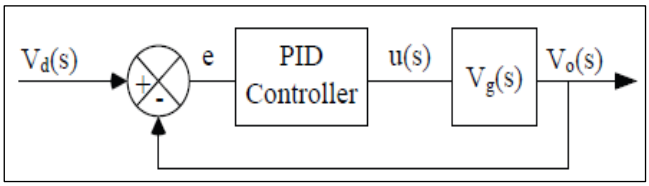

Figure 2: PID Controller.
Source: Authors, (2025).

Output of PID controller is expressed as

$$u(s) = k_p e(s) + k_i \frac{1}{s} e(s) + k_d s e(s) \quad (1)$$

and transfer function is expressed as:

$$G(s) = \frac{u(s)}{e(s)} = k_p + k_i \frac{1}{s} + k_d s \quad (2)$$

Where

$$e(s) = |v_d - v_g| \quad \text{or } e(s) = |v_d - v_o| \quad (3)$$

Increasing K_p can lower rising time but will not remove steady-state inaccuracy. While raising K_i can minimise steady-state error, it may degrade transient responsiveness. On other hand, boosting K_d can increase system stability, minimise overshoot, while improving transient responsiveness.

III. 2. MAYFLY ALGORITHM

Mayflies, an ancient insect group dating back to the Ephemeroptera order, are especially prominent in the UK during May, hence their name. Mayfly algorithm was inspired by behaviors of adult mayflies, including crossover, swarming,mutation, mating rituals and random movement. Initially, randomly generated populations of male and female mayflies are established. In second phase, male flies' velocities are updated, and they are ranked based on their speed. The highest-ranking males then mate with female flies [11]. This algorithm is also used to adjust gain values. Figure 3 depicts MA's functional flow chart.

Male Mayfly Movement

Male mayflies' movements are influenced by the positions of themselves and their neighboring males. location change is computed by adding velocity v^{t+1}, is expressed in Equ (4) and (5)

$$x_i^{t+1}=x_i^t + v_i^{t+1} \quad (4)$$

Speed of male mayfly

$$v_{ij}^{t+1} = v_{ij}^t + a_1 e_p^{\beta r^2}(P\ best_{ij} - x_{ij}^t) + a_1 e_p^{\beta r^2}(g\ best - x_{ij}^t) \quad (5)$$

Where

v_i^{t+1}= Velocity of Mayfly (ith at time t).
ij = Search space dimension.
x_i^t =Fly position at time t.
$a1$, $a2$ = Coefficients of collective effects.
$P\ best_{ij}$ = best local value.
$g\ best_i$ = Mayfly best location.

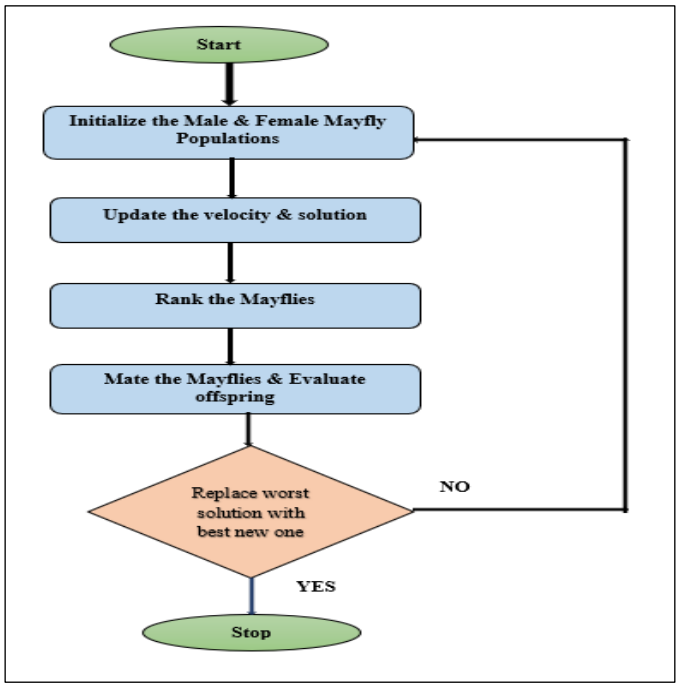

Figure 3: Flowchart of MA.
Source: Authors, (2025).

Leading mayflies in team continuously modify their speed to enhance overall performance. Equation (6) presents updated velocity formula. Dance coefficients 'd' and 'r' are random numbers within range of -1 to 1.

$$v_{ij}^{t+1}=v_{ij}^t + d + r \quad (6)$$

Female Mayfly Movement

Female mayflies increase their speed to update their positions, and y_{t+1} represents the position of i^{th} mayfly at time t.

$$y_i^{t+1} = y_i^t + v_i^{t+1} \quad (7)$$

Attraction occurs randomly, beginning with first-ranked female being drawn to best male. leftover flies are enticed based on their aptness. For depreciation problems, velocity is calculated using following formula, where r_{mf} represents the distance between male and female flies.

$$v_{ij}^{t+1}=\left\{v_{ij}^t + a_2 e^{-\beta r_{mf}^2}(x_{ij}^t - y_{ij}^t)\right\} \quad \text{if} \quad f(y_i) > f(x_i) \quad (8)$$

Many common optimization methods focus on locating points where the derivative is zero. To tackle nonlinear problems, additional variables are often introduced, widening the search area. Numerical techniques can become trapped in suboptimal solutions, hindering their ability to discover the optimal global solution. To overcome these challenges, metaheuristic algorithms are gaining popularity for complex optimization tasks. The Mayfly algorithm is adaptable, suitable for both persistent and distinct problems, and less prone to becoming stuck in local optima [12].

The research proposes using the Mayfly Algorithm (MA) to enhance secondary controller criterion, including K_p, K_i, and K_d. The primary benefits of Mayfly Algorithm are:
Quick convergence with a high convergence rate.
Mating rituals and erratic flight facilitate an equilibrium between exploitation and exploration.

IV. EXPLANATION OF PROPOSED MICRO-GRID

Suggested hybrid energy system incorporates variable-speed wind turbine with a doubly fed induction generator, photovoltaic array, battery, fuel cell, and an additional battery. Wind and solar energy sources are supervised using maximum power point tracking (MPPT) algorithms and connected to a shared DC bus. For wind turbines,

MPPT is implemented at speeds below the nominal value. Above nominal speed, pitch angle control is used to maximize power output. The battery functions as storage device and is connected to DC bus through a bidirectional DC/DC Buck-Boost converter. Wind and solar power generation are subject to weather conditions, and solar power is absent during nighttime.

Photovoltaic Cell

To achieve maximum power output from a photovoltaic (PV) array, it must be operated at optimal power point. An MPPT device, which is high-frequency boost DC-DC converter, is positioned within PV array and DC bus. This device adjusts DC input from PV array, modifying voltage and current to ensure array is properly aligned with DC bus.

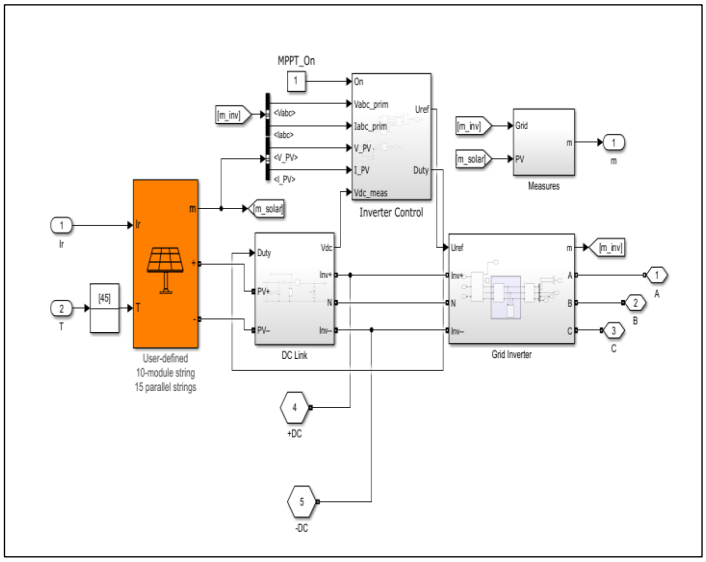

Figure 4: Modeling of PV with irradiance and temperature.
Source: Authors, (2025).

A. Wind Energy Conversion

Figure 4 demonstrates a direct relationship between output power and irradiance from a PV module. Lower irradiance levels govern to reduced power output. However, output current is primarily affected by irradiance, as it may be proportional to photon flux. The MPPT results indicate that has 15 parallel strings, each comprising 10 modules connected in parallel.

In Figure 5 modelling of wind turbine with converters is shown which has wound rotor induction generator, wind turbine control and drive train. The following formula provides the aerodynamic power at the turbine's rotor for wind energy conversion systems:

$$P_{wind} = \frac{1}{2}\rho A V^3 c_p(\lambda, \theta) \quad (9)$$

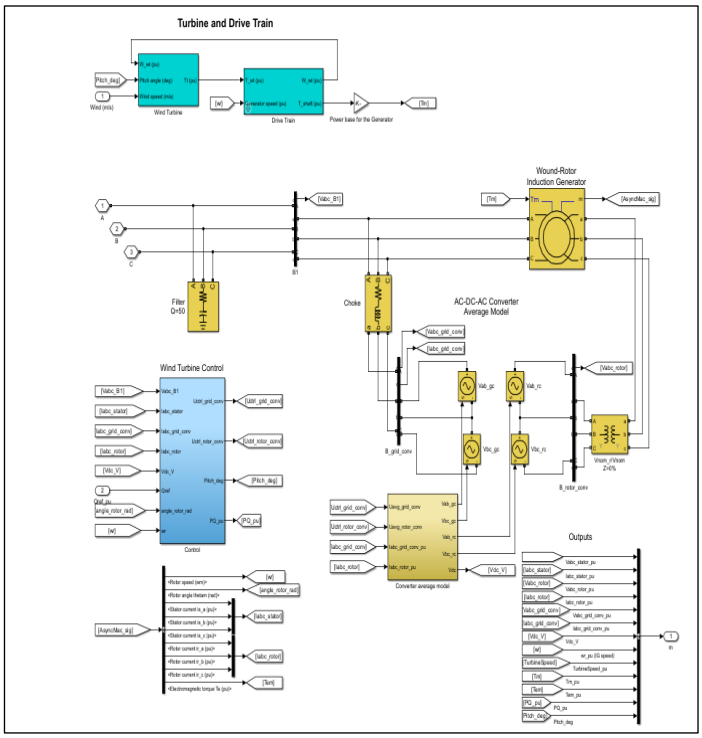

Figure 5: Modeling of PV with irradiance and temperature.
Source: Authors, (2025).

The pertinent variables are represented by the variables p (air density in kilogrammes per cubic metre), A (area swept by the rotor blades in square meters), and v (wind velocity in meters per second). The power coefficient (sometimes called rotor efficiency or Cp) is based on the tip speed ratio (A) and pitch angle (θ).

B. Battery

The voltage-current (V-I) characteristics of battery model in this study indicate that higher operating temperatures govern to lower terminal voltages for a given current. Initially, excess energy is stored in battery until it reaches full charge.

Afterward, additional power is managed by a buck DC/DC converter. Control actions are triggered by comparing the battery's maximum state of charge (SOC) with its current SOC. When the SOC surpasses 80%, the controller adjusts by increasing the duty cycle to manage the elevated DC bus voltage.

V. SIMULATION RESULT AND DISCUSSION

A simulation test for suggested WT-DFIGs/PV/Battery energy system has been constructed in MATLAB/Simulink utilising component models, with parameters for WT-DFIGs and PV described in the preceding section.

To analyze system performance under various situations, simulations were done utilizing changing load data and variations in weather inputs, such as wind speed, solar irradiation and temperature. Figure 6 below presents the proposed system model, and its performance has been verified.

From the above Figure 7 graph it indicates a stable battery voltage throughout the simulation. The current fluctuations, suggesting that the battery is actively charging and discharging. The power supplied to or drawn from the battery is directly related to the current flow. The SOC graph shows a gradual decrease, indicating that the battery is being discharged.

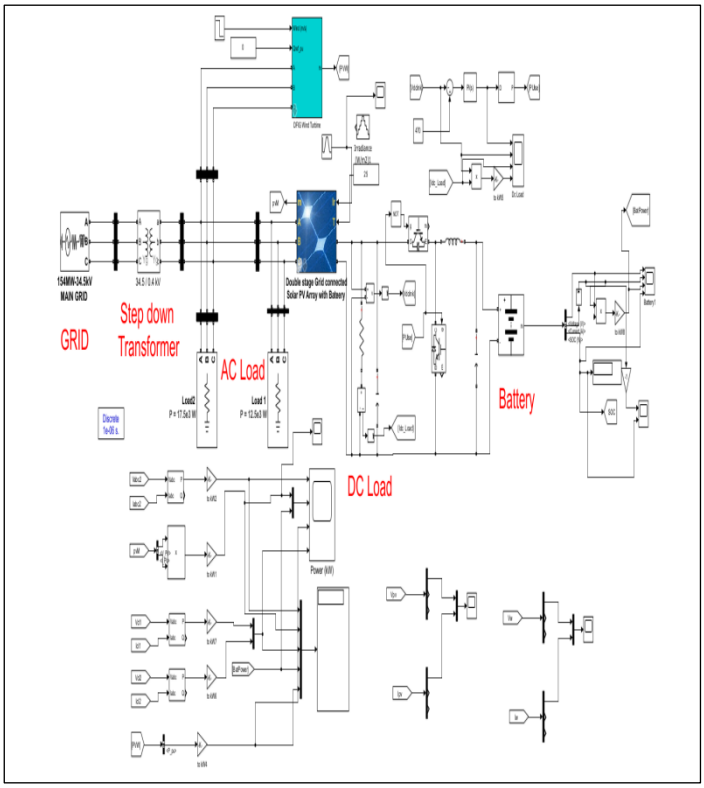

Figure 6: Simulink model of the proposed system.
Source: Authors, (2025).

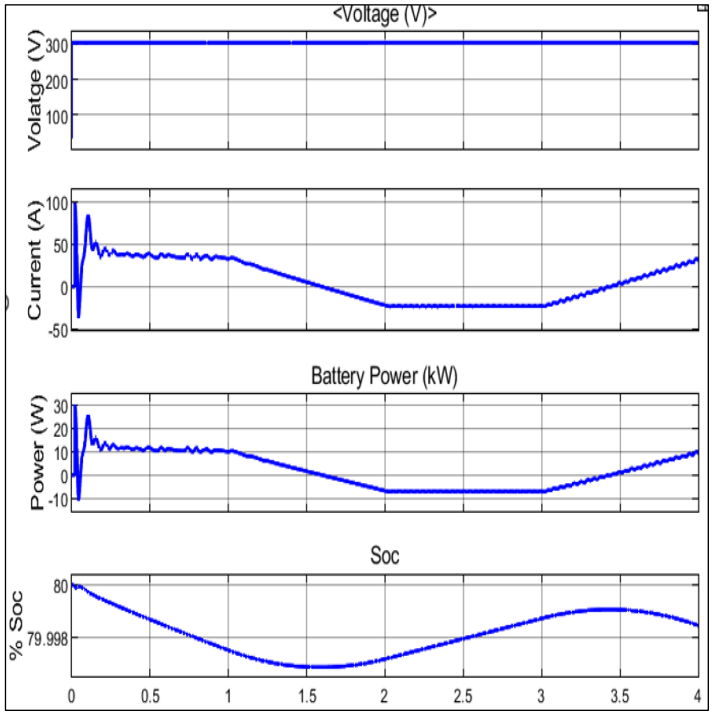

Figure 7: SOC, Current and Voltage of Battery.
Source: Authors, (2025).

From the Figure 8 it shows the DC load characteristics as it appears that the power converter is successfully supplying power to the DC load. The stable duty cycle and DC link voltage indicate that the converter's control system is functioning correctly. The increasing load current and power suggest that the load demand is growing.

From the Figure 9 graphs of power shows that the micro grid is operating effectively, with multiple sources contributing to the power supply. The initial grid power surge might be due to a sudden increase in load or a transient event. The rapid response of the solar PV, battery, and DFIG indicates that micro grid is well-equipped to handle dynamic load changes.

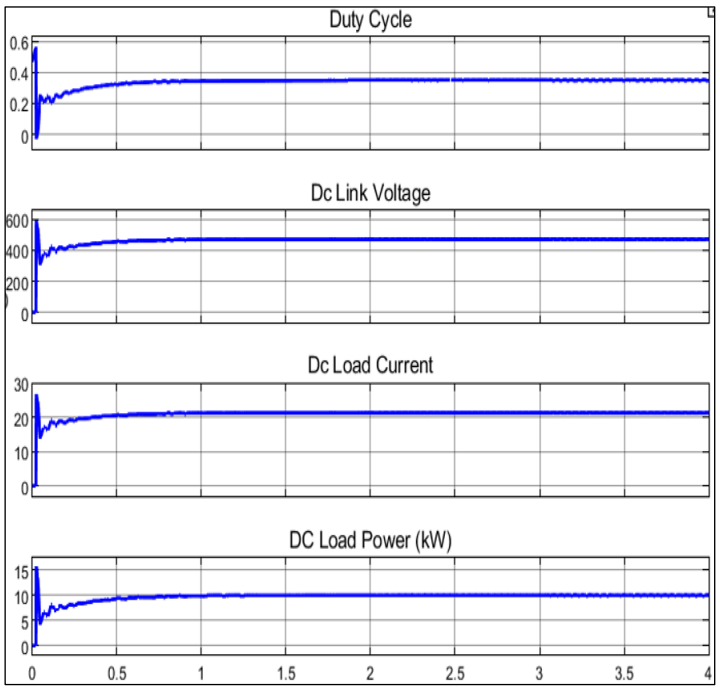

Figure 8: DC load characteristics.
Source: Authors, (2025).

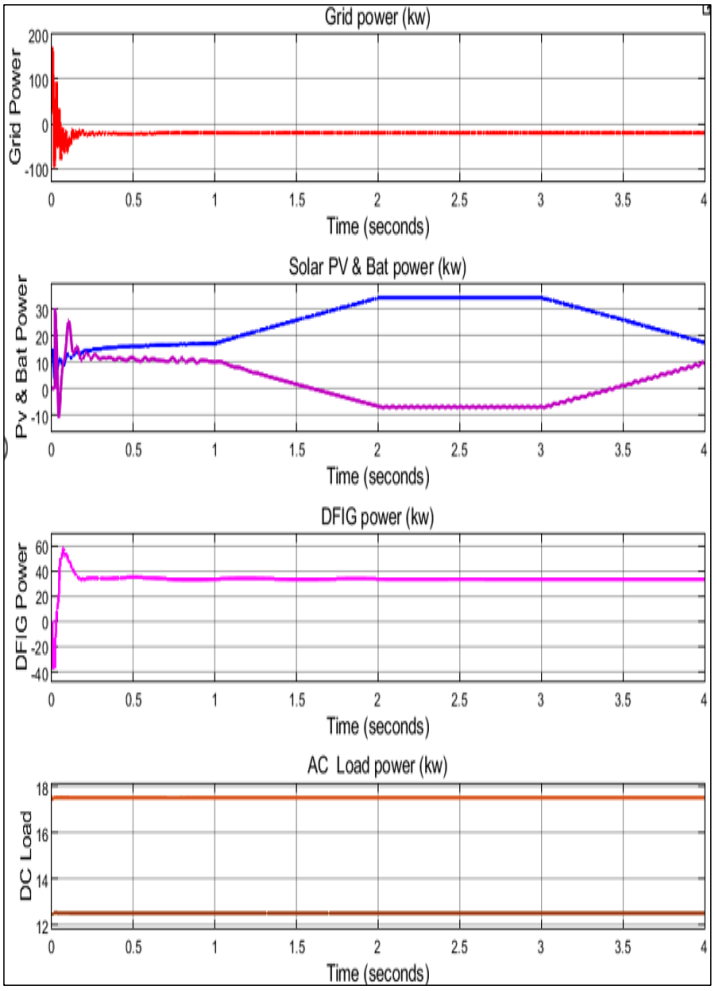

Figure 9: Power Characteristics.
Source: Authors, (2025).

