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# Optimized Offloading in Vehicular Edge Computing: A Game Theoretic Analysis

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## ABSTRACT

This paper introduces a novel approach to Vehicle Edge Computing (VEC), addressing the need for low-latency, high-reliability applications in vehicle networks. By leveraging nearby Multi-access Edge Computing (MEC) resources, VEC enhances data processing speed and reliability for applications like autonomous driving, real-time traffic management, and infotainment systems. The proposed solution models a multi-user non-cooperative computation offloading game in vehicular MEC networks, where each vehicle adjusts its offloading probability based on factors like distance to the MEC access point, communication model, and competition for resources. Additionally, a best response-learning algorithm is designed based on the computation offloading game model. The approach focuses on maximizing each vehicle's utility while ensuring convergence to a single, stable equilibrium under defined conditions. To demonstrate the effectiveness and performance of the proposed algorithms, comprehensive experiments were performed. Numerical results demonstrate the fast convergence and improved performance achieved.

**Keywords:** Game theory, Non-cooperative game, Vehicle Edge Computing, Computation offloading

## 1. Introduction

The rapid progress in Intelligent Transportation Systems (ITS) and automated driving technology has led to the development of numerous promising applications, including driving safety, traffic optimization, and in-vehicle entertainment [1], [2]. The demand for enhanced in-vehicle computing and storage capabilities has increased due to the proliferation of computationally intensive and time-critical applications [3], [4]. However, it is challenging for individual vehicles to fully satisfy the requirements of these applications using their own local resources due to constraints such as physical space limitations and economic costs. The emergence of 5G networks has stimulated the development of MEC as a solution to reduce end-to-end transmission delays and alleviate compute and storage constraints [5], [6], [7]. However, MEC (Mobile Edge Computing) servers are constrained by limited computing and storage resources [8], [9], which can pose significant challenges when faced with the increasing computational demands from vehicles. This resource limitation may result in degraded Quality of Service (QoS) for vehicle applications, diminishing the benefits of offloading tasks. Thus, efficient task offloading decisions become essential [10]. Vehicles must carefully manage the trade-off between application execution time and the availability of MEC resources. This balance is critical to avoid resource exhaustion, maintain optimal workload distribution, and ensure seamless application performance in ITS.

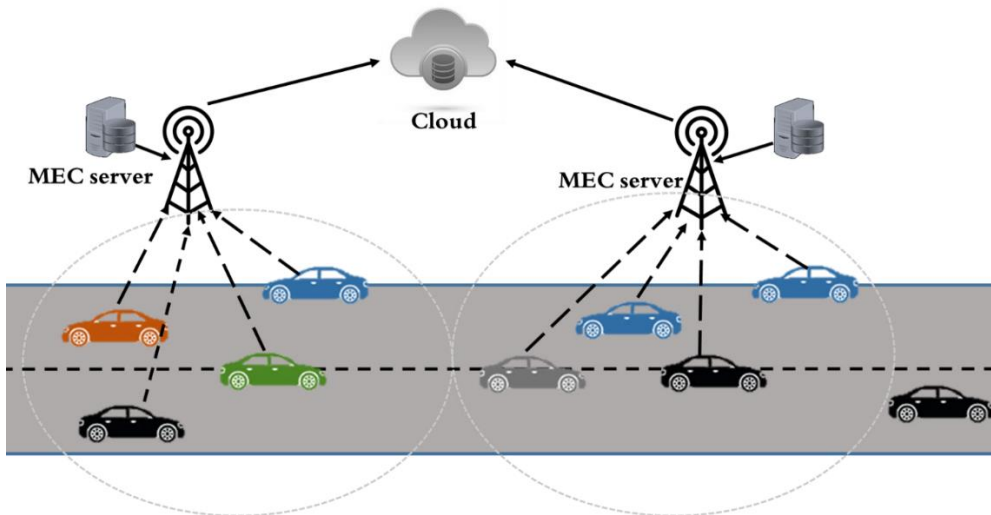


Figure 1. Competition-Based Offloading in Vehicular MEC Networks

In multi-vehicle computation offloading scenarios, as illustrated in Figure 1, both centralized and distributed approaches are employed to manage offloading strategies. Centralized methods focus on optimizing resource allocation for all vehicles through server-side planning, whereas distributed methods depend on interactions among vehicles to evaluate resource availability and maximize individual utility before offloading tasks to MEC servers [11], [12]. This paper focuses on distributed computation offloading, where each vehicle competes for MEC server resources. Vehicles independently determine their offloading strategies based on the current availability of MEC resources. The interaction among vehicles is modeled using a game-theoretic framework, which analyzes offloading strategies by assuming rational decision-making behavior. This paper's main contributions include:

- 1) Proposing a multi-user non-cooperative computation offloading game for MEC scenarios.
- 2) Designing a participant's payoff function considering factors like distance to MEC access points and competition for resources.
- 3) Developing a distributed algorithm ensuring convergence to a stable equilibrium.
- 4) Conducting experiments to analyze the proposed algorithms' effectiveness and performance.

The rest of this paper is structured as follows: Section II presents a review of related work. Section III introduces the computation offloading game model, including detailed discussions of the utility and price functions within the payoff structure. Section IV describes a distributed algorithm for solving the game. In Section V, we discuss the results, focusing on the convergence and uniqueness of the Nash equilibrium. Lastly, Section VI concludes the paper and suggests directions for future research.

## 2. Related Works

The challenge of computation offloading for mobile devices within MEC (Mobile Edge Computing) or MCC (Mobile Cloud Computing) architectures has been widely researched. Muoz et al. in [13] presented a framework for jointly optimizing the use of radio and computing resources using the trade-off between energy consumption and latency. In their approach, the authors focus on balancing energy consumption and latency by jointly optimizing the use of radio and computing resources. To minimize both the execution latency of all tasks and the energy consumption of the mobile device. Dinh et al. [14] proposed an optimization framework of offloading from a single mobile device to multiple edge devices. Zhang Jianchao studied multi-user computation offloading in dynamic mobile cloud computing environments [15]. Their research used a stochastic game approach to show that dynamic offloading decisions can achieve a pure-strategy Nash Equilibrium (NE). To ensure convergence to this NE, they developed the MASL algorithm, which provides a guaranteed convergence rate. The author of [16] formulates a bi-level optimization framework for efficient computation offloading in MEC systems, using game theory to achieve Nash equilibrium and optimize