From Figure 10 that the battery is initially subjected to a sudden charging demand. It then charges at a relatively constant rate until it reaches a certain SOC level. After that, the battery starts discharging, potentially due to a change in system conditions or a controlled discharge process

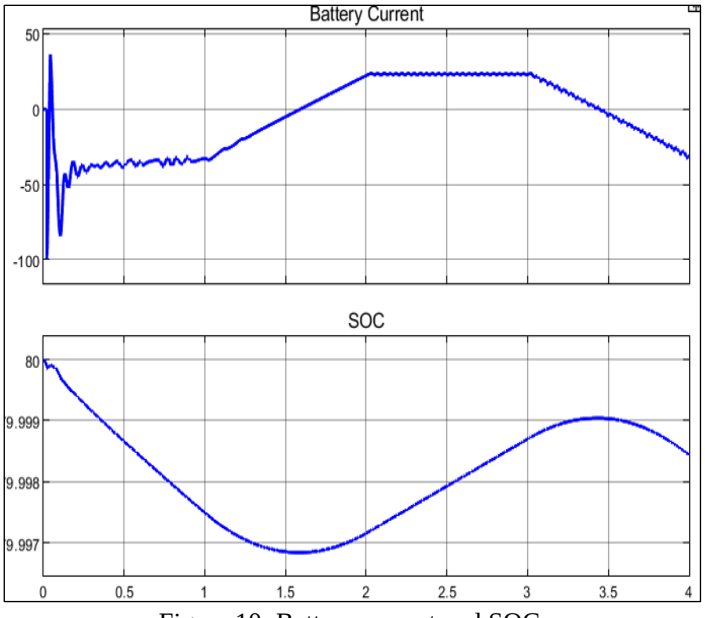

Figure 10: Battery current and SOC.
Source: Authors, (2025).

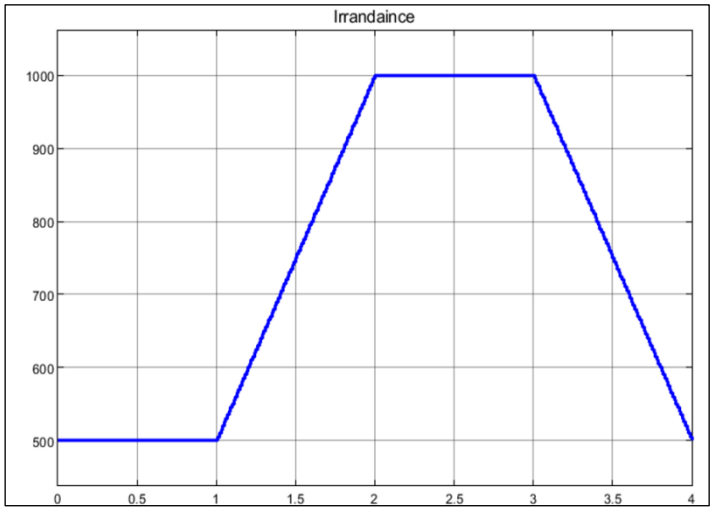

Figure 11: Solar irradaince
Source: Authors, (2025).

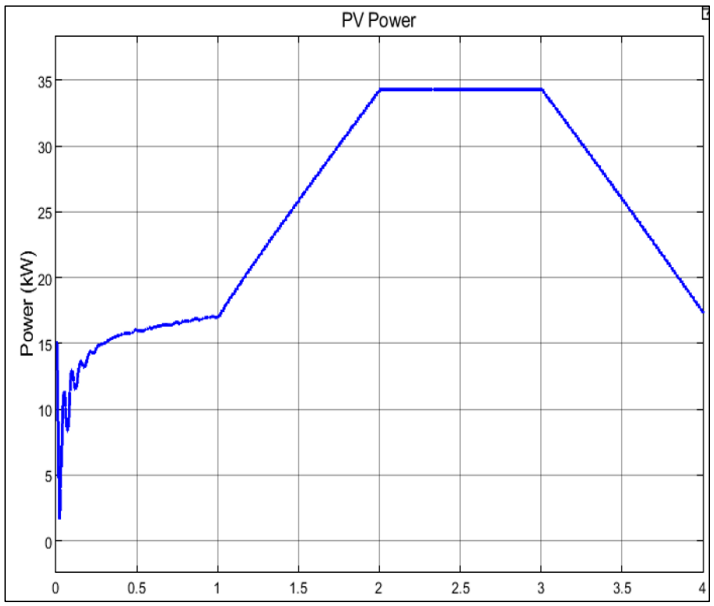

Figure 12: PV power
Source: Authors, (2025).

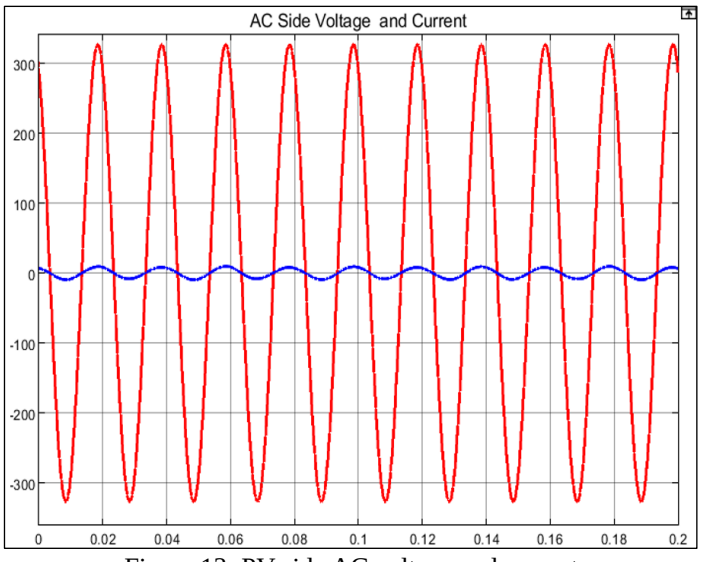

Figure 13: PV side AC voltage and current
Source: Authors, (2025).

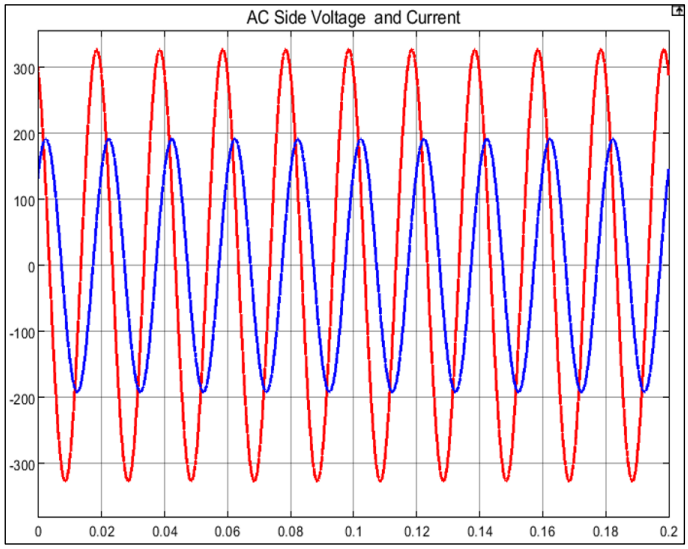

Figure 14: Wind side AC voltage and current
Source: Authors, (2025).

MA-PID controller demonstrated exceptional performance in all vital system scenarios, as illustrated in Figures 7-14. Based on this comprehensive performance analysis, proposed MA-PID controller is appropriate choice for micro grid power system.

The battery parameters used for the simulation are : the type of battery is lead acid battery with nominal voltage of 300 V and rated capacity of 400 Ah. The initial state of charge of battery is 80%. The output of solar array is 0.336x100 KW. The output of wind turbine is 1.5 MW at wind speed of 11 m/s. Two AC type loads and one DC load are used for the simulation. The power demand of one of the AC load is 17.5 KW and the other is of 12.5 KW. The power demand of DC load is 10 KW. The PID controller is fine tuned by using Mayfly Algorithm. The optimal P value is 0.001 and I value is 0.01.

VI. CONCLUSIONS

This research introduces a hybrid microgrid system enhanced by a Mayfly Algorithm-based PID controller to address the pressing challenges associated with renewable energy integration. The microgrid system, comprising wind turbines (WT), photovoltaic (PV) arrays, and hybrid energy storage systems (ESS), demonstrates an effective synergy for maintaining power balance and stability under fluctuating conditions. By leveraging the advantages of a hybrid configuration and advanced control algorithms, the study underscores the potential of microgrids in achieving sustainable and reliable energy systems. The implementation of the MA-PID controller addresses critical concerns such as frequency instability, power fluctuations, and the nonlinear nature of renewable energy output. The controller optimizes the proportional, integral, and derivative gains, ensuring rapid adaptation to changing system dynamics. Simulation results validate the proposed system's capability to maintain stable frequency, regulate voltage, and manage energy efficiently across various scenarios, including load variations and unpredictable weather conditions.

The MA-PID controller significantly improves system stability, minimizing overshoots and steady-state errors. Efficient power sharing among distributed energy resources (DERs) ensures maximum utilization of renewable sources. The modular design of the hybrid microgrid and adaptive control strategy make it applicable for standalone and grid-connected operations. The

system effectively adapts to real-time changes, such as varying load demands and abrupt environmental shifts, while maintaining performance.

Despite the promising results, the study recognizes several areas for further research. Real-world implementation of the MA-PID controller would provide deeper insights into its operational reliability and scalability. Additionally, integrating more advanced energy management systems (EMS) and exploring other metaheuristic optimization techniques could enhance the microgrid's performance further. The proposed hybrid microgrid system not only addresses the current challenges of renewable energy integration but also provides a scalable blueprint for future energy systems. By focusing on efficient control mechanisms and robust system design, this study contributes to advancing the deployment of microgrids, thereby supporting global efforts toward a sustainable and resilient energy future.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: M Murali and Dr A Hema Sekhar.
Methodology: M Murali and Dr A Hema Sekhar.
Investigation: M Murali and Dr A Hema Sekhar.
Discussion of results: M Murali and Dr A Hema Sekhar.
Writing – Original Draft: M Murali.
Writing – Review and Editing: M Murali.
Resources: Dr A Hema Sekhar.
Supervision: Dr A Hema Sekhar.
Approval of the final text: M Murali and Dr A Hema Sekhar

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RESEARCH ARTICLE OPEN ACCESS

NUMERICAL INVESTIGATION OF TWO-PHASE THERMAL-HYDRAULIC, CHARACTERISTIC AND ENTROPY GENERATION OF WATER-BASED AL_2O_3-CU HYBRID NANOFLUIDS IN MICROCHANNEL HEAT SINK

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entropy generation.

ABSTRACT

This study employs numerical simulations to investigate the impact of water-based hybrid nanofluid containing copper-alumina nanoparticles using two-phase Eulerian-Eulerian model and finite volume approach to solve the conjugate heat transfer problem in a three-dimensional microchannel heat sink. The aim is to numerically evaluate the thermal behaviour and performance criteria of the microchannel heat sink using Ansys workbench, while determining the influence of volume concentration and Reynolds number (*Re*) on Nusselt number, friction factor and entropy generation. Generally, the heat sink consists of a silicon cylindrical structure block forming a microchannel heat sink with an internal heat generation of 10^8 W/m^3. The study involves varying the Reynolds number across a range of 100 to 500. This variation applies to distinct volume concentrations of alumina-copper nanoparticles, specifically alternating between 0.25%, 0.50%, and 0.75% for a volume fraction of 1%. Additionally, the volume concentration was further adjusted within the range of 1% to 4%. The verification of the numerical models shows excellent agreement with literature. The results reveal that higher relative concentrations of copper nanoparticles lead to improved thermal enhancement of the hybridized nanofluid. An increase in both the Reynolds number (*Re*) and the concentration of Cu in the hybrid nanofluids caused a reduction in total entropy generation and thermal entropy generation. For *Re* = 500 and volume concentration of 4% in relation to the base fluid, the friction factor increases by less than 1%, the Nusselt number experienced an increase of 8.73% while the total entropy generation rate experiences 4.9% increase. At a concentration of 4.0% volume, the maximum figure of merit corresponds to a Reynolds number of 100 with 9.10% shift from 1.0% volume of hybrid nanofluid.

I. INTRODUCTION

Non-uniform heat generation is a prevalent occurrence in electronic equipment Feng et al [1]. To relieve the thermal load on electrical gadgets, this heat creation necessitates an optimized and clear channel with cooling fluid. Over the years, engineers and scientists have applied different methods from single phase, two phase to multiphase as an efficient way to remove the heat dissipated in the system, but due to the limitation of low thermal conductivity, Choi and Eastman [2] engineered a new fluid through the incorporation of metallic nanoparticles into heat transfer fluids, resulting in a suspension. This innovation is what is known as

Nanofluid (NF) today and circulated in thermal systems as alternative to conventional fluids.

II. THEORETICAL REFERENCE

The study of nanofluids and heat removal continue to grow gradually from homogeneous single phase to two-phase and multiphase. For single phase flow, Olakoyejo et al [3] investigated and optimized cylindrical micro-cooling channels with variable cross - section using the constructal theory. Their results showed that there were optimal inlet and outlet diameters that enhanced the performance of the micro-cooling channel. Also, in order to observe the heat transmission and drop in pressure of a system, Kumar and Sarkar [4] considered a 2-phase model to replicate the flow of forced convection in a heat sink (microchannel), using water/Al_2O_3 NF and Al_2O_3-MWCNT hybrid NF. The homogeneous and heterogeneous models display a good relationship with experiment results.

Hybrid nanofluids are group of fluids that comprise two or more types of nanoparticles and base fluids. They have gained significant acceptance recently due to their potential to alter the transfer of heat performance in two-phase flow systems, such as condensation and boiling. The circulation of hybrid nanofluids in thermal systems has shown promising results in various industrial applications, including power generation and refrigeration. This results in a unique set of properties that are not present in either the individual nanoparticles or the base fluid alone. This innovation has attracted significant attention in recent years due to its potential to enhance transfer of heat and improve the performance of cooling systems. Recently, Dey and Sahu [5] studied and reviewed the advantages of two-phase heat transfer and the potential benefits of using NFs in various two-phase heat transfer applications. According to the research, the convective transfer of heat coefficient is notably more with two-phase transfer of heat in comparison with alternative modes of transfer of heat.

Various studies have examined the usage of hybrid NFs for improving the transfer of heat performance in two-phase flow systems. In literature,transfer of heat and pressure drop are affected by circulating hybrid nanofluids through and or around heat sink using two-phase model [6 - 9]. Similarly,entropy generation has also been influenced whenever nanofluids and hybrid NF are circulated in thermal systems [10], [12]. Nimmagadda and Venkatasubbaiah [13] investigates the convection flow (laminar – forced) of different nanofluids in a micro-channel of rectangular shape with low *Re* (10 - 50). The results indicate that nanofluids with less particle diameter are preferred for heat transfer enhancement, while raising the concentration of nanofluids enhances the *Nu* and improves thermal conductivity, the solid/liqud interface region temperature increases with increase in length of channel.

Alfaryjat et al [14] numerically investigated the heat transfer enhancement of hexagonal heat sink microchannel using Alumina/H_2O, CuO/H_2O, SiO_2/H_2O and ZnO//H_2O nanofluid. The authors compared the performance of the nanofluids while varying volume fractions from (0% - 4%) at *Re* 100-1000. Their results indicate that Alumina/H_2O is favourable due to its minimal dimensionless temperature, coupled with the highest heat transfer coefficient (*h*). On the other hand, SiO_2/H_2O exhibits the greatest pressure drop, while pure water experiences the least..

Balaji et al [15] analyzed how functionalized Graphene Nanoplatelets (f-GnP) suspended in distilled water affected convective heat transfer. The study found that f-GnP-based nanofluids having concentration between 0% to 0.2% could improve convective h and Nu by 71% and 60% respectively at mass flow rate of (5g/s - 30g/s). The researchers suggested that these nanofluids could replace concentional cooling fluids to enhance electronic chips' performance via improved transfer of heat and thermal conductivity.

Krishna et al [16] examined the pressure drop and transfer of heat capacity MWCNT-CuO/water-based hybrid nanofluid in MCHS with circular cross section with *Re* ranging from 500-2000. The study shows that drop in pressure was less with hybrid-nanofluids in comparison with CuO/water nanofluids and 3% maximum enhancement of Nu was found for the hybrid NF.

Vinoth and Sachuthananthan [17] compared the performance of pentagonal and triangular oblique finned microchannel heat sinks, using different nanofluids (CuO/H_2O, Al_2O_3/H_2O and Al_2O_3-CuO/H_2O) at varying mass flow rate of 0.1-0.5 litres per minute. The pentagonal mini-channel performed better, especially with hybrid nanofluid due to secondary flow, and had higher Performance Evaluation Criterion than the triangular heat mini-channel.

The use of hybrid nanofluids has shown promising results in enhancing the transfer of heat performance in two phase flow systems. The studies have explored the potential of hybrid nanofluids for various industrial applications, including power generation, refrigeration, and heat exchangers.

The present research is driven by the existing gap in numerical investigations utilising the two-phase Eulerian method within the ANSYS – Fluent framework. The objective is to comprehensively examine the thermal-hydraulic behavior of a hybrid NF in a multi-scale cylindrical channel. This investigation is also inspired by the preceding works conducted by Muzychka [18] and Omoshin et al [19], which shed light on the impact of smaller microchannels on the overall thermal efficiency of systems and effect of nanoparticles hybridization, respectively. This work introduces arrays of smaller microchannels to cylindrical channel in order to improve its performance and design was further streamlined into a sector multiscale elemental volume.

III. METHODOLOGY

II.1 PROBLEM FORMULATION

Figure 1(a) depicts the physical configuration of the model considered in this study. The model is considered to be micro-electronic component that comprises of an array of sector cooling channels with fixed global volume, *V* and length *L*. The entire solid material experiences s an internal heat of 10^8 W/m^3, which is denoted as q'''. Fig. 1(b) shows an elemental volume containing a sector and interstitial circular cooling while and Table 1 summarizes the dimensions of the elemental volume used for this study. Forced convection is employed to remove heat from the system, where coolant, water-(Al_2O_3-Cu) hybrid nanofluid with 0%, 1%, 2%, 3% and 4% nanoparticle concentration is circulated into the cooling channels at varying inlet Reynold numbers over the channel length *L*. The analysis assumes a uniform heat distribution within the channel, given that the surrounding element is used in the analysis. The fluid was considered to be two-phase Eulerian fluid with particle diameter of 10^{-8} and interfacial area of ia-particle. The fluid was circulated through the six-patterned holes and centered circular channel to remove heat from the solid body at every hotspot.