resource pricing and allocation. his algorithm reduces system costs and maximizes profits for both ESP and DMs. Chen introduced a game-theoretic framework for efficient computation offloading in mobile cloud computing environments [17]. The study modeled the decision-making process for decentralized offloading among mobile users as a decentralized computation offloading game. To enhance system utility, Lyu et al. proposed a semi-distributed heuristic offloading decision algorithm (HODA) that optimizes both offloading decisions and the allocation of communication and computation resources [18]. In a different approach, Bi et al. developed an offloading strategy aimed at maximizing computation rates within a multi-user MEC network powered by wireless power transfer (WPT) [19]. Their scheme uses a binary computation offloading policy, where each energy-harvesting device chooses between processing tasks locally or offloading them to an MEC server. An adaptive task offloading and resource allocation algorithm using deep reinforcement learning in mobile edge computing is proposed in [20] to optimize response time, energy consumption and system utility, taking user mobility into account. In [21], the authors introduce a Stackelberg game to optimize task offloading and pricing in mobile edge computing, proposing a differentiated pricing strategy to enhance server profit and reduce user latency. Cardellini et al. explored a three-tier architecture for mobile computing by proposing a model to assess how computation offloading impacts user-perceived performance [22]. They framed the problem as a generalized Nash equilibrium and developed a distributed algorithm to compute this equilibrium. Liu et al. tackled the task offloading challenge using a matching theory approach, introducing pricing-based matching algorithms aimed at minimizing overall network delay [23]. The authors in [24] developed the ECORA strategy to enhance resource allocation in vehicular networks, focusing on collaborative computation and storage, as well as adaptive task offloading, which significantly reduced task processing delays and improved network load balancing. The authors [25] explore online task offloading in mobile edge computing networks, focusing on time-variant task arrivals and diverse user requirements. They introduce a collaboration architecture that divides edge nodes into public and private ones, developing a system model for task latency analysis. A deep reinforcement learning-based online task scheduling algorithm is proposed, demonstrating significant latency reductions of 1.09%, 2.65%, and 4.34% compared to offline methods for varying correlation coefficients. The authors in [26] introduce a method that deploys passive RIS in a cell free network to enhance wireless capacity. Using deep reinforcement learning (DRL), the authors formulate a joint beamforming optimization problem to address complexity, achieve better latency and energy efficiency in mobile edge computing (MEC) environments. The work presented in [7] explores task scheduling strategies for MEC servers located on Roadside Units (RSUs). The primary aim is to minimize the total completion time for various applications. The authors introduce an optimized algorithm that prioritizes tasks and applications, meeting specific time constraints for task completion. Dai introduced a new offloading scheme for Vehicular Edge Computing (VEC) in [27], leveraging deep reinforcement learning to minimize processing latency. This scheme effectively reduces latency by dynamically optimizing offloading decisions between vehicles, edge servers, and the cloud, adapting to the changing conditions of the computing environment. In this paper, we emphasize the importance of incorporating vehicle locations and task deadline constraints into the MEC offloading process. Based on these factors, a best-response algorithm is utilized to guarantee that the strategy chosen by each vehicle leads to a unique Nash equilibrium.

### 3. Computation Offloading Model

For Vehicular Edge Computing, the development of an efficient compute offloading model is crucial for optimizing resource allocation and improving system performance. In this section, a description of the main elements and parameters of the offloading model is given, with a detailed perspective on the decision-making framework and the criteria used to evaluate system performance.

#### 3.1. Parameters Abstraction

The application in each vehicle is abstracted using three essential parameters: input data size ( $L_i$ ), computational complexity ( $\alpha_i$ ), and completion deadline ( $t_{i,max}$ ). These parameters encapsulate the fundamental characteristics of the application, influencing its execution time and resource requirements.

#### 3.2. Local Execution Time

The time taken for vehicle  $i$  to execute a task locally depends on the computational power of its onboard CPU ( $f_{i,l}$ ) and the complexity of the application ( $\alpha_i$ ). This can be mathematically represented as:

$$t_{i,l} = \frac{\alpha_i L_i}{f_{i,l}} \quad (1)$$

### 3.3. Communication Model

The communication link between each vehicle and the MEC access point is represented by a frequency-flat block-fading Rayleigh channel. The path loss ( $\theta_i$ ) is influenced by the distance ( $d_i$ ) between the vehicle and the access point. Additionally, the model incorporates the channel-fading coefficient ( $h_i$ ) and the noise power ( $N_0$ ) from white Gaussian noise. The data transmission rate ( $R_i$ ) for vehicle  $i$  is then calculated based on the available channel bandwidth ( $W_i$ ) and the transmission power ( $P_i$ ) as follows:

$$R_i = W_i \log_2 \left( 1 + \frac{P_i d_i^{-\theta_i}}{N_0} h_i^2 \right) \quad (2)$$

### 3.4. Transmission Delays

The transmission delays for vehicle  $i$  during computation offloading include uplink ( $t_{i,U}$ ) and downlink ( $t_{i,D}$ ) components. These delays are determined by the uplink and downlink transmission overheads ( $\beta_{i,U}$  and  $\beta_{i,D}$ ), as well as the data transmission rate ( $R_i$ ). Mathematically, they are given by:

$$t_{i,U} = \frac{\beta_{i,U} L_i}{R_i} \quad (3)$$

$$t_{i,D} = \frac{\beta_{i,D} L_i}{R_i} \quad (4)$$

### 3.5. MEC Execution Time

The execution time ( $\tau_{i,e}$ ) for vehicle  $i$ 's application in the MEC is dependent on the size of the input data ( $L_i$ ) and the processing capability of the MEC server ( $f_e$ ). This can be represented as:

$$\tau_{i,e} = \frac{\alpha_i L_i}{f_e} \quad (5)$$

### 3.6. Total Execution Time

The total computation offloading time ( $t_{i,e}$ ) for vehicle  $i$  is the combination of three factors: uplink transmission delay, processing time at the MEC server, and downlink transmission delay.

$$t_{i,e} = t_{i,U} + \tau_{i,e} + t_{i,D} \quad (6)$$

A clear understanding of these components is fundamental for designing efficient utility and pricing models in the offloading game, allowing for optimized decision-making and resource allocation.