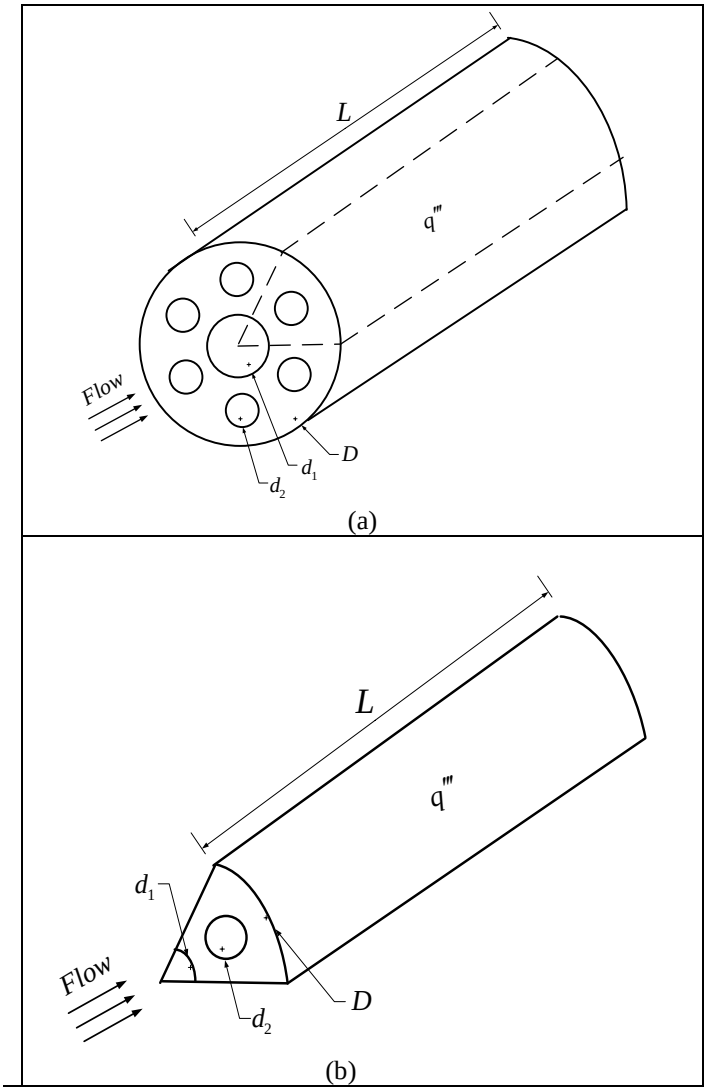

Figure 1: The three-dimensional (a) global and elemental volume with circular and (b) sector channels
Source: Authors, (2025).

D (μm)	d_1 (μm)	d_2 (μm)	L (μm)
1200	400	200	10000

In Figure. 1(b), the elemental volume, is conceptualized to be made up of an elemental channel with sector channel diameters d_1 and interstitial channel circular d_2:

II.2 GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

A. Governing equations

The mathematical (continuity, momentum, energy) equations that describe the behavior of this numerical study are formulated with the assumption that the flow is two phase using hybrid-nanofluid.

Continuity equation

$$\nabla \cdot (\alpha_1 \rho_1 \vec{u}_1) = 0 \tag{1a}$$

Solid phase:

$$\nabla \cdot (\alpha_2 \rho_2 \vec{u}_2) = 0 \tag{1b}$$

$$\nabla \cdot (\alpha_3 \rho_3 \vec{u}_3) = 0 \tag{1c}$$

where ρ, α, $\vec{u}$ are the density, volume concentration, and velocity vector while subscripts 1, 2, 3 represents primary phase (water), secondary phase (alumina nanoparticles), secondary phase (copper nanoparticles) respectively.

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{1d}$$

Momentum equation

Liquid phase:

$$\nabla \cdot (\alpha_1 \rho_1 \vec{u}_1) = -\alpha_1 \nabla p + \nabla \cdot \left[\alpha_1 \mu_1 (\nabla \vec{u}_1 + \nabla \vec{u}_1^{\,T}) \right] + F_d + F_{MV} \tag{2}$$

Solid phase:

$$\nabla \cdot (\alpha_2 \rho_2 \vec{u}_2) = -\alpha_2 \nabla p + \nabla \cdot \left[\alpha_2 \mu_2 (\nabla \vec{u}_2 + \nabla \vec{u}_2^{\,T}) \right] - F_d - F_{MV} + F_{col} \tag{3}$$

$$\nabla \cdot (\alpha_3 \rho_3 \vec{u}_3) = -\alpha_3 \nabla p + \nabla \cdot \left[\alpha_3 \mu_3 (\nabla \vec{u}_3 + \nabla \vec{u}_3^{\,T}) \right] - F_d - F_{MV} + F_{col} \tag{4}$$

where P, μ_2, F_d, F_{MV}, F_d F_{MV} and F_{col} are the the pressure, dynamic viscosity, drag, virtual mass, and particle-to-particle interaction forces, respectively. However, according to Kalteh et al. [20], the virtual mass and particle to particle interaction force have an insignificant effect on heat transfer characteristics (Nusselt number). Hence, only the drag force and convective heat transfer between the primary and secondary phases are considered. The particle-to-particle heat transfer is neglected, and the gravitational and the lift forces attributable to the small size of the particles are also ignored.

The drag force between the primary phase and each secondary phase (alumina and copper particle) is calculated as

$$F_d = -\beta(\vec{u}_1 + \vec{u}_P) \tag{5}$$

$$\beta = \frac{3}{4} C_d \frac{\alpha_1 \alpha_p}{\varphi_p d_p} \rho_1 \left| \vec{u}_1 + \vec{u}_P \right| \alpha_1^{-2.65} \tag{6}$$

where C_d is the drag coefficient.

Energy equation

$$\nabla \cdot (\alpha_1 \rho_1 C_{p_1} T_1 \vec{u}_1) = \nabla \cdot (\alpha_1 K_1 \nabla T_1) - Q_h \tag{8a}$$

$$\nabla \cdot (\alpha_2 \rho_2 C_{p_2} T_2 \vec{u}_2) = \nabla \cdot (\alpha_2 K_2 \nabla T_2) + Q_h \tag{8b}$$

$$\nabla \cdot (\alpha_3 \rho_3 C_{p_3} T_3 \vec{u}_3) = \nabla \cdot (\alpha_3 K_3 \nabla T_3) + Q_h \tag{8c}$$

where *T, K, C_p,* are the temperature, thermal conductivity specific heat capacity. Q_h is the volumetric energy transfer rate between the primary and each secondary phase, and it is expressed as

$$Q_{pq} = h_{p,1}\frac{6\alpha_p}{d_p}(T_P - T_1) \quad (9)$$

where *h*, *d*, and subscript *p* are the heat transfer coefficient, diameter, and particulate, respectively

B. Boundary conditions

The expression for the heat flux across the solid-liquid interfaces is given as:

$$k_s\frac{\partial T}{\partial n}\bigg| = k_{nf}\frac{\partial T}{\partial n}\bigg| \quad (10)$$

The fluid velocities close to the channel walls are expressed as:

$$\vec{v} = 0 \quad (11)$$

The inlets conditions are given as:

$$T = T_{in} \quad (12)$$

$$u_f = u_{in} \quad (13)$$

Eq. (24) is uniform axial velocity for both base fluid and particulate phases at bottom channel while the outlet condition is ambient outflow condition.

The solid boundary given as:

$$\nabla T = 0 \quad (14)$$

II.3 PERFORMANCE CRITERIA

The criteria that are utilized to determine the performance characteristics of the cooling channel are now discussed.

II.3.1 NUSSELT NUMBER

Average Nusselt number (*Nu*) is one of the measures of heat transfer performance for this study and this was determined by taking the value obtained by multiplying transfer of heat coefficient and the hydraulic diameter divided by the thermal conductivity.

$$Nu = \frac{q'''D_hL}{k_f\left(T_w - T_{in}\right)} \quad (15)$$

where *kf*, is the thermal conductivity of the liquid [4,5]. and T_w is the area-weighted average wall temperature. T_w is the wall temperature at the center of the heated base and D_h average hydraulic diameter.

II.3.2 FRICTION FACTOR

The calculation of the friction factor *f*, which is a measure of microchannel performance characteristics, was carried out and presented as follows:

$$f = \frac{2\Delta pD_h}{\rho u_{nf}^2 L} \quad (16)$$

II.3.3 ENTROPY GENERATION

This study also investigated the practical importance of total volumetric entropy generation rate ($S'''_{g\text{-}total}$), which is a measure of the inability to reverse a process. This criterion was conveyed as shown by Alfaryjat et al [21]

$$\dot{S}'''_{g-total} = \dot{S}'''_{g-th} + \dot{S}'''_{g-fr} \quad (17)$$

where the thermal entropy generation ($\dot{S}'''_{g-th}$) and the friction entropy generation ($\dot{S}'''_{g-fr}$) were determined as expressed individually as:

$$\dot{S}'''_{g-th} = \frac{k_{nf}}{T^2}\left(\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right) \quad (18)$$

$$\dot{S}'''_{g-th} = \frac{\mu_{nf}}{T}\left\{\begin{array}{l} 2\left(\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right) \\ +\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 \end{array}\right\} \quad (19)$$

II.3.2 FIGURE OF MERIT

In order to assess the trade-off between increasing power required for pumping and the rate of heat transfer improvements, the Figure of Merit (FOM) is utilized to evaluate the overall performance of each of the suggested designs. FOM is give according to Ali et al [22].

$$FOM = \left(\frac{Nu_{nf}}{Nu_{bf}}\right) \div \left(\frac{f_{nf}}{f_{bf}}\right)^{\frac{1}{3}} \quad (20)$$

III COMPUTATIONAL PROCEDURE

III.1 NUMERICAL TECHNIQUE

This CFD study was conducted using ANSYS Fluent software. A phase coupled SIMPLE approach was utilized for pressure/velocity couple with the pressure, momentum, volume fraction, granular temperature and the energy equations solved using the second-order upwind technique. A multiphase approach with an homogeneous Eulerian model was assumed while the number of Eulerian phase and volume fraction parameters formulation were set to two and implicit respectively. The primary phase used was water-liquid and secondary phase was aluminium-oxide and copper hybrid nanofluid with syamlal-obrien assumed for the granular viscosity, solids pressure and granular conductivity. The temperature granular model was solved with partial differential equation. For phase interaction, phase 1 was given a drag coefficient of syamlal-obrien and a virtual mass drag of 0.5 with no lift and surface tension coefficient. The phase 2 was given a collision coefficient of 0.9 in the force setup while interfacial area of ia-particle was set for the phases.

III.2 GRID INDEPENDENCE TEST

Different grid tests were performed to ascertain this study's accuracy and the convergence criterion was determined using:

$$\gamma = \frac{\left|(T_{\max})_i - (T_{\max})_{i-1}\right|}{\left|(T_{\max})_i\right|} \leq 10^{-5} \quad (21)$$

Figure. 2. shows the computational mesh of this study. Table 2 outlines grid independence test carried out in this study. The number of elements corresponding to the number of nodes 15715, 60649, 96783 and 270 520 are 80711, 322051, 1458163 respectively. The *i*-1 mesh was chosen because it fulfilled the criterion convergence and a further increment had no influence on the result. The test shows that increasing the number of elements beyond 96873 could not cause a significant change in the maximum temperature. Hence, the mesh with 96,783 nodes and 510,569 elements was used for this computational study

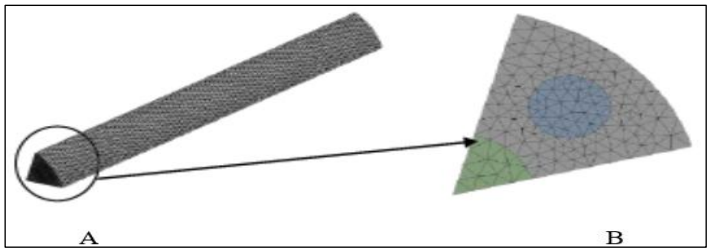

Figure. 2: Computation study mesh
Source: Authors, (2025).

Table 2: The grid independence study for CFD study

L = 0.01 m, R = 600 µm, D_c = 200 µm, R_s = 200 µm, Re = 100 and $\varnothing$ = 1%			
Number of Nodes	Number of Elements	T_{max} (K)	γ
15,715	80,711	301.1814	-
60,649	322,051	302.2358	0.0034890
96,783	510,569	302.2318	0.00001323
270,520	1,458,163	302.2302	0.0000005294

III.3 NUMERICAL CODE VALIDATION

Figure 3 presents a validation of the numerical model, comparing it with previous experiments conducted by Azizi et al. [23]. These experiments utilized a circular microchannel with a heat flux set at 35 kW/m² and *Re* between 280 and 780. The observed trends align closely, with a mean average deviation of less than 10%.

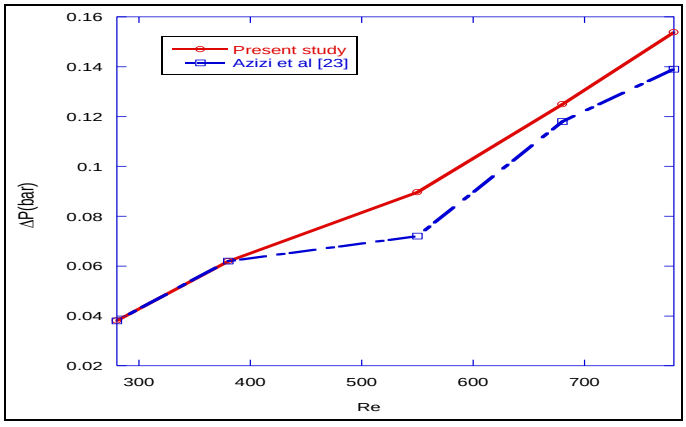

Figure 3: Validation of present study with Azizi et al [23]
Source: Authors, (2025).

IV. RESULTS AND DISCUSSIONS

This section outlines the findings of this study's investigation on the impact of hybrid NFs on the friction factor, entropy generation and avergae Nusselt numbers *Nu* of both inlet configurations. The study involved testing various combinations of hybrid nanoparticles at nanoparticle concentrations ranging from zero (pure water) to 4.0% volume concentration, while the *Re* was varied between 100 and 500.

IV.1 INFLUENCE OF NANOPARTICLE CONCENTATION (*Φ*) AND REYNOLDS NUMBERON NUSSELT NUMBER

In Figure 4, the relationship between Reynolds numbers (*Re*) and avergae Nusselt numbers (*Nu*) is shown. As *Re* increases, there is a clear upward trend in *Nu*, consistent with observations made by Zheng et al. [24]. The study also evaluates the heat transfer effects of differing concentrations of Al_2O_3 and *Cu* within hybrid nanofluids.

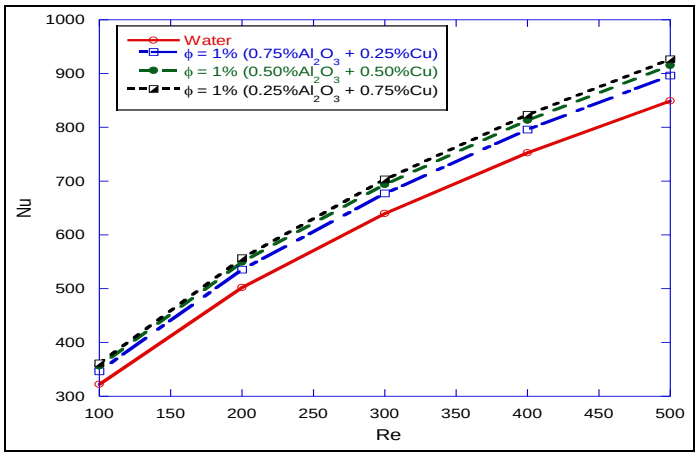

Figure 4: Effect of Reynolds number on average Nusselt number at fixed hybrid nano particle concentration
Source: Authors, (2025).

Results demonstrate that Cu, at higher concentrations, tends to perform better than Al_2O_3. In scenarios where Al_2O_3 and Cu are present in equal concentrations, their performance surpasses that of both pure water and Al_2O_3 alone, suggesting significant improvements in heat transfer when Cu is incorporated into hybrid nanofluids. At a *Re* of 100, without any nanofluid particles, the *Nu* stands at 321.85. This figure climbs to 346.34 when the concentration of Cu in the hybrid nanofluid reaches 0.25%. As the Cu concentration increases to 0.50% and 0.75%, the *Nu* further ascends to 356.45 and 360.97, respectively. Additionally, at a *Re* of 500, *Nu* values corresponding to Cu concentrations of 0.25%, 0.50%, and 0.75% are 896.65, 915.34, and 926.67, respectively. These findings indicate an enhancement in *Nu* by 10.17% at a *Re* of 100 and by 7.49% at a Re of 500 when Cu concentration is raised from 0.25% to 0.75%.

IV.2 EFFECT OF NANOPARTICLE HYBRIDIZATION ON THE AVERAGE NUSSELT NUMBER

The Nusselt number, expressed non-dimensionally, serves as a crucial indicator for assessing and forecasting the heat transfer efficiency of thermal systems. As depicted in Figure 5, there is a notable rise in the Nusselt number with increases in Reynolds number, Reynolds number which shows similar trends with worked presented by Ataei et al [25].

It is observed that a higher concentration of Cu within the hybrid nanofluids leads to improved thermal performance. Notably, the hybrid nanofluid with 4% Cu concentration exhibits the most significant enhancement in thermal performance.

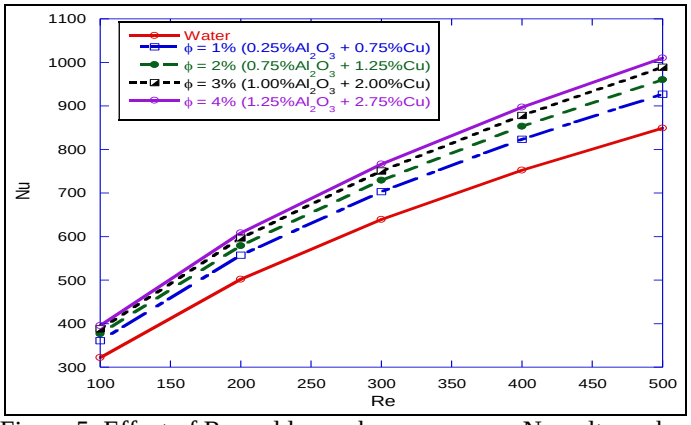

Figure 5: Effect of Reynolds number on average Nusselt number at different hybrid nanoparticle concentration
Source: Authors, (2025).

Furthermore, increasing the proportion of Cu in the Al2O3 mixture results in greater improvements in heat transfer capabilities. Specifically, at a Reynolds number of 100, the Nusselt number progresses from 360.97 to 376.84, 388.10, and finally 395.73 as the Cu concentration increases to 1%, 2%, 3%, and 4%, respectively. At a Reynolds number of 500, the Nusselt numbers associated with Cu concentrations of 1%, 2%, 3%, and 4% are 926.67, 960.43, 989.02, and 1010.1, respectively. This indicates that a rise in Cu concentration from 1% to 4% escalates the Nusselt number by 12.15%, 17.09%, 20.58%, and 22.95% compared to the base fluid, at a Reynolds number of 100.

IV.2 4.3 INFLUENCE OF NANOPARTICLE CONCENTATION (*Φ*) AND REYNOLDS ON FRICTION FACTOR (*f*)

The bar chart in Figure 6 explores the response of hybrid nanofluids to changes in Reynolds number and alumina nanoparticle content. The experiments maintained a constant nanoparticle concentration of 1% while varying the Reynolds number from 100 to 500. The data demonstrate that variations in nanoparticle concentration have a negligible impact on the friction factor.