## 4. System Model

In this section, we begin by presenting the fundamental model of the computation offloading game, delineating the specific utility and price functions within the payoff framework based on parameters given in table 1. Next, we model the computation offloading as a non-cooperative game, applying the concept of Nash equilibrium. We also present proofs to demonstrate the existence and uniqueness of the equilibrium.

| Parameter         | Meaning                    |
|-------------------|----------------------------|
| $n = 7$           | Number of vehicles         |
| $\sigma_i = 0.7$  | MEC pricing factor         |
| $\lambda_i = 0.7$ | Task arrival rate          |
| $t_{i,\max}$      | The maximum execution time |

|                |                                                        |
|----------------|--------------------------------------------------------|
| $\alpha_i$     | Task computational complexity                          |
| $\beta_{i,U}$  | Overhead of uplink transmission                        |
| $\beta_{i,D}$  | Downlink transmission overhead and the ratio of output |
| $L_i = 1Mbits$ | The input data size                                    |
| $f_{il}$       | Local computation capability                           |
| $f_e$          | MEC computation capability                             |
| $\theta_i$     | Path loss exponent                                     |
| $h_{ij}$       | The channel fading coefficient                         |
| $d_i$          | Distance to RSU                                        |
| $W_i$          | Channel bandwidth                                      |
| $N_0 = 0.01$   | The white Gaussian noise power                         |
| $P_i = 0.2$    | Transmit power                                         |

Table 1. Parameters Table

#### 4.1. Utility of Non-cooperative of the Computation Offloading

Task execution time plays a crucial role in determining the vehicle's utility, considering the variables  $t_{i,l}$ ,  $t_{i,e}$ , and  $t_{i,max}$  discussed in the previous section. Shorter execution times, whether the task is processed locally or offloaded to the MEC server, lead to higher utility. However, if the execution time exceeds  $t_{i,max}$ , the vehicle gains no benefit and may incur penalties. As a result, the utility function for vehicle  $i$  in a game with computation offloading can be derived as follows:

$$U_i(\rho) = \frac{t_{i,max}-t_{i,l}}{t_{i,max}}(1 - \rho_i) + \frac{t_{i,max}-t_{i,e}}{t_{i,max}}\rho_i \quad (7)$$

MEC environments can benefit from implementing a dynamic pricing mechanism to manage the offloading of vehicles due to limited computing and storage resources [28], [29]. By adjusting the pricing factor  $\sigma \in [0; 1]$  according to the task arrival rate  $\lambda$ , the platform can ensure a balanced load, preventing both over- or under-utilization of available resources.

$$C_i(\rho) = \rho_i^2 \sigma [1 - \prod_{j \neq i} (1 - \lambda_j \rho_j)] \quad (8)$$

The payoff function for vehicle  $i$  in the computation offloading game can be formulated as follows:

$$\Pi_i(\rho) = \frac{t_{i,max}-t_{i,l}}{t_{i,max}}(1 - \rho_i) + \frac{t_{i,max}-t_{i,e}}{t_{i,max}}\rho_i - \rho_i^2 \sigma [1 - \prod_{j \neq i} (1 - \lambda_j \rho_j)] \quad (9)$$

#### 4.2. Game Formulation

In this paper, the computation offloading game is modeled as  $\Gamma = \{N; (\rho_i)_{i \in N}; (\Pi_i)_{i \in N}\}$ , where  $N = \{1, 2, \dots, n\}$  denotes the set of vehicles within the coverage of a MEC access point.  $\rho_i \in [0, 1]$  represents the probability that vehicle  $i$  chooses to offload its computation, also known as its strategy, and  $\Pi_i$  is the payoff function of vehicle  $i$ . The term  $\rho_{-i} = (\rho_1, \dots, \rho_{i-1}, \rho_{i+1}, \dots, \rho_n)$  refers to the offloading probabilities of all other vehicles in the system except vehicle  $i$ . The Nash equilibrium concept is then applied to characterize the equilibrium of this computation offloading game.

**Definition 1.** A probability vector for computation offloading, represented as  $\rho^*$ , is termed a Nash equilibrium (NE) if no vehicle can improve its payoff by unilaterally changing its strategy from the equilibrium. i.e.:

$$\Pi_i(\rho_i^*; \rho_{-i}^*) \geq \Pi_i(\rho_i; \rho_{-i}^*) ; \forall \rho_i \quad (11)$$

**Theorem 1.** In the game, Nash equilibrium of the computation offloading exists and is unique.

##### Proof

The condition established by Rosen [30], [31] for proving the concavity of the utility function is as follows:

$$\frac{\partial^2 \Pi_i}{\partial \rho_i^2} < 0$$

The first derivative of the function can be defined mathematically with the following equation:

$$\frac{\partial \Pi_i}{\partial \rho_i} = -\frac{t_{i,\max} - t_{i,l}}{t_{i,\max}} + \frac{t_{i,\max} - t_{i,e}}{t_{i,\max}} - 2\rho_i \sigma [1 - \prod_{j \neq i} (1 - \lambda_j \rho_j)] \quad (12)$$

In the same line, the computation offloading of utility function is:

$$\frac{\partial^2 \Pi_i}{\partial \rho_i^2} = -2\sigma [1 - \prod_{j \neq i} (1 - \lambda_j \rho_j)] < 0 \quad (13)$$

Thus, we conclude that a Nash equilibrium exists in the system.

To establish the uniqueness of the Nash equilibrium using the contraction-mapping theorem [32], [33], we demonstrate that the norm of the Jacobian matrix is less than 1, i.e., ( $\|J\| < 1$ ).

$$J_{ij} = \frac{\partial \rho_i}{\partial \rho_j} = \begin{cases} 0, & i = j \\ \frac{-(t_{i,l} - t_{i,e}) \prod_{k \neq i,j} (1 - \lambda_k \rho_k)}{2\sigma t_{i,\max} [1 - \prod_{j \neq i} (1 - \lambda_j \rho_j)]^2}, & i \neq j \end{cases} \quad (14)$$

The maximum value of the off-diagonal elements of  $J_{ij}$  is found by calculating the sum of their absolute values.

$$\|J\|_\infty = \sum_{i \in \{1 \dots N\}} \frac{|t_{i,l} - t_{i,e}| \prod_{k \neq i,j} (1 - \lambda_k \rho_k)}{2\sigma t_{i,\max} [1 - \prod_{j \neq i} (1 - \lambda_j \rho_j)]^2} < 1 \quad (15)$$

While  $\|J\|_\infty < 1$ , then equation (9) is a contraction mapping. Finally, the uniqueness of the Nash equilibrium is established.

### 4.3. Distributed Best-Response Algorithm for Computation Offloading Game

The Distributed Best Response algorithm 1 permits vehicles in a multi-access edge computing (MEC) environment to make decentralized offloading decisions through a trade-off between local computation and offloading to the edge server. This algorithm works iteratively, so that each vehicle can update its offload strategy according to local execution time, transmission conditions and the strategies of other vehicles.

---

#### Algorithm 1 Distributed Best-Response Algorithm for Computation Offloading Game

---

1: Initiation:  $s = 0$ , the offloading probability vector  $\rho_s$ , the pricing vector  $\sigma$ , and the task arrival rate vector  $\lambda$ .

2: Locally at each node  $i$ , iterate through  $s$ .

3: Set  $s \leftarrow s + 1$ .