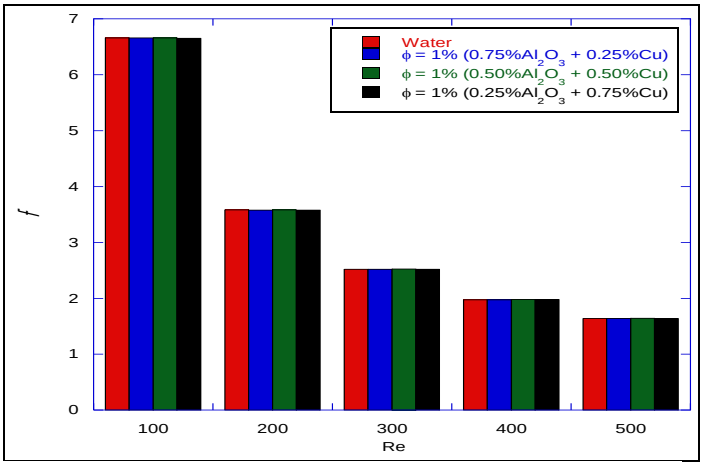

Figure. 6: Effect of Reynolds number on friction factor at fixed hybrid nanoparticle concentration
Source: Authors, (2025).

Furthermore, the friction factor remains relatively consistent at a given Reynolds number, irrespective of the nanoparticle concentration mixed with water. This trend corresponds with the findings from previous studies by Ghale et al [26] and Zhang et al [27]. Specifically, Ghale et al's research, which employed Al_2O_3/Water mixtures in both single and dual-phase setups in ribbed microchannels, indicated that increasing the proportion of particles does not significantly affect the friction factor. Consequently, this suggests that the energy required for pumping the nanofluid remains stable regardless of the Reynolds number.

IV.4 EFFECT OF NANOPARTICLE HYBRIDIZATION ON THE FRICTION FACTOR

Figure 7 demonstrates that an increase in Reynolds number (*Re*) results in a reduction in the friction factor for various concentrations of the hybrid nanofluid. The decline in friction factor, associated with increasing *Re*, is attributed to the dominant effect of inertial forces over the viscous forces in the fluid, as detailed by Lodhi et al [28].

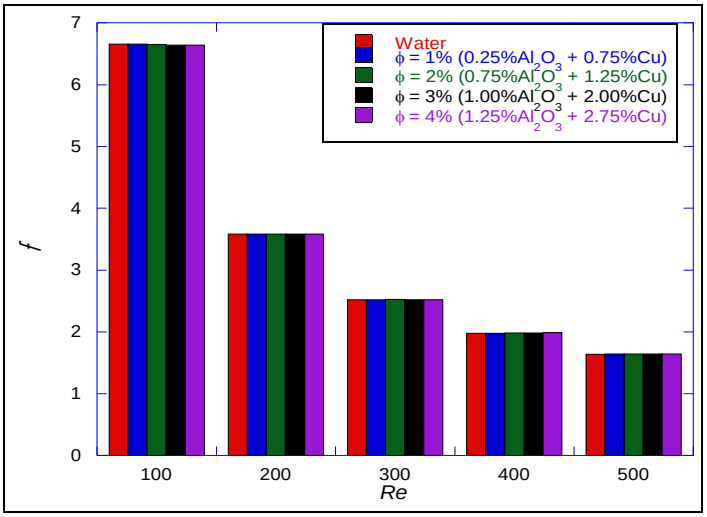

Figure. 7: Effect of Reynolds number on friction factor at diferente hybrid nano particle concentration
Source: Authors, (2025).

Despite these observations, variations in nanoparticle composition appear to have minimal impact on the friction factor, echoing findings by Mohammed et al [29]. This lack of dependency on the friction factor, regardless of changes in the concentration of Al_2O_3 nanoparticles, suggests that the nanofluid behaves similarly to a single-phase fluid, as noted by Byrne et al [30]. A comparable behavior was also observed in the studies by Lee and Mudawar [31], who investigated heat transfer in microchannels using single- and two-phase nanofluids. However, it is generally observed that increasing the concentration of Cu within the mixture enhances the thermal conductivity and heat removal efficiency of the suspension.

IV.5 INFLUENCE OF *RE* ON ENTROPY GENERATION $S'''_{g\text{-}th}$, $S'''_{g\text{-}fr}$, AND $S'''_{g\text{-}total}$

According to Figures 8 and 9, an increase in both *Re* and concentration of Cu in the hybrid nanofluids caused a reduction in $S'''_{g\text{-}th}$ with large deviation at 500 Reynolds number (Figure 8), and $S'''_{g\text{-}total}$ (Figure 9), while $S'''_{g\text{-}fr}$ (Figure 8), increases. The $S'''_{g\text{-}total}$ of the base fluid surpasses that of Al_2O_3/Cu hybrid nanofluid. Mehrali et al [32] utilized a hybrid Fe_3O_4/graphene ferro-nanofluid and

noticed a decrease in entropy generation compared to water. At particle concentrations of 0.25% Cu / 0.75% Al_2O_3, 0.50% Al_2O_3 / 0.50% Cu, and 0.75% Cu / 0.25% Al_2O_3, the value of $S'''_{g\text{-}th}$ in Figure 8 is reduced by 0.86%, 3.16%, and 12.18%, respectively, in comparison to base fluid. While $S'''_{g\text{-}fr}$ in Figure 8 experiences an increase of 10.03%, 8.55%, and 6.67% deviation from the base fluid at particle concentrations of 0.25% Cu / 0.75% Al_2O_3, 0.50% Al_2O_3 / 0.50% Cu, and 0.75% Cu / 0.25% Al_2O_3, respectively.

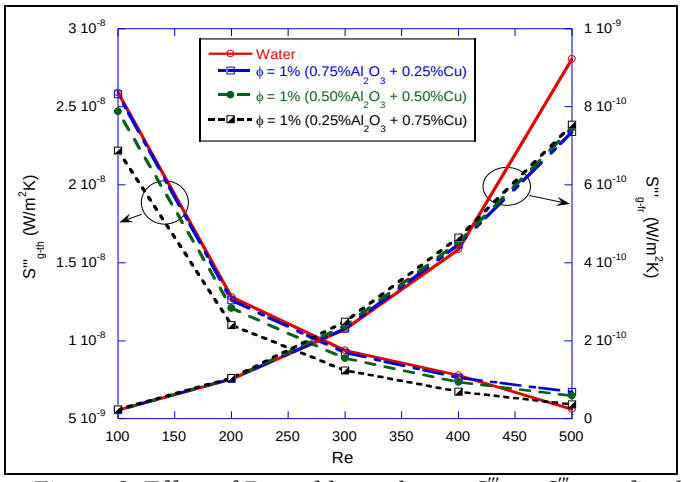

Figure. 8: Effect of Reynolds number on $S'''_{g\text{-}th}$, $S'''_{g\text{-}fr}$ at fixed hybrid nano particle concentration
Source: Authors, (2025).

In Figure 9, the $S'''_{g\text{-}total}$ is reduced by 0.55%, 3.27% and 11.96% at particle concentration of 0.25% Cu / 0.75% Al_2O_3, 0.50% Al_2O_3 / 0.50% Cu and 0.75% Cu / 0.25% Al_2O_3, respectively, compared to the base fluid. These similar trends were observed in the work presented by Saleh and Sundar [33].

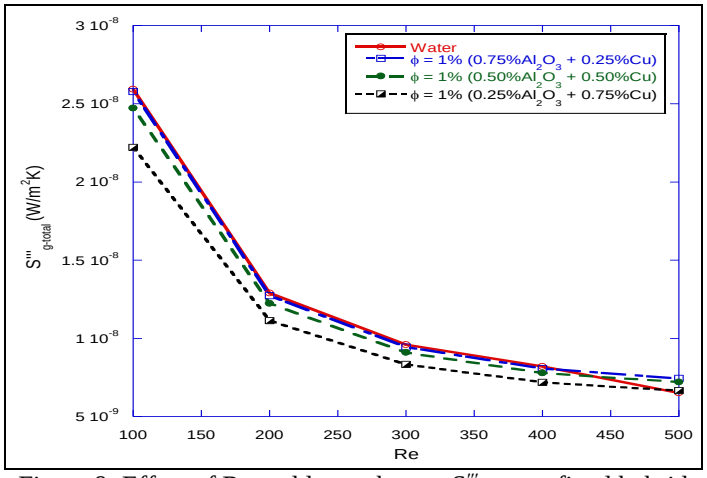

Figure 9: Effect of Reynolds number on $S'''_{g\text{-}total}$ at fixed hybrid nano particle concentration
Source: Authors, (2025).

IV.6 EFFECT OF NANOPARTICLE HYBRIDIZATION ON THE $S'''_{G\text{-}TH}$, $S'''_{G\text{-}FR}$, AND $S'''_{G\text{-}TOTAL}$

Figure 10 illustrates the changes in $S'''_{g\text{-}fr}$ and $S'''_{g\text{-}th}$ as influenced by nanoparticle hybridization. With increasing Reynolds number and nanoparticle concentration, there is an observed rise in $S'''_{g\text{-}fr}$, attributed to the improved thermal conductivity and viscosity of the hybrid nanofluid. Conversely, $S'''_{g\text{-}th}$ decreases with higher Reynolds numbers. These results align with the study by Kanti et al. [34], which investigated heat transfer, entropy generation, and pressure drop using an ash-Cu hybrid nanofluid in tubes. The increase in Reynolds number enhances heat transfer between the fluid and the microchannel wall. Compared to the base fluid, $S'''_{g\text{-}th}$ experienced shifts of 3.27%, 7.71%, 15.98%, and 15.98% for volume fractions of 1%, 2%, 3%, and 4%, respectively. Meanwhile, $S'''_{g\text{-}f}$ showed changes of 6.67%, 5.82%, 5.79%, and 4.76%.

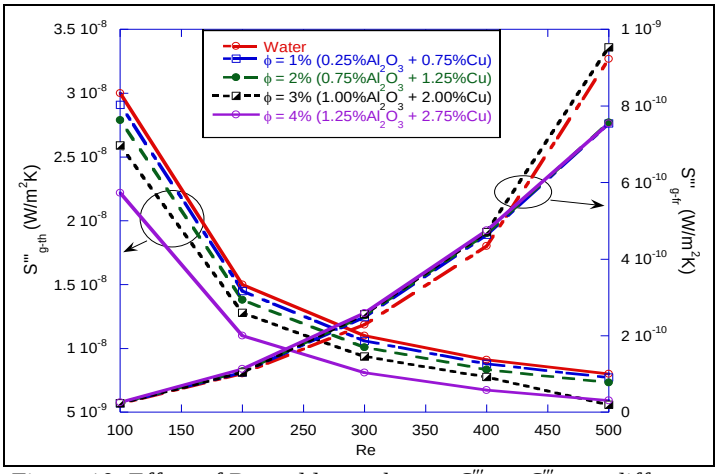

Figure 10: Effect of Reynolds number on $S'''_{g\text{-}th}$, $S'''_{g\text{-}fr}$ at different hybrid nano particle concentration
Source: Authors, (2025).

IV.7 EFFECT OF NANOPARTICLE HYBRIDIZATION ON FIGURE OF MERIT (FOM)

In most methods aimed at enhancing heat transfer, there is a common trade-off: while heat transfer improves, pressure drop also increases. The Figure of Merit (FOM) enables the analysis and comparison of the increment in heat transfer with the energy required to propel the fluid. When FOM >1, this signifies that the thermal efficiency surpasses the energy expended in fluid movement. The impact of hybridization on the FOM becomes evident as the Reynolds number increases. Figure 11 demonstrates that as the average thermal conductivity or fraction of Cu in the hybridized nanofluid rises, the FOM also increases. Specifically, the nanofluid with a concentration of 0.25%Al_2O_3 / 0.75%Cu exhibits a higher effective thermal conductivity compared to the nanofluid with a concentration of 0.5%Al_2O_3 / 0.3%Cu. While they both showed 2.41% and 3.76% shift from 0.75%Al_2O_3 / 0.25%Cu.

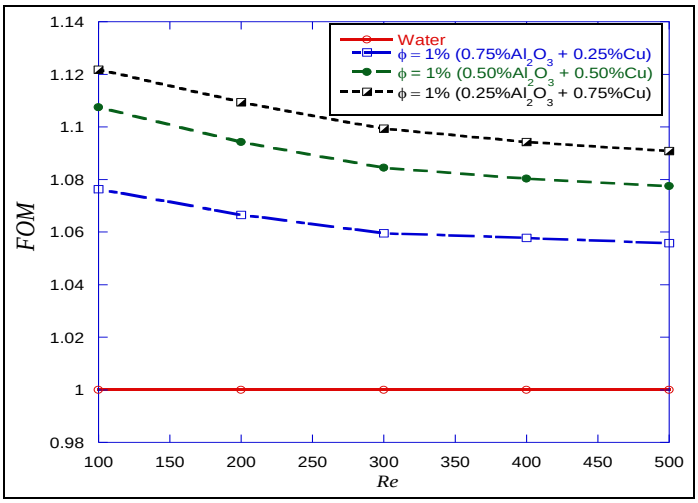

Figure 11: Variation of FOM with Reynolds number at fixed hybrid nanoparticle.
Source: Authors, (2025).

In Figure 12, for a concentration of 4.0% volume, where the copper nanoparticle composition is really high, the maximum FOM corresponds to a *Re* of 100 with 9.10% shift from 1.0% volume of hybrid nanofluid. Conversely, for 1.0% hybrid nanofluid and lower copper concentrations (0.75% volume), the maximum FOM also occurs at a Reynolds number of 100. The lowest FOM is observed at *Re* = 500 for all fractions of hybrid nanofluid. For 1.0% hybrid nanofluid and copper concentrations of 0.75% volume, FOM corresponding to 1.09, while at a value of *Re* = 500, FOM of 1.12 was obtained. However, Kanti et al [34] used fly ash-Cu hybrid nanofluid with Re in turbulent region to obtain similar trends.

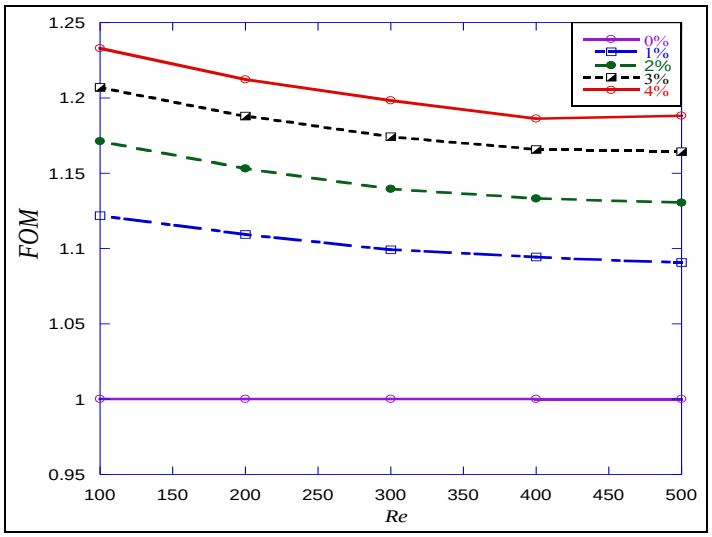

Figure 12: Effect of Reynolds number and hybrid nanoparticle on FOM
Source: Authors, (2025).

V. CONCLUSIONS

This study numerically examined the thermal performance and pressure characteristics of a water-based nanofluid with alumina and copper nanoparticles flowing through a cylindrical microchannel heat sink with internal heat generation at 10^8 W/m³.

The simulation, conducted using ANSYS Fluent computational fluid dynamics software, evaluated the effects of hybridizing copper and alumina nanoparticles on friction factor, Nusselt number, and entropy generation. Parameters included a Reynolds number range of 100 to 500, volume concentrations between 1.0% and 4.0%, and varying proportions of alumina and copper nanoparticles.

Key findings include that increasing the concentration of copper nanoparticles in the hybrid nanofluid did not significantly impact the friction factor. Additionally, thermal and total entropy generation decreased with higher copper concentrations, while Nusselt number and friction entropy generation increased. Notably, increasing both the Reynolds number and copper concentration in the hybrid nanofluids reduced total and thermal entropy generation ($S'''_{g\text{-}th}$), with a deviation observed around Reynolds numbers of 400–500.

In conclusion, the study highlights that the thermal properties of the fluid are critical for designing efficient microchannel heat sinks and confirms the Figure of Merit (FOM) as a valuable tool for performance evaluation.

VI. AUTHOR'S CONTRIBUTION

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Investigation: Olabode Thomas Olakoyejo, Emmauel Adeyemi, SettingsOlayinka Omowunmi Adewumi, Sogo Mayokun Abolarin, Ibrahim Ademola Fetuga, SettingsAdekunle Omolade Adelaja.
Discussion of results: Olabode Thomas Olakoyejo, Emmauel Adeyemi, SettingsOlayinka Omowunmi Adewumi, Sogo Mayokun Abolarin, Ibrahim Ademola Fetuga, SettingsAdekunle Omolade Adelaja.
Writing – Original Olabode Thomas Olakoyejo, Emmauel Adeyemi, SettingsOlayinka Omowunmi Adewumi, Sogo Mayokun Abolarin, Ibrahim Ademola Fetuga, SettingsAdekunle Omolade Adelaja.
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Resources: Olabode Thomas Olakoyejo, Emmauel Adeyemi, SettingsOlayinka Omowunmi Adewumi, Sogo Mayokun Abolarin, Ibrahim Ademola Fetuga, SettingsAdekunle Omolade Adelaja.
Supervision: Olabode Thomas Olakoyejo, Emmauel Adeyemi, SettingsOlayinka Omowunmi Adewumi, Sogo Mayokun Abolarin, Ibrahim Ademola Fetuga, SettingsAdekunle Omolade Adelaja.
Approval of the final text: Olabode Thomas Olakoyejo, Emmauel Adeyemi, SettingsOlayinka Omowunmi Adewumi, Sogo Mayokun Abolarin, Ibrahim Ademola Fetuga, SettingsAdekunle Omolade Adelaja.

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RESEARCH ARTICLE

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STEALING SOME NOTATION FROM BIG O NOTATION TO DEVELOP A NEW MULTITHREADING PRIORITY FORMULA

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ABSTRACT

This work aims to develop the CPU industry by distributing its time between the threads efficiently. To do so, an unprecedentedly developed equation is suggested as a new powerful software to increase the CPU performance. This proposed equation dedicates to solve the problem of children inheriting their parents priorities equivalently without a thoughtful basis in multithreading by involving big O to give threads different values, whose importance is inversely proportional to their O(n)s. The second originality is breaking complexity rule, which considers loop iterations if the threads have the same O(n), since usually threads run on the same computer. Therefore, the ratio (No. of loop's iterations to go/total iterations multiplied by O(n)) determines thread importance inversely. The third novelty is replacing Round Robin with Big O and iteration ratio. A parser is applied to seek "for" and "while" tokens for O(n) measuring purposes. Three threads, p1 $O(n^2)$, p2 O(n), and p3 $O(n^2)$, approved the equation with results of 32, 51, and 8 time slices, respectively, during the period 0-1000 ms. Meanwhile, Round Robin gives the children the same slice number.

I. INTRODUCTION

In modern computer systems, threads are preferred over processes, and multithreading over multitasking [1]. Multithreading has a problem that has not touched before which is the equivalency among the priorities of threads. This problem prevents exploiting the full multithreading utilities efficiently since its objective is to decrease CPU idle time in order to improve system performance, use less memory, and execute context switching in order to share memory and speed up thread switching (scheduling) [2]. The scheduling policy includes these rules: the threads with higher priority receive more CPU time than those with lower priority; a higher priority thread may preempt a lower priority thread; and threads with equal priority receive equal CPU time [3]. The problem is with the third rule because the scheduler gives equal priorities to the children threads without studying their background. For example, any Java program that is executed starts its code from the main function. In order to begin running the code included in the main function, the JVM generates a thread which is referred to as "main thread". The main thread is crucial to understand since it inherits the priority of all other threads, is the source from which they are formed, and must be the last thread to complete execution at all times as depicted in Figure 1 [4]. Each new process is therefore formed with a single thread that competes using priority over its parent process for the processor with the threads of other processes and shares the private segment and other resources [5].

Therefore, they are given arbitrarily the same priority causing unfair competitive between high and low priorities threads as can be seen in the priority techniques that are used by Java and IBM. So, as known, Java is fully based object-oriented which operates in a multithreading environment where a thread scheduler allocates the processor to a thread based on its priority. Java requires that every thread be given a priority when it is created. Priorities can vary from 1 to 10, with 10 being the highest priority. With IBM, for each thread, the kernel keeps track of a priority value, also known as the scheduling priority. The significance of the thread corresponds in reverse with the priority value, which is a positive integer. In other words, a thread with a lower priority value has higher priority. [6], [7].

Moreover, there are two types of thread priorities: fixed and nonfixed; the fixed-priority has an unchanged value, whereas a nonfixed-priority adjusts depending on the processor-usage penalty, the thread's nice value (20 by default), and the least priority

of user threads (40). A thread's priority value is subject to quick and frequent adjustments. The scheduler's priorities recalculation method is the consequence of the ongoing movement. However, for threads with fixed-priority, this is not the case. Meanwhile, the time slice is the maximum amount of time that a thread can be in charge before it risks being displaced by another thread [8].

There are many efforts has been done to improve the priority or utilize it in other systems. For instant, in [9], Based on the RTCOP framework and using multithreading, an architecture for preemptive layer activation called as PLAM has been presented. The non-exception handling layers can be triggered concurrently using PLAM. More work, the majority of complicated processing issues can be solved by applying the Chip Multiprocessor (CMP) technique, which is known for its good performance and high speed for personal computers and Smartphone [10], [11]. For example, in [12] and [13] Multithreading on Android Matrix multiplication program run on single and multi-core for comparing purposes in order to determine the constraints that stand up as obstacles against accomplishing the best execution of time reduction.

Additionally, multithreading middleware for sensor virtualization is built in both the sensor node and the gateway, which lessens the latency brought on by the virtualization of the sensors. Otherwise, scheduling policy, energy use, and memory resources are the three fundamental networking challenges; [14-16] offer prioritization approach to resolve these problems by spotting in the thread priorities' derivation mechanism that is based on inputs from three different sources: threads, the operating system, and external sources like timers to meet the needs of their unique nature. Else, [17] and [18] demonstrate that, in the best instances, the schedulable utilization for the hardware under consideration is roughly multiplied compared to partitioned scheduling without SMT. On the other hand, time complexity is a crucial component for efficient usage on real platforms to decrease the executing time of the algorithm and the completion time of applications, which results in lowering user waiting time [19].

The size of the input is multiplied by the time complexity of an algorithm to determine how long it will take to run [20]. Time complexity involves in many pieces of research specially these are related to the algorithms. For example, designing algorithms to reduce the schedule time for linear and binary PSO, [21] Develops an algorithm to address the issue of the subsequence matching's inherent time complexity.

Other studies, [22] and [23] identify the most effective Traveling Salesman Problem algorithm by evaluating complexity, which has been confirmed to be polynomial equation. All these works are the most related pieces of research to our paper, and it is noticeable that they are located either in multithreading priority field or time complexity field without combining between them which makes this paper the first attempt. So, in this study, a new priority equation is developed to involve time complexity for deciding the next run thread among threads that have equal priorities. Furthermore, an iteration ratio supports the time complexity taking decision among the same polynomial rank threads.

II. METHODOLOGY

This work suggests a developed Multithreading priority equation to solve the equivalent priorities problem by involving constant O(1) and polynomial O(ni) times from Big O notation as one of its terms for the first time in the priority world.

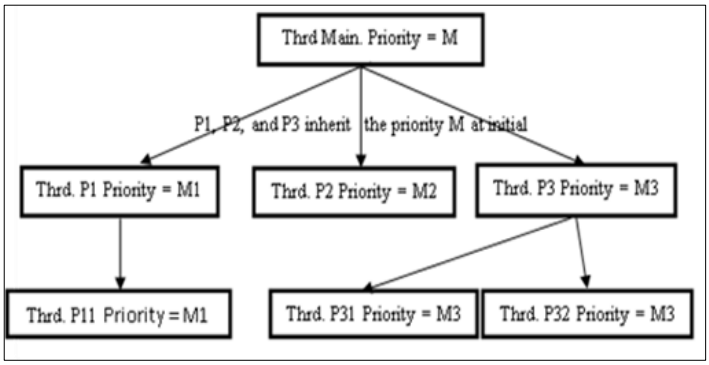

Figure 1: Priority inheriting: P1, P2, and P3 inherit the priority M of the parent Main when they are created. P11 inherits the P1 priority at its creating time t1 = M1. P31 and P32 inherit the P3 priority at their creating time t3= M3.
Source: Authors, (2025).

The big O task is the engaging in the equation calculation, Eq. (1), whenever there are equivalent priorities to give them different values which their importance is being inversely with their O(ni) levels. The second originality is breaking the rule of time complexity which is the number of loop iterations taking part in the equation calculation, Eq. (2), if the threads have the same O(ni) since usually threads run at the same computer and operating system. Therefore, Eq. (2) is multiplied by O(ni) to decide thread importance inversely as well. Third novelty is replacing the Round Robin method, which gives the same slice number to all threads with the sane priorities, by Big O and iteration ratio. The time slice is the time that a thread is allowed to consume without interrupting by the scheduler and swapping it with another same priority thread. In this algorithm, the priority value is increased by the CPU usage counter causing lowering the priority since the relation between them is reciprocal. A thread's most recent CPU usage is utilized to determine the processor penalty. At the end of each time slice (10 ms), the recent processor usage value or counter grows by 1, until reaching the value 120 when the swapper recalculates it for all threads. The swapper recalculates the recent processor usage values every second as well. The minimum priority and the nice value in Eq. (1) equal the defaults 40 and 20 respectively [6].

$$Priority = base\ process\ priority + nice\ value + ((time\ slices\ counter) \times (schedo - o\ sched\_R)) + (iteration\ ratio \times O(n)) \quad (1)$$

$$Iteration\ Ratio = \frac{Number\ of\ loop's\ iterations\ to\ go}{Total\ number\ of\ iterations} \quad (2)$$

Where nice value is the factor that controls the priority and considered a measure of how much the thread cooperates in sharing the CPU, schedo is a CPU scheduler tuning by changing its parameters that are used to calculate threads' priority [6].

For complexity and the iteration ratio part, the formula is applied as is follows:

1- The priority of thread = swapper calculation, if its iteration ratio × O (n^i) is the lowest among all threads.

2- If the thread has the lowest (iteration ratio × O (n^i)) among all threads with same O (n^i), then its priority = highest priority among all threads of O (n^i-1) + 1.

3-If the thread has higher (iteration ratio × O (n^i)) than other threads which have the same O (n^i), then the thread priority = Highest priority among these threads + 1.

So, instead of giving arbitrary equal priorities for all threads at time zero, time complexity assigns actual priorities at the same time.

II.1 MULTITHREADING

In a multithreading, the priority is assigned to thread by the scheduler of the operating system. There are multi priority levels where each thread is granted a specific priority level according to its importance [24], [25]. With large number of threads and limited resources execution environment, control the priority becomes very crucial to organize threads competing for CPU time [26]. Different operating systems implement different priority scheduling algorithms such as Earliest Deadline First (EDF), Multilevel Feedback Queue Scheduling (MLFQ), and Fixed-Priority Scheduling (FPS). Developing any priority scheduling algorithm always faces two major deficiencies that are thread inversion and starvation. Thread inversion is holding resource by low priority thread when the higher priority thread demands it. Starvation, on the other hand, is depriving a thread with lower priority of CPU time consistently because of overtaking by higher priority threads [27]. Figure 2 illustrates these problems, where threads P1 and P2 share S1 and S2 resources, according to these scenarios: if P1 priority > P2 priority and holds S1 or S2 without releasing and P2 demands that resource, then the starvation occurs. On the other hand, if the same scenario is happened, but with P1 priority < P2 priority, then inversion occurs. These two scenarios are represented by the vertical gray and white box in the figure and vice versa if P2 holds S1 or S2 which may enter P1 into starvation or inversion state represented by the horizontal light gray box in the figure. So, in this work, these two problems are solved by limiting the count of successive time slices that thread may get them. Each algorithm offers advantages and trade-offs, but no one solves the equivalent multithreading priorities, which is unique to this research, by abolition this disorder using a new priority equation, Eq. (1) that has a new pathless concept [28], [29].

II.2 TIME COMPLEXITY

Run time and scalability are the most important parameters to evaluate the algorithms' performances. Since the relation between these features is reversible, algorithms' worst-cases measuring is represented by runtime growth rate verses the increasing of the input size, and big O notation is the tool that is used as measurement for these algorithms which is called a complexity [30], [31]. The complexity of an algorithm is a scale of the data segment that is needed for processing in order to function sufficiently. The number of times the algorithm must execute, relative to the length of the input, is known as time complexity [32], [33]. Since other factors such as operating system, processor power, and programming language are considered, time complexity is not working as a measure of how long a specific algorithm taking to run. Time complexity depicts the run time needed to finish the whole algorithm, not measures exact running time in second or millisecond [34]. So, one of the tools to describe the algorithm time complexity is the Big O notation that applies mathematical equations. These equations include constant time O(1), divide and conquer O(log(n)), polynomials $O(n^i)$, exponentials $O(2^n)$, factorials O(n!) [35]; Table 1 shows some of the runtimes for various algorithms.

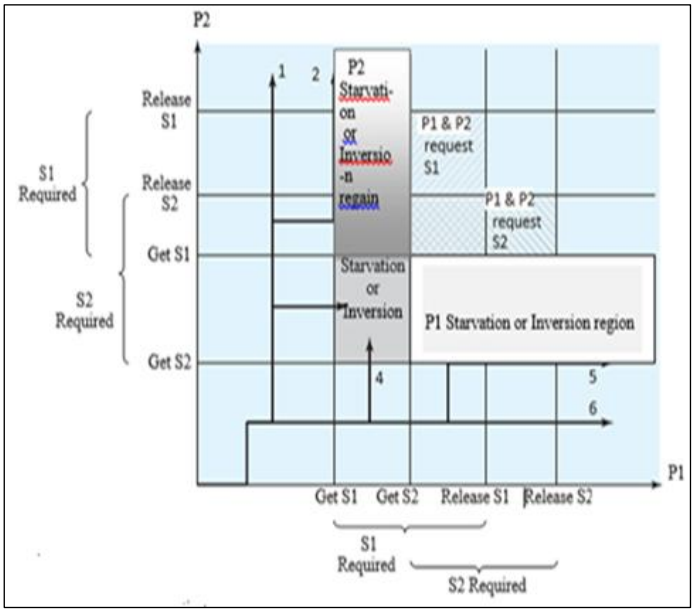

Figure 2: Threads P1 and P2 Starvation and Inversion diagram. P1 execution is represented as x-axis (arrow) and P2 is waiting. P2 execution is represented in the y-axis (arrow) and P1 is waiting.
Source: Authors, (2025).

Where:

= P1 & P2 request resource S1.

= P1 & P2 request resource S2.

= Starvation or Inversion starting region of P1 or P2.

= Starvation or Inversion region of P1.

= Starvation or Inversion region of P1.

= Starvation or Inversion region of P2.

= Possible progress path of P and Q.

Horizontal portion of path indicates P is executing and Q is waiting. Vertical portion of path indicates Q is executing and P is waiting.

Since this work is the first work that Big O notation is involving in multithreading priority, just two of its equations, constant and polynomials times, have been chosen to prove the idea since the basic concept is the same for all equations just needed to extend the parser. Figure 3 is the flowchart that illustrates the individual algorithmic loop process to measure the thread complexity that is used in this work by finding nested loop with the highest depth to use it later to specify the thread priority. By tracking the flowchart path, two things are gotten as outputs: first, the highest depth among nested loops, and second, the loop with the largest remaining iteration count. So, from the "into" and "out of" the flowchart the dominant loop is specified which is taking the largest part to the algorithm's runtime. Next, the growth rate of the dominant loop is used in the algorithm's time complexity calculation. So, let's take the bubble sort algorithm as an example to calculate the complexity where the goal of the algorithm is sorting unarranged members. To do so, the number of nested loops is calculated guiding to complexity of $O(n^2)$ because the algorithm needs two loops (nested) to reorder the members [36-38]. A parser

program in C++ has been written to seek "for" and "while" tokens for $O(n^i)$ measuring purposes. The flowchart in Figure 3, depicts the parser flow of the thread algorithm to get its complexity according to the count of nested loops in order to use it in to assign priority to the thread. The second output of the flowchart is the loop with highest remaining iteration count, which is used as priority backup plan to differentiate threads with same complexity.

Table 1:Runtime complexity for various algorithms with least numbers of consecutive operations.

Algorithm	Runtime Complexity	Consecutive Operation
Recurrent	O(n)	O(n)
Transformer	$O(n^2)$	O(1)
Sparse Transformer	$O(n\sqrt{n})$	O(1)
Reformer	O(n log(n))	O(log(n))

Source: Authors, (2025).

III. IMPLEMENTATION

For the implementation, this paper applies an experiment with three threads: p1 $O(n^2)$, p2 O(n), and p3 $O(n^2)$ as its steps are shown below where they are started at time T = 0 and ended at T = 1000 msec. By running the three threads, this information is gotten: p2 needs 70 time slices, meanwhile p1 and p3 need 2817 and 4205 time slices respectively; Figures 4-6 are the screenshots of the number of slices calculation program that are needed by each thread to finish their whole executions. Therefore, p2 should have higher priority and that would not be discovered without time complexity. Furthermore, the iteration ratio supports time complexity by differentiating threads with the same complexity. So, p2 runs first, and then gives up the processor after time slice number 8 because its priority value rises and becomes equivalent to p1 priority values because of CPU usage counter.

Next, iteration ratio gives the control to p1 since iteration numbers of p1 and p2 are 10000000, 15000000 respectively. Here, the iteration ratio is not applied at time zero because it is always equals 1 for all threads. So, the equation assigns at T = 0 the priorities 61, 60, 62 to p1, p2, and p3 respectively. Below is the actual calculations based on Eq. (1).

T = 0 p2 = 40 + 20 + (0 * 4/32) = 60
p2 takes the control
T = 0 p1 = p2 + 1 = 61
T = 0 p3 = p1 + 1 = 62
T = 10 ms p2 = 40 + 20 + (1 * 4/32) = 60
T = 20 ms p2 = 40 + 20 + (2 * 4/32) = 60
T = 30 ms p2 = 40 + 20 + (3 * 4/32) = 60
T = 40 ms p2 = 40 + 20 + (4 * 4/32) = 60
T = 50 ms p2 = 40 + 20 + (5 * 4/32) = 60
T = 60 ms p2 = 40 + 20 + (6 * 4/32) = 60
T = 70 ms p2 = 40 + 20 + (7 * 4/32) = 60
T = 80 ms p2 = 40 +20 + (8 * 4/32) = 61
p2 releases control
T = 90 ms p1 = 40 + 20 + (9 * 4/32) = 61
……
T = 160ms p1 = 40 + 20 + (16 * 4/32) = 62
p1 releases control

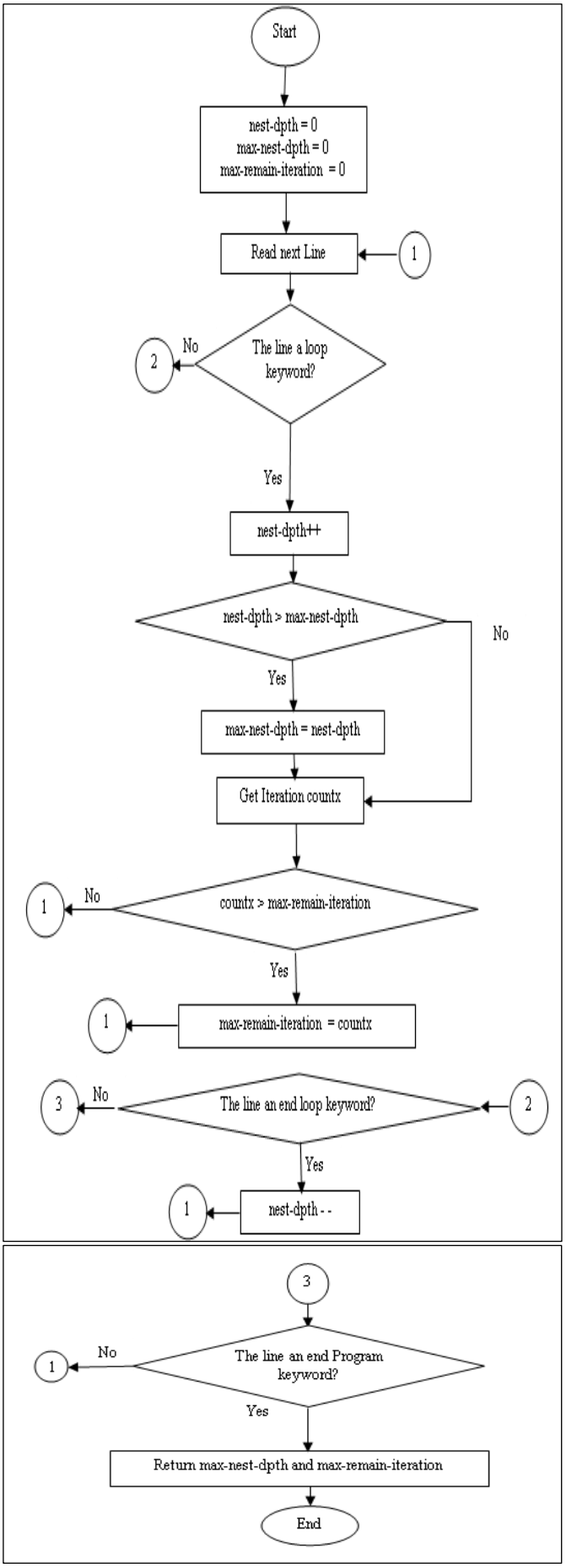

Figure 3: Parser flowchart to get thread complexity according to the count of nested loop with highest depth.
Source: Authors, (2025).

Reset counter = 9
T = 170ms p2 = 40 + 20 + (9 * 4/32) = 61
……
T = 240ms p2 = 40 + 20 + (16 * 4/32) = 62
p2 releases control
Apply Eq. (1):
P1 = 40 + 20 + (17 * 4/32) + ((10000000–26418)/10000000 × 2) = 63.9947164
P2 = 40 + 20 + (17 * 4/32) + ((40000000–49835804)/40000000 × 1) = 62.8754
P3 = 40 + 20 + (17 * 4/32) + (15000000/15000000 × 2) = 64
Therefore, p2 = 62, p1 = 63, p3 = 64, so p2 takes control
T = 250ms p2 = 40 + 20 + (17 * 4/32) = 62
……
T = 320ms p2 = 40 + 20 + (24 * 4/32) = 63
T = 330ms p1 = 40 + 20 + (25 * 4/32) = 63
……
T = 400ms p1 = 40 + 20 + (32 * 4/32) = 64
Reset counter = 25
T = 410ms p2 = 40 + 20 + (25 * 4/32) = 63
……
T = 480ms p2 = 40 + 20 + (32 * 4/32) = 64
Apply Eq. (1):
P1 = 40 + 20 + (33 * 4/32) + ((10000000–26418)/10000000 × 2) = 65.9894326
P2 = 40 + 20 + (33 * 4/32) + ((40000000–9937962)/40000000 × 1) = 64.75155095
P3 = 40 + 20 + (33 * 4/32) + (15000000/15000000 × 2) = 66
Therefore, p1 = 65, p2 = 64, p3 = 66, so p2 takes control

T = 490ms p2 = 40 + 20 + (33 * 4/32) = 64
……
T = 560ms p2 = 40 + 20 + (40 * 4/32) = 65
T = 570ms p3 = 40 + 20 + (41 * 4/32) = 65
……
T = 640ms p3 = 40 + 20 + (48 * 4/32) = 66

(Skipping forward to 1000msec or 1 second)
.
T = 1000ms p2 = 40 + 20 + (60 * 4/32) = 67
T = 1000ms swapper recalculates the accumulated CPU usage counts of all processes. For the above process:
new_CPU_usage = 67 * 31/32 = 64 (if d=31)
After decaying by the swapper: p = 40 + 20 + (64 * 4/32) = 68
Apply the equation:
P1 = 40 + 20 + (64 * 4/32) + ((10000000–26418)/10000000 × 2) = 69.9788174
P2 = 40 + 20 + (64 * 4/32) + ((40000000–15600330)/40000000 × 1) = 68.6099917
P3 = 40 + 20 + (64 * 4/32) + ((15000000-20896)/15000000 × 2) = 69.997213866
Therefore, p1 = 69, p2 = 68, and p3 = 70

Table 2 is a tracing example of p1, p2, and p3, which its explanation is as follows:

At T = 0, p1 = 61, p2 = 60, p3 = 62, therefore, p2 controls the CPU since it has the lowest time complexity.