4: **for**  $i \in \{1, \dots, n\}$  **do**

5: Calculate the local execution time of the task without computation offloading:

$$\tau_{i,e} = \frac{\alpha_i L_i}{f_e}$$

6: Estimate the data transmission rate based on the distance between vehicle and MEC access point:

$$R_i = W_i \log_2 \left( 1 + \frac{P_i d_i^\alpha h_i^2}{N_0} \right)$$

7: Calculate the total execution time of the task with offloading:

$$t_{i,e} = t_{i,U} + \tau_{i,e} + t_{i,D} = \frac{\beta_{i,U} L_i}{R_i} + \frac{\alpha_i L_i}{f_e} + \frac{\beta_{i,D} L_i}{R_i}$$

8: Update the best-response strategy according to offloading probabilities of other vehicles in the previous stage:

$$\rho_i^s = \left[ \frac{-(t_{i,l} - t_{i,e}) \prod_{k \neq i,j} (1 - \lambda_k \rho_k)}{2\sigma t_{i,\max} [1 - \prod_{j \neq i} (1 - \lambda_j \rho_j)]^2} \right]_0^1$$

9: **if**  $\rho_i^s$   $i$  has converged **then**

10: Vehicle  $i$  decides whether to offload its task with a probability  $\rho_i^s$ .

11: **end if**

12: **end for**

13: Go to Step 3.

---

Initially, the algorithm initializes several key variables, in particular the offload probability vector ( $\rho^s$ ), the pricing vector ( $\sigma$ ) and the job arrival rate vector ( $\lambda$ ). Each vehicle calculates the time required to process a task locally, based on the task size ( $L_i$ ), the workload coefficient ( $\alpha_i$ ) and the vehicle CPU frequency ( $f_{i,l}$ ). Then, this local execution time is compared with the time required to download the calculation to the MEC server. After calculating the local and offloading execution times, the vehicle updates its offloading probability based on the difference between the two times and the offloading strategies of other vehicles in the network. The updated offloading probability ( $\rho_i^s$ ) considers the impact of other vehicles' decisions by incorporating a probability function that reflects the task arrival rates and offloading probabilities from the previous iteration.

The algorithm repeats this process, iteratively refining each vehicle's offloading probability until convergence is achieved. Convergence occurs when the offloading probability stabilizes, meaning no further significant updates are needed. At this point, each vehicle has decided whether to offload its computation to the MEC server with an optimal probability, resulting in efficient resource utilization and balanced task execution across the network.

The algorithm's structure is formally outlined below, illustrating how each vehicle independently adjusts its offloading strategy in response to network conditions and other vehicles' decisions. This distributed and iterative process ensures that the system reaches a Nash equilibrium, optimizing computation offloading across all vehicles. The algorithm 1 efficiently optimizes the computation offloading decisions, ensuring that vehicles achieve a balance between local processing and offloading, thereby enhancing system-wide performance in the MEC environment.

## 5. Numerical Results

### 5.1. Tuning Parameters

The following section aims at providing a test case demonstrating the ability of the proposed game-theoretical model to enhance resource allocation of each vehicle. In particular, it is worth noting that our analysis is confined to the computation offloading game within a single MEC platform and does not account for inter-MEC handover concerns. Additionally, we assume that each vehicle has knowledge of the offloading probabilities of other vehicles from the previous MEC stage. Based on the parameters and variables described in table 2, we have designed the algorithm 1. This algorithm is developed to obtain the results discussed in the following subsection.

| Parameter     | Veh-1 | Veh-2 | Veh-3 | Veh-4 | Veh-5 | Veh-6 | Veh-7 |
|---------------|-------|-------|-------|-------|-------|-------|-------|
| $\alpha_i$    | 1.5   | 2.0   | 1.8   | 1.6   | 1.7   | 1.9   | 2.1   |
| $\beta_{i,U}$ | 0.8   | 1.2   | 1.0   | 0.9   | 1.1   | 1.3   | 1.4   |
| $\beta_{i,D}$ | 0.1   | 0.05  | 0.08  | 0.07  | 0.06  | 0.09  | 0.11  |
| $f_{i,l}$     | 1.0   | 1.2   | 0.9   | 1.1   | 1.3   | 1.0   | 0.8   |
| $f_e$         | 2.5   | 2.0   | 1.5   | 2.2   | 2.1   | 1.8   | 1.9   |
| $\theta_i$    | 1.8   | 2.5   | 2.0   | 2.3   | 2.1   | 1.9   | 2.2   |
| $h_{i,j}$     | 0.6   | 0.7   | 0.8   | 0.75  | 0.65  | 0.7   | 0.8   |
| $d_i$         | 0.15  | 0.18  | 0.2   | 0.17  | 0.16  | 0.19  | 0.21  |
| $W_i$         | 6     | 8     | 7     | 6.5   | 7.5   | 8.0   | 7.0   |

Table 2. Simulation Parameters for Each Vehicle

### 5.2. Convergence of Vehicles' Strategies towards Nash Equilibrium

The convergence of the vehicle competition towards the Nash equilibrium is clearly illustrated in Figure 2 below. Throughout 8 iterations, we observe rapid convergence, showing that the vehicles swiftly adjust their

strategies to reach a stable equilibrium. This rapid convergence highlights the efficiency of the competition dynamics in achieving a balanced result within a brief period.

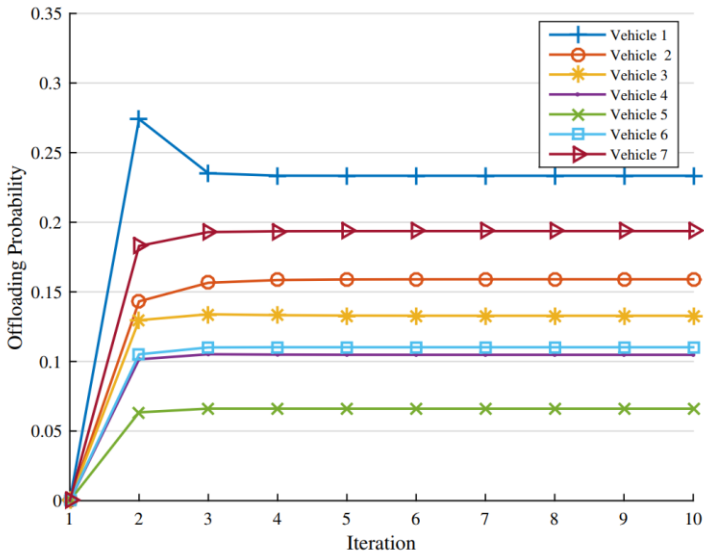


Figure 2. Offloading Probability Convergence for Each Vehicle ( $n = 7$ )

**5.3. Offloading Probability as a Function of Distance: Non-Competitive vs. Competitive Behavior**

As shown in figure 3. In the absence of competition among vehicles for computation offloading, each vehicle offloads to the MEC with a probability of 1 when it is near the MEC. As the vehicle moves away from the MEC, its offloading probability decreases, which is expected in isolation without competition from other vehicles.

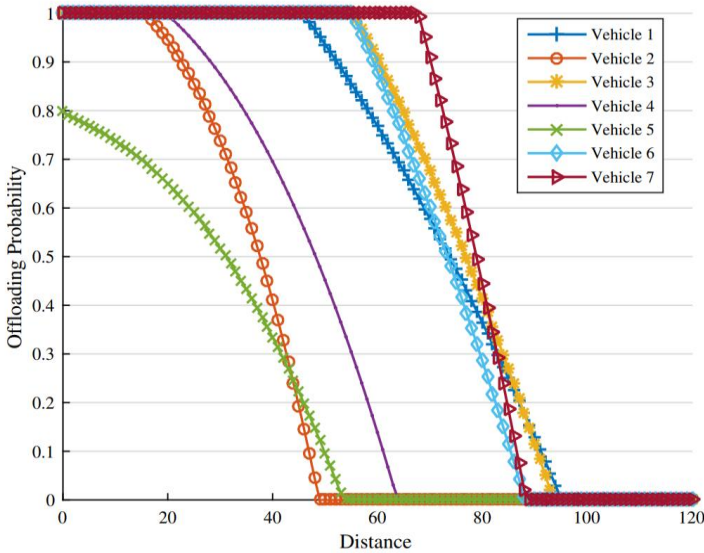


Figure 3. Offloading Probability versus Distance: No Competition

Figure 4 illustrates the competitive offloading behavior of vehicles. When they are close to the MEC, the probability of offloading is approximately the same for all vehicles. Nevertheless, as they move further away, distinct trends can be observed. The probability of offloading increases for vehicles 1, 3 and 7, while it decreases for vehicles 2, 4, 5 and 6, until it reaches zero before 75 meters. In particular, vehicle 1's offloading probability decreases to zero at 90 meters, followed by vehicle 3 at 105 meters, and finally, vehicle 7 at 120 meters. This behavioral variation underlines the strategic adjustments that each vehicle makes in response to the actions of others and their distance from the MEC.

In this way, the observed dynamics demonstrate the impact of competition on offloading strategies, with vehicles continually adapting their probabilities in order to optimize their performance within the MEC. The result confirms the idea that competitive interactions significantly influence offloading decisions, regardless of distance from the MEC.

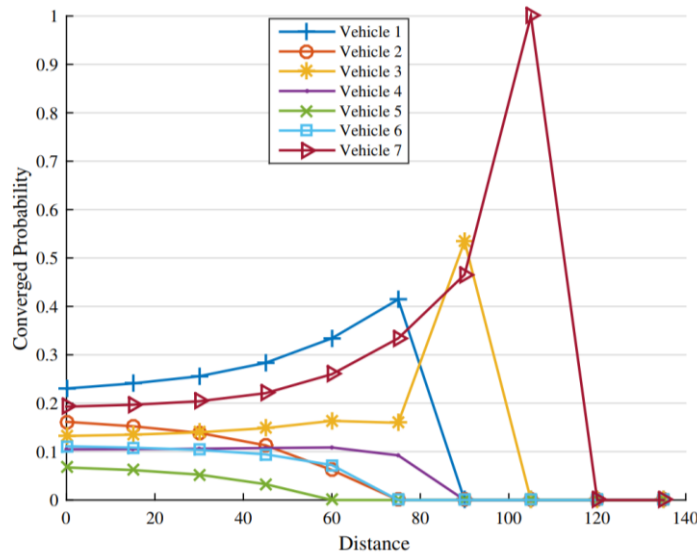


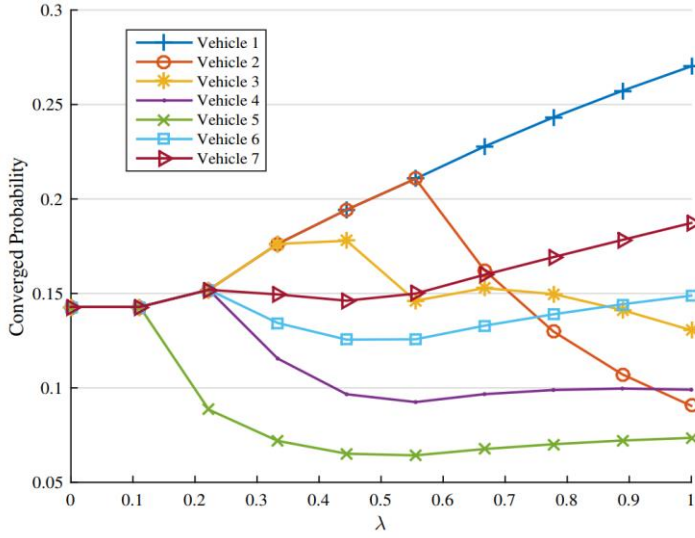
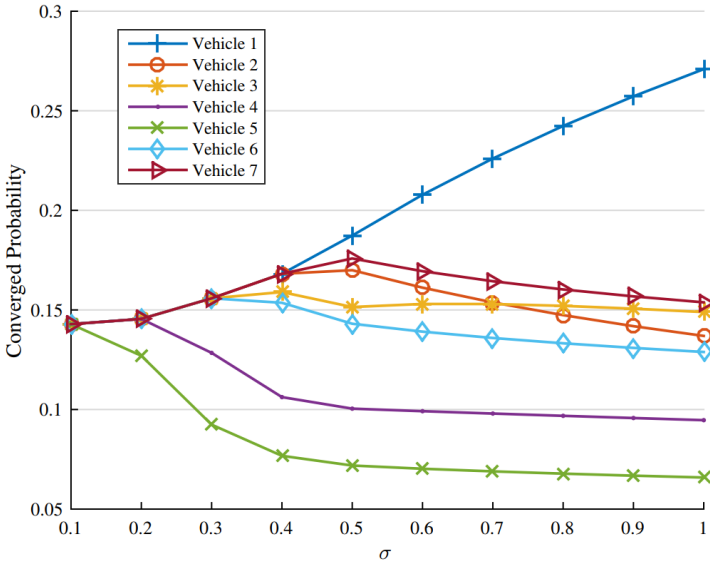
Figure 4. Offloading Probability versus Distance: With Competition

#### 5.4. Impact of Resource Competition and Pricing on Offloading Strategies

From the results of figures 5 the observed phenomenon can be explained through resource competition dynamics in MEC networks. Initially, vehicles exhibit similar offloading probabilities, driven by utility maximization principles. As task arrival rates and pricing factor increase beyond 0.5, indicating ample resources in the MEC server, vehicles adapt their offloading strategies based on the probabilities of others. This strategic response reflects the dynamic nature of resource allocation and allows vehicles to optimize utility given changing network conditions. MEC server operators can further influence competition intensity by deploying varying server resources.