At T = 90, p2 relinquishes the control since its priority value becomes equivalent to the p1 priority value = 61. Therefore, p1 takes the control since the iteration ratios for both of p1 and p3 =1,

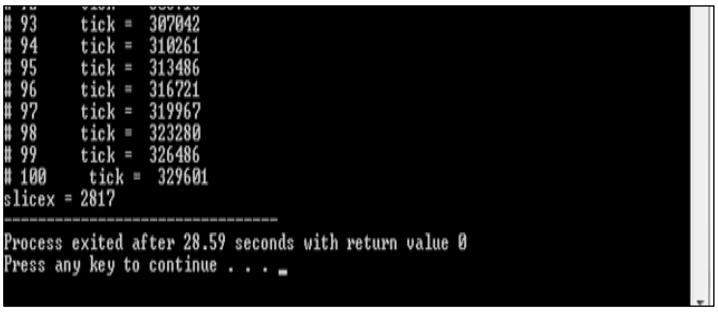

Figure 4: P1's total execution slice number calculation.
Source: Authors, (2025).

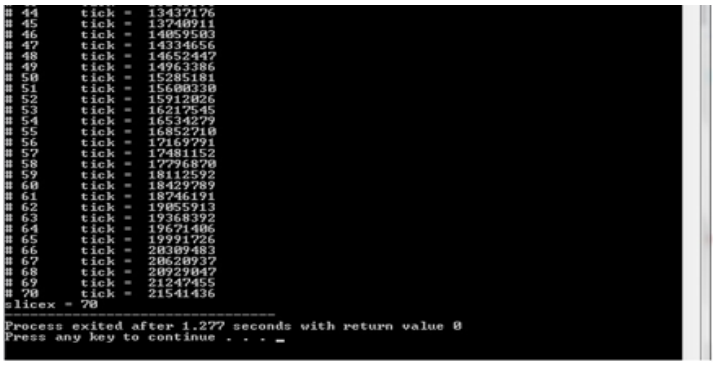

Figure 5: P2's total execution slice number calculation.
Source: Authors, (2025).

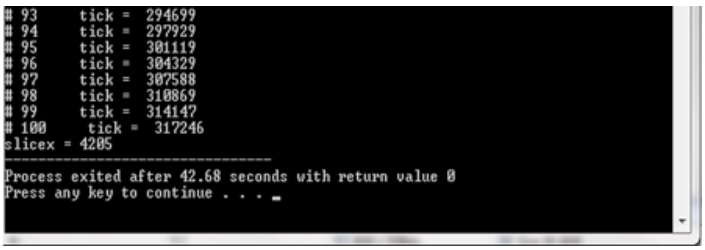

Figure 6: P3's total execution slice number calculation.
Source: Authors, (2025).

Table 2: Tracing of p1, p2, and p3.

T (ms)	p1 Priority	p2 Priority	p3 Priority	CPU control	Counter
0	61	60	62	p2	0
90	61	61	62	p1	1
160	62	61	62	p2	9 reset
240	63	62	64	p2	10
320	63	63	64	p1	11
400	64	63	64	p2	25 reset
480	65	64	66	p2	26
560	65	65	66	p3	27
1000	69	68	70	p2	31

Source: Authors, (2025).

but the number of p1 iterations = 10000000 < 15000000 the number of p3 iterations making p1 = 61 and p3 =62.

At T = 160 ms, p1 gives up the control to p2 again since its value rises to 62 while p2 value = 61. But before that, the algorithm reset the counter to 9 the start of value 61 because it reaches 62 while p2 value = 61 which means that p2 will give up the slice right away. For example, the p2 value after one round if the equation applied without resetting the counter is p2 = 40 + 20 + (17 * 4/32) = 62 making the algorithm useless.

At T = 240 ms, p2 releases the control since its value rises up to 62 and becomes equal to p1 and p3 values. Since all the

threads have equal priorities p1 = p2 = p3 = 63, the equation is applied to assign new real priorities. Therefore, the new priorities are p1 = 63, p2 = 62, and p3 = 64. Therefore, p2 takes the control.

At T = 320 ms, p2 = 63 relinquishes the control to p1 = 63 for the second time.

At T = 400 ms, p1 = 64 relinquishes the control to p2 = 63 after resetting counter to 25.

At T = 480 ms, p2 = 64 relinquishes the control. Since p1 = p2 = p3 = 64, the equation is applied and the new proprieties are: p1 = 65, p2 = 64, and p3 = 66. p2 takes the control.

At T = 560 ms, p2 = 65 releases control to p3 = 66 in spite of p1< p3 since p1 has the control two consecutive times.

At T = 1000 ms (1 sec), swapper recalculates the accumulated CPU usage counter, when thr1, thr2, and thr3 had 32, 51, and 8 time slices respectively and the number of completed iterations for each thread are 26418, 15600330, and 20896 respectively. Therefore, p1 = 69, p2 = 68, and p3 = 70, so p2 takes the control.

From the trace, it is clear that the goal is accomplished since p2 has 51 slices, p1 has 32 slices, and p3 has 8 slices during the period of time 0-1000 ms. Meanwhile, traditional method, which applies Round Robin, gives the same opportunity to the all threads with the sane priorities. The concept of this experiment is giving thread with lowest time complexity and loop iterations more time slices. Therefore, they are involving in the equation whenever the priorities of all threads become equivalent because this state turns the equation to Round Robin and gives equal time slices for every thread. So, the task is giving different priorities for each thread whenever this state occurs. Completing the concept, any state rather than the above one, the time complexity will not involve in the priority calculation, but instead Round Robin is replaced with it. So, every time there are two or more threads with the same priority but not all threads, the time complexity and iteration ratio decide the next thread to control the CPU instead of FIFO, which is used by Round Robin method. To avoid starvation among threads with the same time complexity, the algorithm takes the control from the thread with lower iteration ratio and gives it to the other threads after every two consecutive turns. For example, in this work, thr1 iteration number = 10000000, while thr3 iteration number = 15000000, so thr1 is always taking the control since its iteration number to go is always decreasing, meanwhile thr3 time to go iteration number stays still 15000000.

IV. CONCLUSION

1- This work represents a new generation where is no concept of multithreading with equivalent priorities.
2- The technique acts as Round Robin with multithreading that have constant time for all threads since there is no loops to calculate their iteration ratios
3- This equation rules out the first in first out approach including Round Robin from multithreading system.
4- This work does not work with threads having time complexity involving log, exponential, and factorial times, but extending the parser to include them solve it.
5- The starvation avoidance can be manipulated by changing the number of consecutive call times.
6- The probability that the next time slice is allocated to a thread which has allocated many time slices recently is decreasing.
7- Since time complexity considers the time of iterations' numbers trivia, the equation works more efficient with single-processor than multi-processor.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Abdulamir Abdullah Karim, Yaser Ali Enaya and Ghassan Abdulhussein Bilal.
Methodology: Abdulamir Abdullah Karim, Yaser Ali Enaya.
Investigation: Abdulamir Abdullah Karim and Yaser Ali Enaya and Ghassan Abdulhussein Bilal.
Discussion of results: Abdulamir Abdullah Karim, Yaser Ali Enaya and Ghassan Abdulhussein Bilal.
Writing – Original Draft: Abdulamir Abdullah Karim and Ghassan Abdulhussein Bilal.
Writing – Review and Editing: Abdulamir Abdullah Karim and Yaser Ali Enaya.
Resources: Yaser Ali Enaya and Ghassan Abdulhussein Bilal.
Supervision: Yaser Ali Enaya and Ghassan Abdulhussein Bilal.
Approval of the final text: Abdulamir Abdullah Karim, Yaser Ali Enaya and Ghassan Abdulhussein Bilal.

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RESEARCH ARTICLE OPEN ACCESS

SMART-INSPECTION SYSTEM ON ASSEMBLY PROCESS OF PIN-THROUGH COMPONENTS USING MACHINE LEARNING

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ABSTRACT

This paper proposes using machine learning techniques to implement a failure mode classifier for automatic fail classification in pin-through hole (PTH) connector terminals in printed circuit boards (PCB). The Support Vector Machine (SVM), K-nearest neighbor (KNN), and Decision Tree (DT) algorithms were used. It was evaluated using a dataset of real images from manufacturing multimedia centers for the algorithm training phase. Subsequently, it thoroughly evaluated the results of the metrics obtained from each trained model. The main objective is to select the model with the best precision in predicting two failure modes to be implemented at the automotive factory and improve the inspection phase to reduce the defect and rework rates. The failure mode classifier trained with the SVM algorithm obtains the best precision, with an accuracy of 99% in predicting the dataset of tested images. KNN and DT achieved 78% and 79% accuracy, respectively, but DT was unstable. The final decision was to implement the SVM algorithm that obtained the best accuracy in decision-making for the failure modes evaluated in the research.

I. INTRODUCTION

Printed circuit boards (PCBs) are essential in the manufacturing of electronic devices. In recent years, the demand for more sophisticated products with more embedded functions has made PCBs more complex, requiring higher quality and the application of lean thinking theory in production lines [1].

In manufacturing, the search for defect-free products has demanded more sophisticated inspection methods [2], using methodologies and algorithms capable of extracting knowledge from data [3]. PCB inspection is a crucial process to ensure the reliability and quality of the product before it is made available to the end consumer. Inspection is often performed visually by human operators, which can result in variations in the classification of defects due to physical and emotional inconsistencies of each operator [4],[5]. This has led industries to seek more efficient inspection methods to identify defects in the early stages of production [6].

Automatic Optical Inspection (AOI) has been used in industry to assist in identifying defective components in PCBs [7]. AOI systems generally employ defect inspection methods by scanning the board and analyzing it using techniques such as local feature matching with a standard image [8] and morphological image comparison to detect defects, achieving excellent results. However, problems with reflective materials can cause false failures [9].

With the sophistication and miniaturization of components inserted in PCBs, the challenges for fault detection become increasingly complex [10]. Detecting the absence of terminal projections and recognizing components and their similarities are complex tasks by manual visual inspection [11]. This increasingly requires traditional image classification algorithms and convolutional neural network models for defect detection [9]. Studies based on automatic visual inspection for detecting PCB faults through Machine Learning [7] and convolutional neural networks [8] have gained significant space and attention within the scientific community in recent years. According to [1], several methods have been proposed to detect and classify a variety of defects in PCBs. These methods are increasingly used in industry for decision-making, enabling the transformation of traditional

manufacturing to Industry 4.0 [12],[13],[14]. This article proposes methods to detect and classify defects without the projection of power connector terminals using machine learning algorithms. The analyzed PCB dataset was collected from a real production line of an industry installed in the Manaus Industrial Pole located in Brazil. Subsequently, the accuracy of the best method for implementation in detecting the absence of projection of pins will be analyzed.

II. THEORETICAL FRAME

The enumerations of citations in the body of the article must be sequenced in the order in which they appear, according to the example shown below.

The sequence of actions is structured so that the dynamics of the image dataset classification include control mechanisms capable of compensating for possible disturbances. In this way, the classifier can generate a correct output, even if there are interferences in its learning process [15]. This is achieved by comparing the actual prediction values (output) with the input values (test images).

Control systems are physical models that show the dynamics of a system and are usually composed of blocks that can be analyzed mathematically [16]. The block diagram of the Control System for classification is shown in Figure 1.

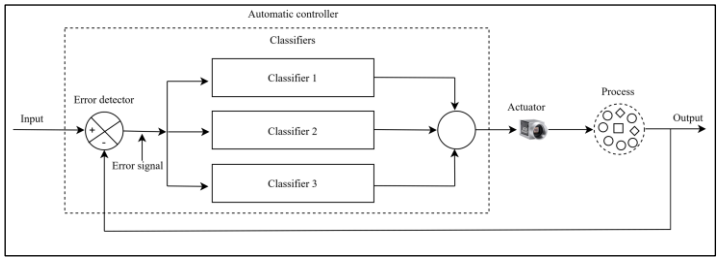


Figure 1: System diagram.
Source: Authors, (2025).

The dynamics of the classification system start with the reference data. To further perform the classification process of the model for each machine learning algorithm to compare the output data with the reference image to verify the failure mode. The acting error signal provides feedback to the system to reduce the error and prevent external changes from affecting the system's behavior. Then it will obtain information from the best failure mode classifier to predict the image classification for deciding the OK or NOK state of the inspected PCB.

II.1 BIBLIOMETRIC ANALYSIS ON MACHINE LEARNING AND SMART INSPECTIONS FOR PTH COMPONENTES

A bibliometric analysis was performed to analyze the dynamics of research evolution, considering machine learning algorithms used for quality inspection of the manufacturing process in the context of Industry 4.0 and Quality 4.0. The final search was realized in December 2024 on the Scopus database and Web of Science Database with the terms "Pin Through-hole" or "PCB" and "Machine Learning" or "SVM" or "KNN" or "Decision Tree" or “smart-vision inspection”, applied in the titles, abstracts, and keywords of the articles. For the portfolio, only articles with publications in English were considered.

Based on the adopted methodology, 220 articles were found in qualitative synthesis; from the articles selected for content analysis from the timespan 2019 to 2024, quantitative analyses were developed with the Bibliometrix tool of the R Studio® software, following the procedure developed by [17].

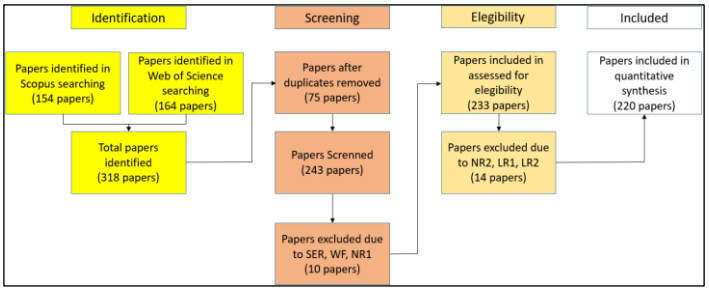


Figure 2: Prisma methodology.
Source: Authors, (2025).

Figure 2 shows the PRISMA methodology used on the research [18].

The final search string is presented as follows:

String to Scopus database- TITLE-ABS-KEY ((“Pin Through-hole” OR “PCB”) AND (“machine learning" OR “SVM” OR “KNN” OR “Decision Tree” OR “smart-vision inspection”))

String to Web of Science database - TS= ((“Pin Through-hole” OR “PCB”) AND (“machine learning" OR “SVM” OR “KNN” OR “Decision Tree” OR “smart-vision inspection”))

Figure 3 shows the temporal evolution of publications in the selected portfolio. 2016 was the first paper in which a publication appeared in an indexed journal in the considered databases. [19] presented a system with a neural network to predict the skew factor of PCB laminate designs. [20] described a model to predict the production cycle time of high-mixed PCB based on machine learning methods.

Since 2019, the number of publications has grown consistently. Between 2019 and 2024, publications increased by 162%. This analysis shows the growing interest in smart inspection using machine learning algorithms.

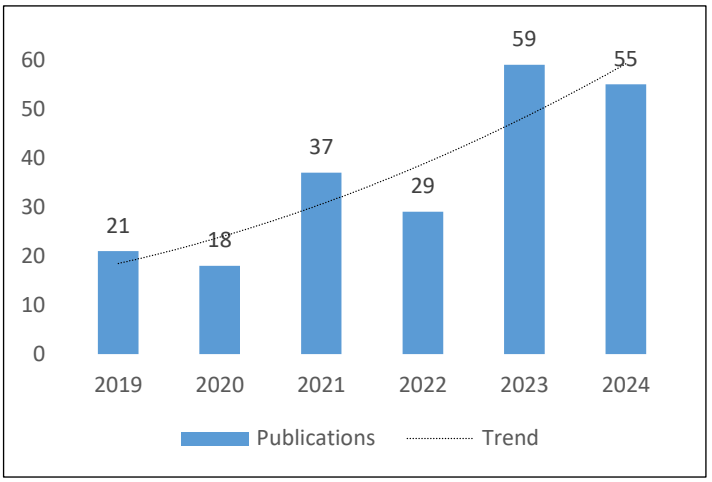


Figure 3: Temporal evolution of publications.
Source: Authors, (2025).

Figure 4 shows the main countries with associated studies in the research area, categorized by publications authored by only one country (in blue) and several countries (in red). China presents great performance with 60 publications, followed by USA with 46, Germany with 19, India with 17, and the other countries with 7 or fewer publications.

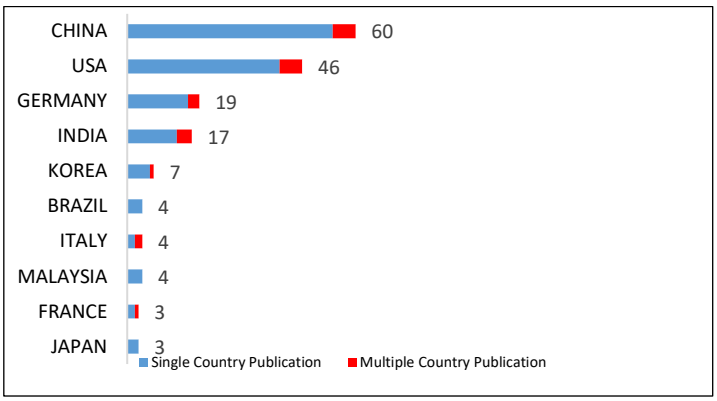


Figure 4: Publication by country.
Source: Authors, (2025).

Figure 5 shows a multidimensional scaling keyword co-occurrence network [21] using an edge betweenness centrality clustering algorithm. This analysis allows the identification of a main group of terms (in red) that deal with the intersection between the themes investigated in this research.

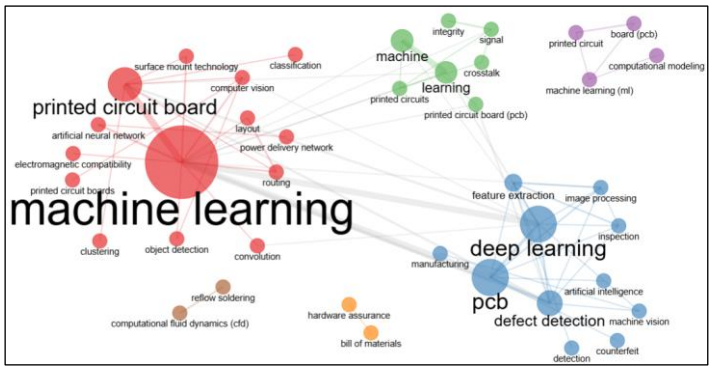


Figure 5: Keyword co-occurrence network based on the bibliometric research.
Source: Authors, (2025).