Both figures 5 and 6 highlight significant changes in the offloading probabilities when the task arrival rate and the pricing factor exceed 0.3, indicating a critical threshold. In particular, vehicles 1 and 7 increase their offloading probabilities, while the others simultaneously reduce their probabilities. The above behavior reflects the impact of competitive interactions and resource availability on strategic adjustments.

This dynamic response of vehicles to these parameters underlines the important role of strategic adaptation in optimizing performance in MEC networks. MEC server operators can influence competition by varying server resources, thus shaping vehicle strategies. Sensitivity to task arrival rate and pricing factor reinforces the need for dynamic resource management in MEC environments.

Figure 5. Offloading probability versus task arrival rate  $\lambda_i$ Figure 6. Offloading probability versus MEC pricing factor  $\sigma_i$ 

### 5.5. Utility Analysis Across Different Offloading Probability Scenarios

In this section, we examine the implications of our results and compares the utilities obtained under different Offloading Probability scenarios. In addition, the comparison of total utilities for different numbers of vehicles is illustrated in table 3 and figure 7.

- **Utility Zero\_Prob:** In the case of no offloading, most vehicles have low or negative utilities. For example, vehicle 3 has a utility of -0.1111 and vehicle 6 has a utility of -0.0555. This scenario, with a total utility of 0.0811, demonstrates the inefficiency of not using offloading.

- **Utility One\_Prob:** It entirely based on offloading without any local treatment also results in poor performance, since several vehicles have negative utilities. As two examples, vehicle 2 has a utility of -0.0375 and vehicle 6 has a utility of -0.1190. Its total utility of -0.2729 is the lowest of all scenarios, and indicates that this approach is not suitable for maximizing system performance.
- **Utility Equi\_Prob:** The equi-probability scenario, based on a uniform distribution of offloading among vehicles. The utility of most vehicles is positive. The total utility of 2.3044 shows that this balanced approach is more efficient than no offloading or full offloading.
- **Utility Final\_Prob:** Our proposed game-theoretic approach, which iteratively optimizes offloading probabilities, achieves the highest utilities for all vehicles. This is because each vehicle has a positive utility. This brings the total utility to 2.4984, which is the highest of all the scenarios. Clearly, this proves the effectiveness of our optimization process in achieving optimal vehicle performance.

| Vehicle      | Utility_Zero_Prob | Utility_One_Prob | Utility_Equi_Prob | Utility_Final_Prob |
|--------------|-------------------|------------------|-------------------|--------------------|
| 1            | 0.166667          | 0.139088         | 0.493416          | 0.532627           |
| 2            | 0.074074          | -0.037587        | 0.362242          | 0.359877           |
| 3            | -0.111111         | -0.097960        | 0.207411          | 0.196504           |
| 4            | 0.191919          | 0.019016         | 0.481546          | 0.499078           |
| 5            | 0.273504          | -0.077733        | 0.515114          | 0.507702           |
| 6            | -0.055556         | -0.119056        | 0.259340          | 0.292444           |
| 7            | -0.458333         | -0.098674        | -0.014628         | 0.110261           |
| All-vehicles | 0,081164          | -0,272907        | 2,304442          | 2,498495           |

Table 3. Utility comparison for different offloading probabilities

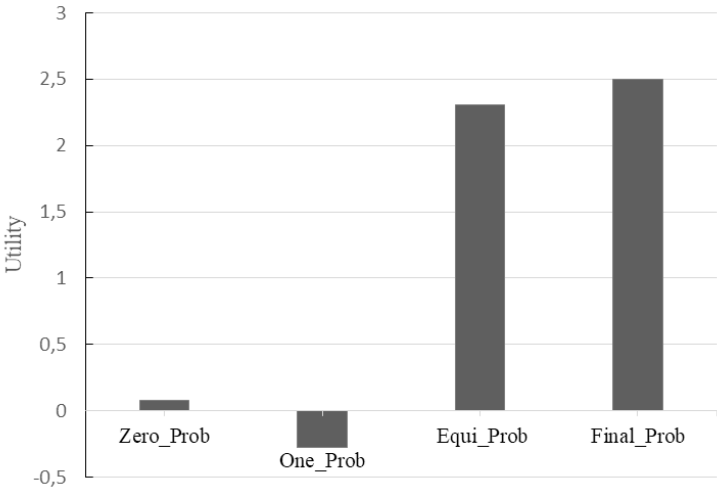


Figure 7. The total utility for different offloading probabilities  $p_i$

The comparative analysis of different offloading probability scenarios underscores the importance of strategic offloading in mobile edge computing environments. The results clearly indicate that neither extreme (zero or full offloading) is optimal. Instead, a balanced and optimized approach, as achieved through our game-theoretic method, ensures the best overall performance.

The superiority of our approach is evident from the consistently higher utilities achieved across all vehicles. This highlights the role of iterative optimization in dynamically adjusting offloading probabilities to match the varying computational demands and resource availability of each vehicle. By doing so, our method not only enhances individual vehicle performance but also maximizes the collective utility of the system.

## 6. Conclusions

This paper proposes an innovative approach to optimize computation offloading in vehicular MEC networks. The system adapts the offloading probability based on factors such as the proximity to MEC access points and resource competition. A distributed best-response algorithm is utilized to guarantee convergence to a stable equilibrium, improving system efficiency. Experimental results demonstrate the approach's ability to achieve fast convergence and enhanced performance. Our study demonstrates that an optimized, game-theoretic approach to computation offloading is critical for maximizing utility in mobile edge computing. Furthermore, our method significantly outperforms existing dynamic offloading strategies, providing optimal utility for all participating vehicles. This underscores the potential of game theory and iterative optimization in improving the efficiency and performance of MEC systems. Future work could explore the application of this approach in more complex and heterogeneous edge computing environments to further assess its robustness and scalability.

## Declarations

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**Conflict of interest:** The authors have no competing interests to declare that are relevant to the content of this article.

**Data availability:** Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

**Ethics approval and consent to participate:** This article does not contain any studies with human participants or animals performed by any of the authors.

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**Author contribution:** All authors wrote the main manuscript text and reviewed and approved the manuscript.

## References

- [1] S. Zhou, B. Yuan, K. Xu, M. Zhang, and W. Zheng, "THE IMPACT OF PRICING SCHEMES ON CLOUD COMPUTING AND DISTRIBUTED SYSTEMS," *J. Knowl. Learn. Sci. Technol.*, vol. 3, no. 3, pp. 193–205, Sep. 2024, doi: 10.60087/jklst.v3.n3.p206-224.
- [2] X. Deng *et al.*, "A review of 6G autonomous intelligent transportation systems: Mechanisms, applications and challenges," *Journal of Systems Architecture*, vol. 142, p. 102929, Sep. 2023, doi: 10.1016/j.sysarc.2023.102929.
- [3] L. Liu, C. Chen, Q. Pei, S. Maharjan, and Y. Zhang, "Vehicular Edge Computing and Networking: A Survey," Jul. 25, 2019.
- [4] A. Biswas and H.-C. Wang, "Autonomous Vehicles Enabled by the Integration of IoT, Edge Intelligence, 5G, and Blockchain," *Sensors*, vol. 23, no. 4, p. 1963, Feb. 2023, doi: 10.3390/s23041963.
- [5] M. Díaz, C. Martín, and B. Rubio, "State-of-the-art, challenges, and open issues in the integration of Internet of things and cloud computing," *Journal of Network and Computer Applications*, vol. 67, pp. 99–117, May 2016, doi: 10.1016/j.jnca.2016.01.010.
- [6] A. Ait Temghart, M. Marwan, and M. Baslam, "Optimization of computational offloading in the mobile edge: a game theoretic approach," *Cluster Comput.*, vol. 28, no. 3, p. 203, Jun. 2025, doi: 10.1007/s10586-024-04886-6.
- [7] Y. Liu *et al.*, "Dependency-Aware Task Scheduling in Vehicular Edge Computing," *IEEE Internet of Things Journal*, vol. 7, no. 6, pp. 4961–4971, Jun. 2020, doi: 10.1109/JIOT.2020.2972041.

- [8] M. Marwan, A. A. Temghart, F. Sifou, and F. AlShahwan, "A Decentralized Blockchain-based Architecture for a Secure Cloud-Enabled IoT," *JMM*, Nov. 2020, doi: 10.13052/jmm1550-4646.1636.
- [9] A. A. Temghart, D. A. Omar, M. Baslam, and M. Marwan, "Game theoretical approach for a fair and effective pricing strategy in cloud computing," *International Journal of High Performance Systems Architecture*, vol. 10, no. 1, p. 43, 2021, doi: 10.1504/IJHPSA.2021.115512.
- [10] M. Marwan, A. Ait Temghart, S. Ouhmi, and M. Lazaar, "Security, QoS and energy aware optimization of cloud-edge data centers using game theory and homomorphic encryption: Modeling and formal verification," *Results in Engineering*, vol. 24, p. 102902, Dec. 2024, doi: 10.1016/j.rineng.2024.102902.
- [11] A. Ait Temghart, M. Marwan, and M. Baslam, "Stackelberg Security Game for Optimizing Cybersecurity Decisions in Cloud Computing," *Security and Communication Networks*, vol. 2023, pp. 1–13, Dec. 2023, doi: 10.1155/2023/2811038.
- [12] M. Marwan, F. AlShahwan, Y. Afoudi, A. A. Temghart, and M. Lazaar, "Leveraging artificial intelligence and mutual authentication to optimize content caching in edge data centers," *Journal of King Saud University-Computer and Information Sciences*, vol. 35, no. 9, p. 101742, 2023.
- [13] O. Muñoz, A. Pascual-Iserte, and J. Vidal, "Optimization of Radio and Computational Resources for Energy Efficiency in Latency-Constrained Application Offloading," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 10, pp. 4738–4755, Oct. 2015, doi: 10.1109/TVT.2014.2372852.
- [14] T. Q. Dinh, J. Tang, Q. D. La, and T. Q. S. Quek, "Offloading in Mobile Edge Computing: Task Allocation and Computational Frequency Scaling," *IEEE Transactions on Communications*, vol. 65, no. 8, pp. 3571–3584, Aug. 2017, doi: 10.1109/TCOMM.2017.2699660.
- [15] J. Zheng, Y. Cai, and Y. Wu, "Dynamic Computation Offloading for Mobile Cloud Computing: A Stochastic Game-Theoretic Approach".
- [16] F. Li, E. Ge, W. Hu, and R. Xia, "A two-level game theoretic approach for task offloading in mobile edge computing," *Engineering Applications of Artificial Intelligence*, vol. 136, p. 108819, Oct. 2024, doi: 10.1016/j.engappai.2024.108819.
- [17] X. Chen, "Decentralized Computation Offloading Game for Mobile Cloud Computing," *IEEE Transactions on Parallel and Distributed Systems*, vol. 26, no. 4, pp. 974–983, Apr. 2015, doi: 10.1109/TPDS.2014.2316834.
- [18] X. Lyu, H. Tian, C. Sengul, and P. Zhang, "Multiuser Joint Task Offloading and Resource Optimization in Proximate Clouds," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 4, pp. 3435–3447, Apr. 2017, doi: 10.1109/TVT.2016.2593486.
- [19] S. Bi and Y.-J. A. Zhang, "Computation Rate Maximization for Wireless Powered Mobile-Edge Computing with Binary Computation Offloading," Mar. 22, 2018, *arXiv*: arXiv:1708.08810. Accessed: Feb. 17, 2024. [Online]. Available: <http://arxiv.org/abs/1708.08810>
- [20] Z. Tong, X. Deng, F. Ye, S. Basodi, X. Xiao, and Y. Pan, "Adaptive computation offloading and resource allocation strategy in a mobile edge computing environment," *Information Sciences*, vol. 537, pp. 116–131, Oct. 2020, doi: 10.1016/j.ins.2020.05.057.
- [21] Z. Tong, X. Deng, J. Mei, L. Dai, K. Li, and K. Li, "Stackelberg game-based task offloading and pricing with computing capacity constraint in mobile edge computing," *Journal of Systems Architecture*, vol. 137, p. 102847, Apr. 2023, doi: 10.1016/j.sysarc.2023.102847.
- [22] V. Cardellini *et al.*, "A game-theoretic approach to computation offloading in mobile cloud computing," *Math. Program.*, vol. 157, no. 2, pp. 421–449, Jun. 2016.
- [23] P. Liu, J. Li, and Z. Sun, "Matching-Based Task Offloading for Vehicular Edge Computing," *IEEE Access*, vol. 7, pp. 27628–27640, 2019, doi: 10.1109/ACCESS.2019.2896000.
- [24] Y. Zhang *et al.*, "An Efficient Caching and Offloading Resource Allocation Strategy in Vehicular Social Networks," *IEEE Transactions on Vehicular Technology*, vol. 73, no. 4, pp. 5690–5703, Apr. 2024, doi: 10.1109/TVT.2023.3332905.