This analysis allows the identification of a main cluster of terms (in red) that deals with the intercession between “Machine learning” and “printed circuit board”. Around the central terms other topics as “deep learning”, “defect detection”, “artificial intelligence”, “computer vision” appear in the co-occurrence network.

Figure 6 shows a wordcloud graphic regarding the most common expressions among the analyzed articles. Based on that it is possible to summarize that the central themes involved in the area of machine learning, where the research seeks to correlate the concept of printed circuit board and defect detection, are the terms “deep learning”, “artificial neural network”, which demonstrates that most of the studies developed in the area are concerned with defining concepts, implementing new methods to existing models in the smart inspection environment with the objective of improving the digital transformation.

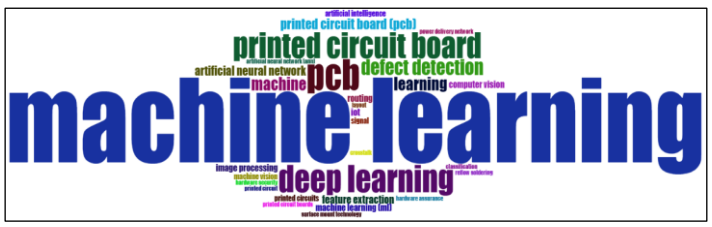


Figure 6: WordCloud based on the bibliometric research.
Source: Authors, (2025).

II.2 MACHINE LEARNING

The growing complexity of the problems to be computationally treated, and the speed and volume generated by different sectors, motivated the development of more sophisticated and autonomous computational tools, more independent from human intervention, for the acquisition of knowledge. Most of these tools are based on machine learning [22].

The main objective of Machine Learning (ML) is to understand structures, just like in most statistical models. It proves itself mathematically, through assumptions that allow systems to be replicated by examining data structures, even if you don't know what the structure looks like. Through the interactivity of understanding machine learning data, it allows for the automation of learning [1].

Machine learning algorithms have been widely used in several tasks, which can be divided into predictive [22],[23], and descriptive [1]

Figure 7 hierarchically illustrates the learning categories and associated tasks.

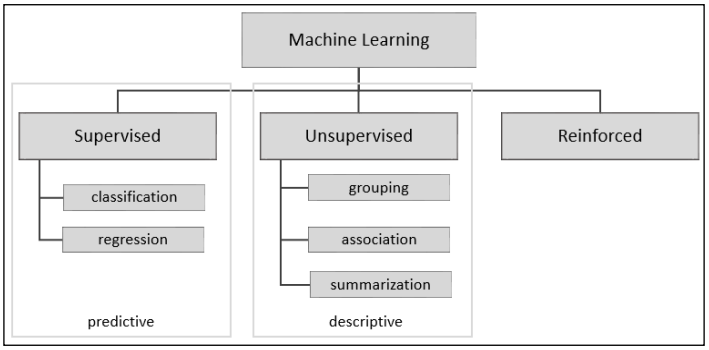


Figure 7: Classical Learning hierarchy.
Source: Authors, (2025).

II.3 SUPPORT VECTOR MACHINE - SVM

Support vector machines (SVMs) are a supervised machine learning technique used in classification and regression problems [24],[25]. SVMs seek to find an optimal hyperplane to separate a data set [26]. Initially, SVMs only allowed linear separation methods [27]. However, it is possible to perform non-linear class separation by transforming the data into a higher dimension, where they can be separated linearly [28].

SVM proposes a hyperplane that separates the data set belonging to each class so that the data characteristics are on one side of the hyperplane. Throughout this process, the SVM maximizes the distance between the hyperplane of each class so that the separation margin is the smallest distance between the points of the hyperplane of each class. The generation of the hyperplane is determined by the subsets of points that form the classes, known as support vectors [28].

SVM uses a standard dataset to create a binary classifier. To perform the function $f: \mathbb{R}^n \rightarrow \{\pm 1\}$ have named as instruction examples, where *xi* contains *n* features in a specific class *yi* [27], illustrated in equation (1).

$$(x_1, y_1), \ldots, (x_n, y_n) \in \mathbb{R}^n \, x \pm 1\} \quad (1)$$

Thus, f will perform the classification of the samples *(x, y)*, where $f(x) = y$ for each *(x, y)* made using the same probabilistic distribution P*(x, y)* of the training data, as per [28]. The structural risk minimization method used by statistical learning theory is the basis of the SVM variable selection. The best-known definition of

statistical learning theory is dimension, which defines the most significant number of points that can be separated in various ways [27].

II.3.1 SEPARATION HYPERPLANE

By using the structural risk minimization principle to identify the optimal hyperplane to maximize the margin of the closest examples, SVMs create a series of hyperplanes whose dimension boundaries can be processed [27]. One example is the patterns for linearly separable classes, in which the class *yi* can only receive values +1 and -1 [28]. Equation (2) illustrates the decision surface of a hyperplane to perform class separation.

$$(\omega . x) + b = 0, \omega \in \mathbb{R}^n, b \in \mathbb{R} \quad (2)$$

The ω gives the adjustable weight vector and *b* gives the threshold. Illustrated in equation (3).

$$\begin{cases} (\omega . x) + b \geq 0, \text{para } y_i = 1 \\ (\omega . x) + b < 0, \text{para } y_i = -1 \end{cases} \quad (3)$$

The closest data point is called the separation margin. Figure 8 illustrates the optimal hyperplane obtained using the maximum class separation margin.

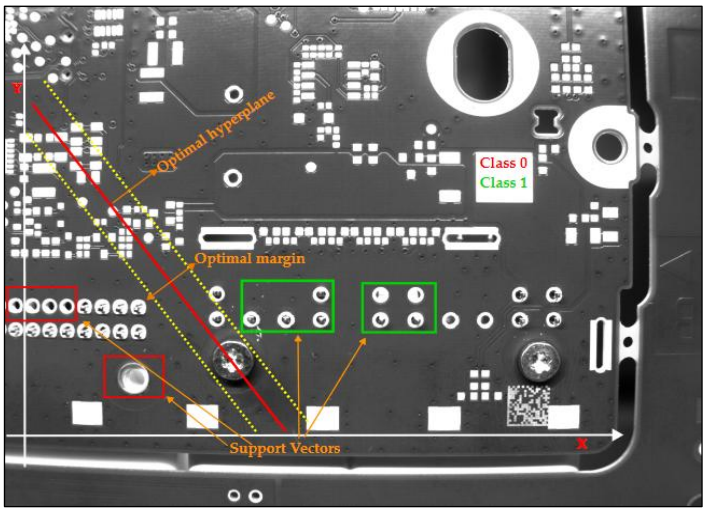


Figure 8: Definition of the optimal hyperplane.
Source: Authors, (2025).

Figure 8 illustrates the maximum margin separator, represented by the solid red line, and the margins, represented by the dashed lines. The support vectors are the holes highlighted by the dashed circle and the connector terminals highlighted by the green squares closest to the separator.

II.4 K-NEAREST-NEIGHBOR - KNN

The *k*-nearest neighbors (KNN) classifier is a classical classification algorithm that uses nonparametric methods. Its basic concept is determining class labels based on their *k* nearest neighbors [29]. KNN classifies the K points of the closest training set to find K elements with the smallest distance. Figure 9 illustrates the definition of KNN.

Figure 9 illustrates the representation of the data already trained with its classifications previously defined for the Pin and Hole classes. In summary, the distance of the new object will be determined by defining the *k* neighbors but closest to the category. When K is defined as having three or four occurrences, it will be classified as Pins since two of the three closest neighbors are Pins.

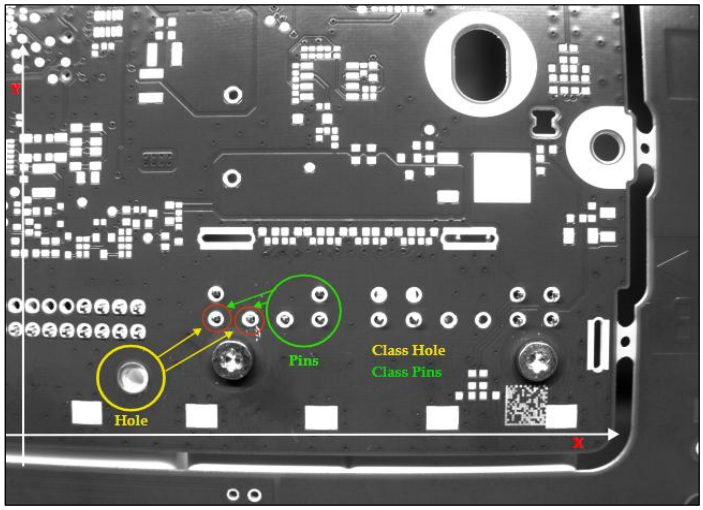


Figure 9: Definition of the KNN.
Source: Authors, (2025).

By approximating the k values, the distance between points x and y is calculated using the Euclidean or Manhattan distance [30],[31]. The calculation of the space between the distances of the objects is demonstrated by the equations (4 and 5).

The Euclidean distance between point *x* and *y* is given by equation (4):

$$d(x,y) = \sqrt{(x_1, y_1)^2 + (x_2, y_2)^2 + \cdots + (x_n, y_n)^2} \quad (4)$$

The smaller distance between points *x* and *y* was determined by measuring the Euclidean distance.

The Manhattan distance between points *x* and *y* is given by the equation (5):

$$(x,y) = |x_1 - y_1| + |x_2 - y_2| + \cdots + |x_n - y_n| \quad (5)$$

The sum of the absolute differences between points *x* and *y* in all dimensions of space will determine the distance to Manhattan.

II.5. DECISION TREE

Nonparametric models for data classification and prediction based on supervised learning are known as decision trees [32]. Decision trees use the splitting strategy, which means that the training data set is divided into several smaller subsets until one of the subsets is of the same class or until the class is the predominant one [33].

The decision tree is constructed from the compactly organized data, which recursively classifies new examples. This creates a data structure [32], corresponding to a node or leaf as a class or decision node that can test several attributes. When each result creates a new subtree [33]. A decision tree is shown in Figure 10.

The decision tree nodes are represented by the NOK attribute and distributed in the tree according to their level. The segments that define the nodes to which each attribute belongs are used to test the values. The attributes of the categorical type are validated using the equal sign, as shown in Figure 10 by the white circles, where each circle is the attribute. Decision trees use algorithms to identify the value assigned to the node and represent quantitative values in a specific range of values. These algorithms also determine the branches' division into subsamples comparable to the variable resulting from the classification [33].

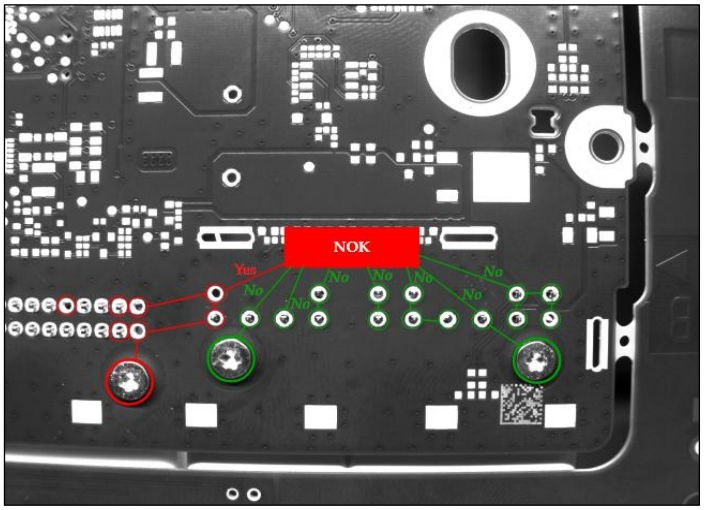


Figure 10: Decision tree model.
Source: Authors, (2025).

III. RESEARCH STAGE 1 - CLASSIFIERS

In this section, the experiments and results used to carry out this work are presented. Accuracy comparisons were made between the machine learning algorithms applied in the training and classification of the database of failure modes in PCBs.

III.1 IMAGE PRE-TREATMENT

The two classes and the number of images for training, testing, and validation of the classifiers are presented in Table 1.

Table 1: Definition of classes for classification.

Classes	Training	Validation	Testing
NOK	380	95	95
OK	380	95	95
Totals of Imagens	**760**	**190**	**190**

Source: Authors, (2025).

The images were captured in grayscale and used for supervised training. Since the process involves object detection, the images need to be cataloged. Figure 11 demonstrates the defined areas of interest.

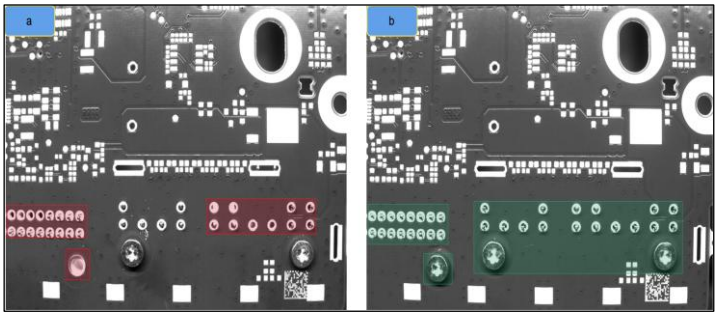


Figure 11: Definition of the image area of interest.
Source: Authors, (2025).

The standardization of classes was implemented because the terminals and screws do not present differences in shape or color. Each class uses images with a resolution of 1280 x 720 pixels for training and validation. The definition of the classes is presented in Figure 12.

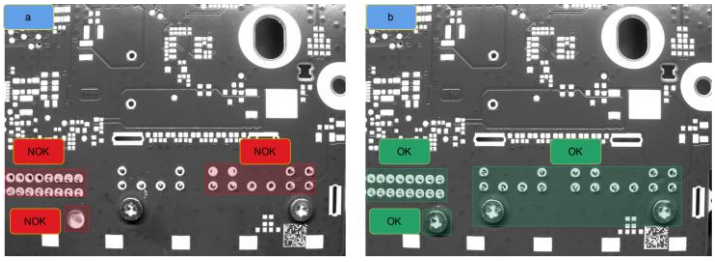


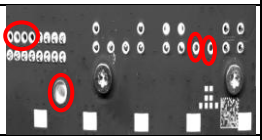
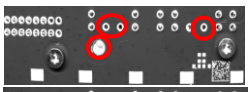
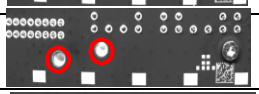
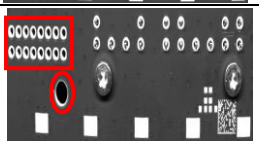
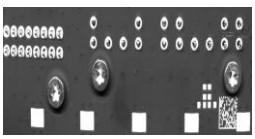
Figure 12: Definition of classes.
Source: Authors, (2025).

III.2 FAILURE MODES DEFINED IN RESEARCH

The acquisition of the dataset to detect the absence of projection of the connector terminals and classification of failure modes were obtained on the production line through the capture of 1140 images of black and white PCBs with different failure modes, using criteria from Failure Mode and Effects Analysis (FMEA) [34], [35],[36],[37],[38], [39].

The creation of only two classes for failure mode detection was considered to represent PCBs without failures and PCBs with failures, as mentioned in Table 2.

Table 2: Failures Modes.

Items	Defect Type	Pictures	Description	Specification
1	Missing Pin and Screw		No evidence of pins and screw	Nok
2	Missing Pin and Screw		No evidence of pins projection and missing screw	Nok
3	Missing Screw		Missing screws (2x)	Nok
4	Missing Pin, Screw and Connector		No evidence of pins projection and missing screw and connector	Nok
5	Missing Pin		There is no evidence of pin projection	Nok
6	Golden Sample		Solder splashes on metal component surfaces impact form, fit or function.	Ok

Source: Authors, (2025).

IV. EXPERIMENTS

During the experiments, three machine learning algorithms were used to build a failure mode detection model, to classify samples, and to determine the class corresponding to the failure mode:

I.To create the failure mode detector, we used the support vector machine (SVM) algorithm in the first experiment with a linear kernel since the 600 images in the database are linearly separable. The classifier performs the classification of each data sample to classify each training sample into its corresponding NOK or OK class. After completion, the classifier will be able to make new predictions of failure modes in the latest samples of PCB images.

II. The decision tree algorithm was used to perform the second experiment. The algorithm created a failure mode detector from an empty tree, iteratively searching for the best attribute to divide the data. The algorithm used the 600 images in the database to achieve this goal. If the data were divided and belong to the same class, a leaf will be created with the NOK or OK label. After training, the classifier predicts the class of new samples of PCB images.

III. The KNN algorithm was used in the third experiment. Data was given to measure the test point of a specific value or label to predict the training set, and then the nearest k points were selected to make the class prediction based on the label of its neighbors to create the failure mode detector. The cross-validation method was used to select the k parameter. The algorithm will have access to the 600 images in the database. If the points in the classification belong to the same class, the nearest neighbor will be labeled as NOK or OK. After training, the classifier will be able to make the predictions.

The experiments were performed using the diagram of the classification methods suggested in Section 2. The objective of the experiments is to verify the efficiency of the algorithms in predicting failure modes. After the training, the metrics generated during the training will be compared to define which models will be implemented in the production line.

V. VALIDATION OF FAILURE MODE DETECTION

The confusion matrix is a popular method for evaluating machine learning algorithm metrics, such as precision, accuracy, and ROC curves [40],[41], whose values are found through the confusion matrix illustrated in Table 3.

Table 3: Confusion Matrix

		Is there an image failure mode?	
		True	False
Was the algorithm detecting the failure mode in the image?	True	True Positive (TP)	False Negative (FN)
	False	False Positive (FP)	True Negative (TN)

Source: Authors, (2025).

The variable (TP) corresponds to the number of failure modes classified as good, as shown in the confusion matrix in Table 3. The variable (TN) corresponds to the approved failure modes. The number of failures (OK) classified as non-failures (NOK) is represented by the variable (FN). In contrast, the number of failures (NOK) classified as failures (OK) is represented by the variable (FP). The variables (TP and TN) indicate the hits that the classifier obtained in its result, while the variables (FN and FP) indicate the errors caused in the classification of the classifier.

Accuracy, sensitivity, and specificity were used to measure the performance of the classifiers. The adequate number of positive and negative samples represents the precision of the model.

VI. RESULTS AND DISCUSSIONS

The paper's main objective is to obtain the accuracy of the best machine learning algorithms for developing a failure mode classifier to perform automatic visual inspection of the projection of the terminals of PTH components.

VI.1 SVM

The experiment metrics, obtained from the SVM classification, are demonstrated through the confusion matrix and learning curve generated after training the failure mode model, according to Figure 13.

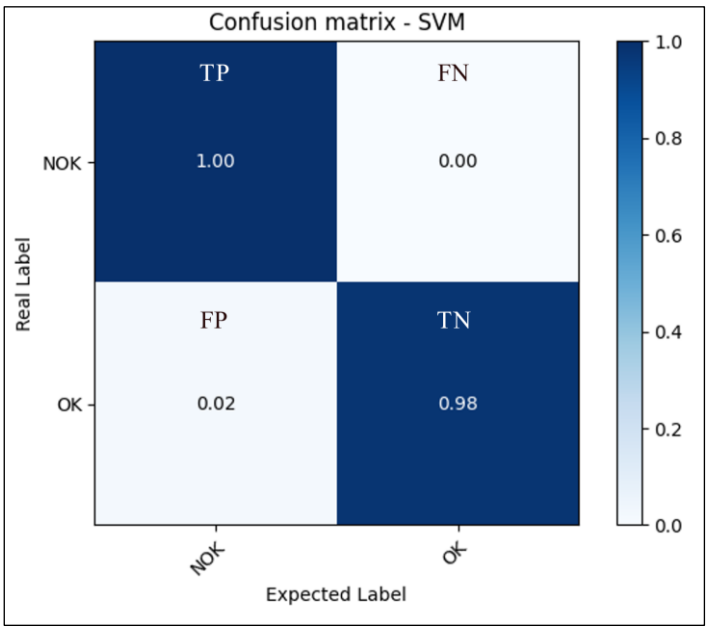


Figure 13: Definition of classes for SVM.
Source: Authors, (2025).

The TP variable demonstrates the accuracy of the failure mode classification of PCBs classified as NOK with a precision of 1.00. The TN variable represents the classification accuracy of OK PCBs with a precision of 0.98. The FP represents the number of OK PCBs classified as NOK with a precision rate of 0.02, demonstrating a small error in the prediction. The FN demonstrates the number of NOK PCBs classified as OK with a precision of 0.00, demonstrating that the classifier did not make a mistake in this prediction.

The classifier performance metrics were obtained using the confusion matrix data of the trained SVM. The most used metrics for evaluating machine learning models are learning and ROC curves, accuracy, specificity, and sensitivity [40]. Figure 14 illustrates the results of the SVM classifier metrics.

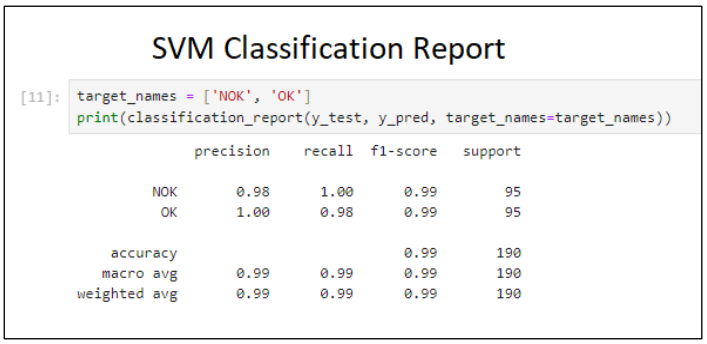


Figure 14: SVM model evaluation metrics.
Source: Authors, (2025).

The accuracy of the model reflects its performance during training and learning. The accuracy calculated is the total number of correct answers divided by the total number of images in the database, demonstrating the model's ability to make correct predictions. The accuracy of the SVM was 99%. Precision considers only true positive values, preventing false positive values from introducing biased errors in the result. The recall metric indicates the frequency with which the image is correctly identified

as belonging to a given class. The f1-score, the harmonic mean between precision and recall, evaluates the quality of the model's training. This metric is fundamental in imbalanced datasets. Figure 15 illustrates the accuracy of the learning curve when testing images classified by the linear SVM algorithm.

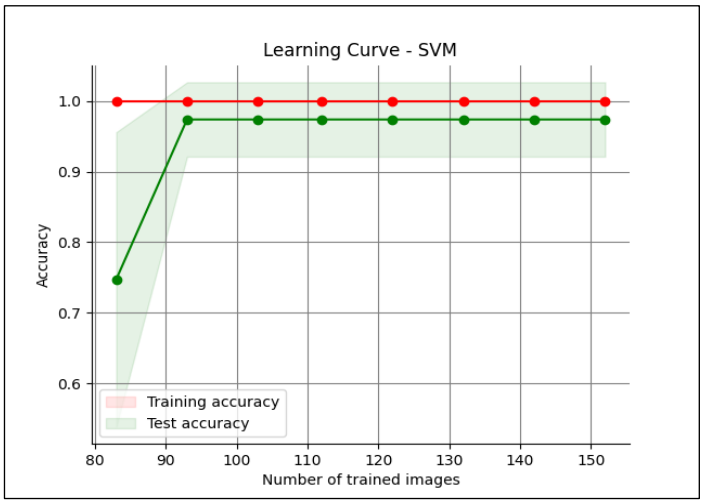


Figure 15: Learning curve for SMV.
Source: Authors, (2025).

Figure 15 shows the accuracy of the model's learning curve. It is noticeable that the training accuracy increases with the number of images used in the algorithm. As we approach 93 tested images, it is evident that the accuracy has increased, remaining consistent and stable, with an accuracy of 99% at the end of training.

VI.2 KNN

The KNN algorithm was used in the second experiment to train the failure modes. In this scenario, the same database was used under the same conditions and quantity mentioned in the first experiment. Figure 16 illustrates the confusion matrix generated after completing the KNN training.

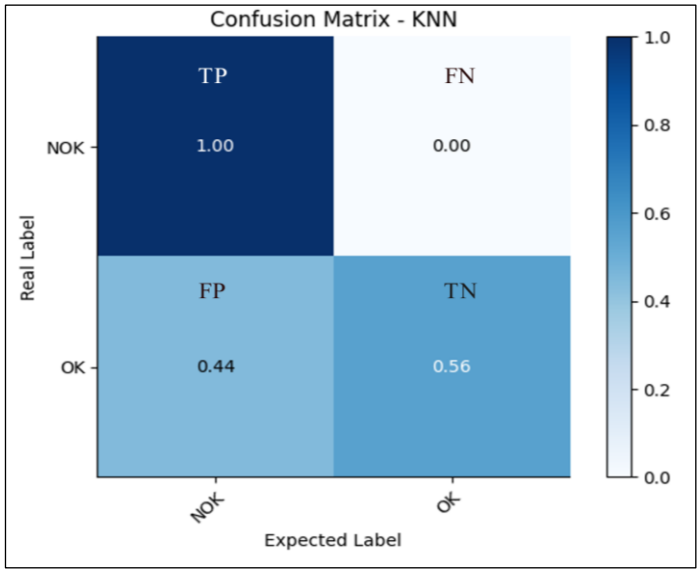


Figure 16: Definition of classes for KNN.
Source: Authors, (2025).

The variable (TP) represents the number of PCBs classified as NOK with an accuracy rate of 1.00. The variable (TN) represents the PCBs approved OK, with an accuracy of 0.56. The variable (FP) represents the total number of PCBs OK and classified as NOK, with an accuracy of 0.44. Moreover, the variable (FN) represents the number of PCBs classified as NOK and classified as OK, with an accuracy rate of 0.00. The results of the metrics are illustrated in Figure 17.

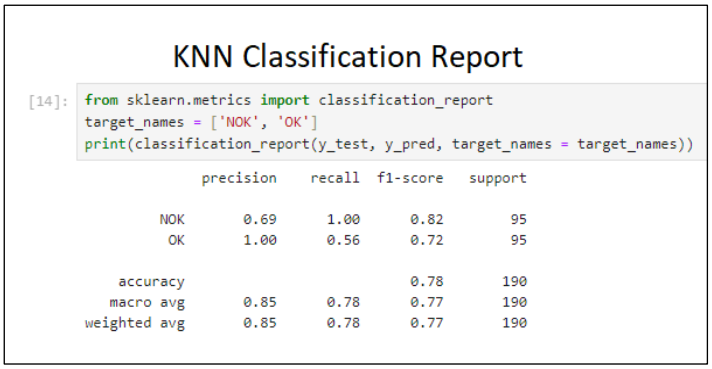


Figure 17: KNN model evaluation metrics.
Source: Authors, (2025).

In the model's accuracy of the KNN was 78%, the precision of values for NOK failed PCBs was 0.69, and for OK PCBs, it was 1.00; only the true positive values were used. In the recall, NOK PCBs had 1.00, while OK PCBs had 0.56. This demonstrated the frequency of an image in a specific class. The final score of the model training can be seen in the f1-score metric, where NOK PCBs had 0.82 and OK PCBs were 0.72. Figure 18 shows the training and testing learning curve accuracy of images classified by KNN.

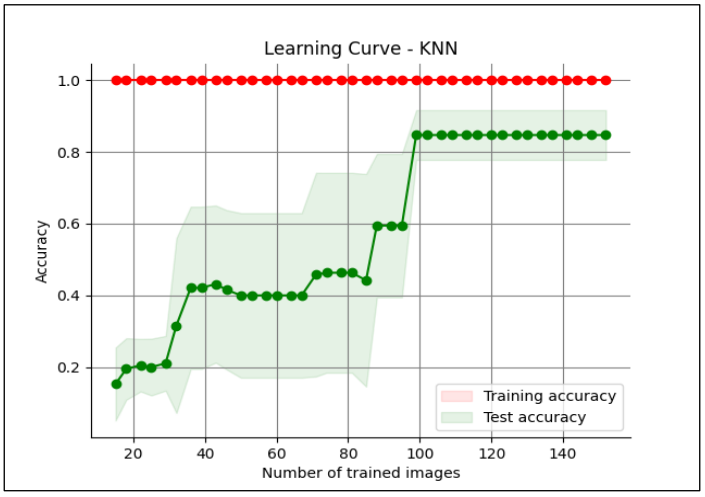


Figure 18: Learning curve for KNN.
Source: Authors, (2025).

Figure 18 shows the accuracy of the learning curve of the model in the second experiment, where the accuracy of the training increases with the number of images used in the algorithm training. The stability of the model is noticeable after 100 images were tested, remaining stable and constant. At the end of the training, the accuracy was 78%.

VI.3 DECISION TREE

The third experiment used the decision tree algorithm to perform failure mode training. The dataset was used in the same quantity and conditions as in the second experiment. The confusion matrix created after the decision tree algorithm training was completed is shown in Figure 19.

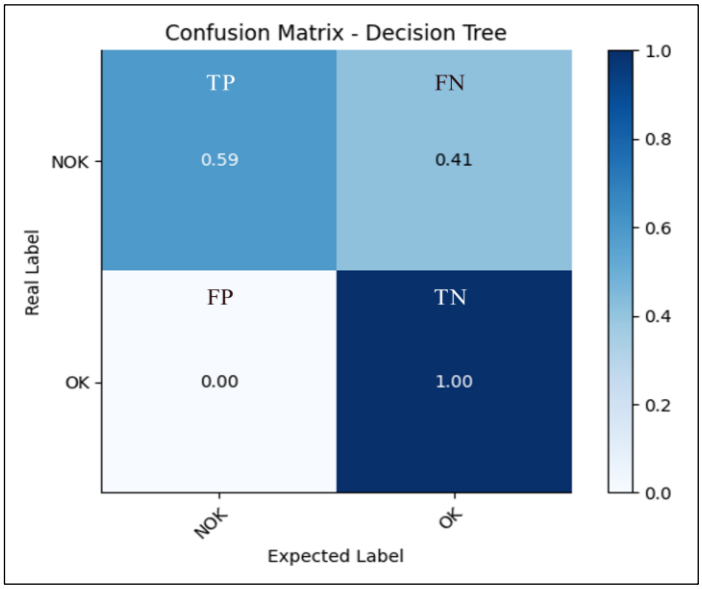


Figure 19: Definition of classes for DT.
Source: Authors, (2025).

The variable (TP) represents the number of PCBs classified as NOK with an accuracy rate of 0.59. The variable (TN) represents the PCBs approved OK, with an accuracy of 1.00. The variable (FP) represents the total number of PCBs OK and classified as NOK, with an accuracy of 0.00. And the variable (FN) represents the number of PCBs classified NOK and classified as OK, with an accuracy rate of 0.41. The results of the metrics are illustrated in Figure 20.

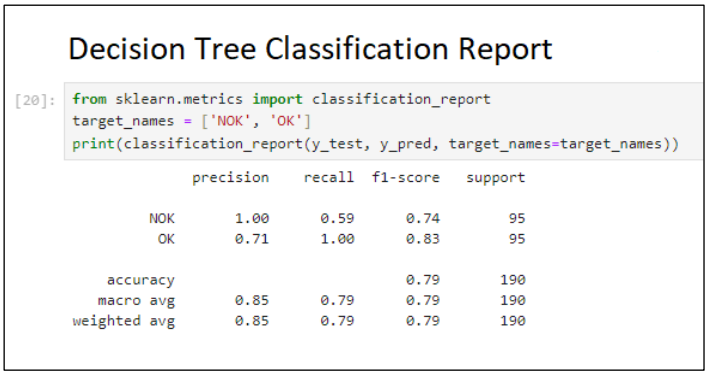


Figure 20: Decision tree model evaluation metrics.
Source: Authors, (2025).

In the model, the accuracy of the DT was 79%, the precision of values for NOK failed PCBs was 1.00, and for OK PCBs, it was 0.71; only the true positive values were used. In the recall, NOK PCBs had 0.59, while OK PCBs had 1.00. This demonstrated the frequency of an image in a specific class. The final score of the model training can be seen in the f1-score metric, where NOK PCBs were 0.74 and OK PCBs were 0.83 on the final classification report.

Figure 21 shows the accuracy of the training and testing learning curve of images classified by DT. The training accuracy varies throughout the training process as the number of images the algorithm processes increases. The model demonstrates instability, reaching a final accuracy of 79%.

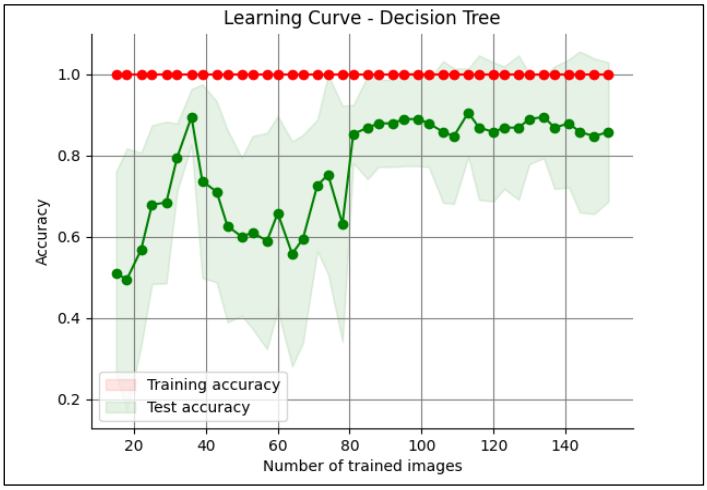


Figure 21: Learning curve for DT.
Source: Authors, (2025).

Table 4 presents the results of the classifier metrics. The accuracy of the classification of failure modes by the SVM algorithm was the best. However, the classification performed with the KNN and DT algorithms did not accurately identify the failure modes.

Table 4: Summary of model classification metrics.

Algorithm	Class	Precision	Recall	f1-score
SVM	NOK	0.98	1.00	0.99
	OK	1.00	0.98	0.99
KNN	NOK	0.69	1.00	0.82
	Ok	1.00	0.56	0.72
DT	NOK	1.00	0.59	0.74
	OK	0.71	1.00	0.83

Source: Authors, (2025).

The performance of the classification models created in this study was evaluated using the ROC curve. Figure 22 shows the relationship between true and false positive rates at various decision thresholds. This allows us to determine the best-performing area under the curve (AUC) in classifying failure modes. The SVM showed the best performance, with an AUC of 1.0, indicating that the model has excellent accuracy. On the other hand, the KNN and DT algorithms had an average AUC of just over 0.5, indicating a tendency towards misclassification and unsatisfactory performance.

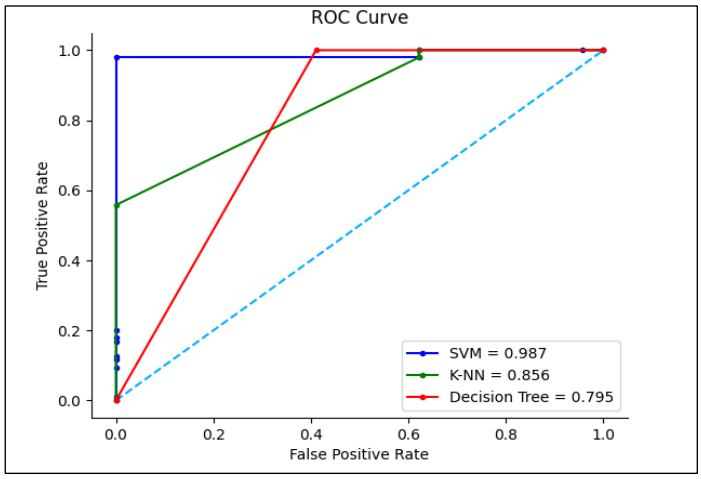


Figure 22: ROC curve of classification models.
Source: Authors, (2025).

VII. CONCLUSIONS

The industrial process depends on detecting failure modes in the production of electronic equipment, especially in visual inspection, which is still performed manually by human operators. It is common for this process to present failures due to factors such as fatigue and emotional problems of the human operator, which can affect the inspection result. The industry has sought to incorporate automatic visual inspection systems into its processes to solve these problems.

The experiment carried out with the failure mode classifier, trained using the decision tree algorithm, aimed to categorize the images from the PCB database into the classes "NOK" (non-conforming) and "OK" (conforming). During the process, the model was evaluated for its ability to distinguish between the classes, but the results were unsatisfactory. The final accuracy obtained was 79% in the images tested, indicating poor performance, with significant errors in classification and prediction. This limitation is evidenced in Figure 20, where the learning curve demonstrated a marked instability throughout the training, suggesting that the model could not adequately generalize the failure patterns, which compromised its effectiveness in classification tasks.

The experiment used a failure mode classifier based on the K-Nearest Neighbors machine learning algorithm. After training, the model presented an accuracy of 78% in the tested images, which evidenced the presence of significant errors in classification and prediction. Figure 17 illustrates the model's performance, demonstrating in the learning curve the instability of accuracy in both the test and training data throughout the classification process. This instability suggests that the KNN model faced difficulties in correctly generalizing the failure patterns, compromising its ability to classify the failure modes accurately and reliably.

In the experiment conducted with the SVM (Support Vector Machine) algorithm for classifying failure modes in images from the PCB database, the objective was to predict the “NOK” and “OK” classes. After training, the model achieved an impressive accuracy of 99% on the tested images, indicating no errors in classification and prediction. Figure 14 corroborates these results, showing that the learning curve remained stable, both in the training and testing data. This stability throughout the classification process confirms the high effectiveness of the SVM, evidencing its robust generalization capacity and accuracy. The high performance of the SVM model suggests that it is highly suitable for implementation in a real production environment, where reliability in fault detection is crucial for the quality of the final product. Furthermore, these results highlight the potential of the SVM as a viable and efficient solution to classification challenges in industrial systems, making it a recommended choice for applications that require accuracy and consistency in visual data analysis.

VIII. AUTHOR’S CONTRIBUTION

Conceptualization: Carlos Americo de Souza Silva and Jorge Eduardo Santos Penedo.
Methodology: Carlos Americo de Souza Silva, Jorge Eduardo Santos Penedo, Edson Pacheco Paladini and Waldir Sabino da Silva Junior.
Investigation: Carlos Americo de Souza Silva and Jorge Eduardo Santos Penedo.
Discussion of results: Carlos Americo de Souza Silva, Jorge Eduardo Santos Penedo, Edson Pacheco Paladini and Waldir Sabino da Silva Junior.
Writing – Original Draft: Carlos Americo de Souza Silva and Jorge Eduardo Santos Penedo.
Writing – Review and Editing: Carlos Americo de Souza Silva and Jorge Eduardo Santos Penedo.
Resources: Carlos Americo de Souza Silva and Jorge Eduardo Santos Penedo.
Supervision: Edson Pacheco Paladini and Waldir Sabino da Silva Junior.
Approval of the final text: Carlos Americo de Souza Silva, Jorge Eduardo Santos Penedo, Edson Pacheco Paladini and Waldir Sabino da Silva Junior.

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