- [25] H. Wu, J. Geng, X. Bai, and S. Jin, "Deep reinforcement learning-based online task offloading in mobile edge computing networks," *Information Sciences*, vol. 654, p. 119849, Jan. 2024, doi: 10.1016/j.ins.2023.119849.
- [26] T. Zhang, D. Xu, A. Tolba, K. Yu, H. Song, and S. Yu, "Reinforcement-Learning-Based Offloading for RIS-Aided Cloud-Edge Computing in IoT Networks: Modeling, Analysis, and Optimization," *IEEE Internet Things J.*, vol. 11, no. 11, pp. 19421–19439, Jun. 2024, doi: 10.1109/JIOT.2024.3367791.
- [27] F. Dai, G. Liu, Q. Mo, W. Xu, and B. Huang, "Task offloading for vehicular edge computing with edge-cloud cooperation," *World Wide Web*, vol. 25, no. 5, pp. 1999–2017, Sep. 2022, doi: 10.1007/s11280-022-01011-8.
- [28] A. Ait Temghart, M. Marwan, M. Ouaskou, and M. Baslam, "Towards Efficient Computation Offloading in Multi-user MEC Environments: A Game-Theoretic Approach," in *Digital Technologies and Applications*, vol. 1101, S. Motahhir and B. Bossoufi, Eds., in *Lecture Notes in Networks and Systems*, vol. 1101, Cham: Springer Nature Switzerland, 2024, pp. 133–143. doi: 10.1007/978-3-031-68675-7\_14.
- [29] N. Chauhan and R. Agrawal, "A Probabilistic Deadline-aware Application Offloading in a Multi-Queueing Fog System: A Max Entropy Framework," *J Grid Computing*, vol. 22, no. 1, p. 31, Mar. 2024, doi: 10.1007/s10723-024-09753-7.
- [30] J. B. Rosen, "Existence and Uniqueness of Equilibrium Points for Concave N-Person Games," *Econometrica*, vol. 33, no. 3, p. 520, Jul. 1965, doi: 10.2307/1911749.
- [31] D. Gabay and H. Moulin, "On the Uniqueness and Stability of Nash Equilibria in Noncooperative Games," *Applied Stochastic Control in Econometrics and Management Sciences*, Jan. 1980.
- [32] G. P. Cachon and S. Netessine, "Game Theory in Supply Chain Analysis," in *Models, Methods, and Applications for Innovative Decision Making*, M. P. Johnson, B. Norman, N. Secomandi, P. Gray, and H. J. Greenberg, Eds., INFORMS, 2006, pp. 200–233. doi: 10.1287/educ.1063.0023.
- [33] R. Abraham, J. E. Marsden, and T. Ratiu, *Manifolds, Tensor Analysis, and Applications*, vol. 75. in *Applied Mathematical Sciences*, vol. 75. New York, NY: Springer New York, 1988. doi: 10.1007/978-1-4612-1029-0.

# Resilience and Self-Efficacy: Keys to Students' Change Readiness in Higher Education

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## ABSTRACT

This study aims to understand the influence of resilience, self-efficacy, and critical thinking on the readiness to change of final-year students, with the moderating roles of organizational culture, technological adaptation, and the mediating role of psychological empowerment in higher education. Data was gathered through an online questionnaire sent to respondents, consisting of 255 final-year students and 205 higher education members. The data was analyzed using Multi-level CFA. At the individual level, study investigates final-year students' readiness to change through resilience, self-efficacy, and critical thinking. At an organizational level, this study focuses on organizational culture, technological adaptation, and psychological empowerment. Organizational culture significantly enhances students' psychological empowerment, boosting readiness for change, as psychological empowerment is a mediator between organizational culture and readiness for change. Technological adaptation strengthens psychological empowerment, where students with higher tech proficiency show greater psychological empowerment and readiness for change. This finding underscores the value of integrating technology into education to improve learning engagement and adaptability.

**Keywords:** Critical thinking, Innovation, Psychological empowerment, Readiness to Change, Resilience, and Self-efficacy

## 1. Introduction

In the current educational landscape, developing resilience, self-efficacy, and critical thinking has become essential for preparing final-year students to adapt to rapid changes and uncertainties in academic and professional lives. Readiness for change is a crucial competency for students as they transition from academic settings into professional environments that are increasingly dynamic and complex [1]. Resilience is the capacity to withstand and recover from challenges, enabling students to face the uncertainties of their evolving roles [2]. Self-efficacy, or belief in one's ability to achieve specific outcomes, is closely linked to enhanced adaptability and engagement in the face of change [3]. Additionally, critical thinking, characterized by objective analysis and judgment, is essential for students to make informed decisions and navigate the demands of the modern workforce (Facione, 2011). Organizational culture within educational institutions is crucial in psychological empowerment and subsequent readiness for change [5]. A positive and supportive organizational culture fosters an environment where students feel empowered and capable of tackling new

challenges, improving their adaptability and resilience [6]. This study posits that organizational culture is a moderator, strengthening the relationship between resilience, self-efficacy, critical thinking, and readiness for change by enhancing students' psychological empowerment [7]. Furthermore, technological adaptation is increasingly recognized as an essential factor of psychological empowerment development, along with the skills and confidence needed to navigate digital and informational resources efficiently [8]. Integrating technology in academics encourages students to engage actively with learning materials, enhancing their preparedness for dynamic professional environments.

Psychological empowerment is a mediating factor through resilience, self-efficacy, and critical thinking to readiness for change. By feeling competent, autonomous, and impactful, students are more likely to take the initiative and engage with new challenges, thus enhancing their adaptability (Spreitzer, 1995). Technological adaptation and supportive organization are expected to increase psychological empowerment, thereby strengthening students' readiness for change for professional transitions [10]. This research seeks to expand upon previous studies by examining how organizational culture and technological adaptation as moderating factors in the relationship between core individual competencies—resilience, self-efficacy, and critical thinking—and students' readiness for change, with psychological empowerment as a crucial mediating influence [11]. Theoretical frameworks such as Bandura's Social Cognitive Theory and Schein's organizational culture model underscore the importance of individual agency and environment in fostering readiness for change, while technological adaptation represents a modern dimension that enhances students' learning and empowerment capabilities [3], [6]. By exploring the interrelationships among these constructs, this study provides insights into the conditions that support final-year students in cultivating readiness for change and preparing for the demands of a constantly evolving professional environment.

This study constructs a conceptual model to examine the influence of resilience, self-efficacy, and critical thinking on final-year students' readiness for change, with organizational culture and technical adaptation as moderating factors and psychological empowerment as a mediating factor. By including organizational culture and technological adaptation as moderators, the study fills a research gap in understanding how external and environmental factors impact internal competencies of resilience, self-efficacy, and critical thinking. This approach highlights a supportive organizational culture and effective technological adaptation integration in students' adaptability and engagement, preparing them for change. The novelty of this research lies in its application of a moderated mediation model, where organizational culture and technical adaptation are assessed as moderating influences on the relationship between students' core competencies and readiness for change. At the same time, psychological empowerment serves as the mediating role. This model provides a comprehensive view of how students' psychological empowerment is shaped by resilience, self-efficacy, and critical thinking and strengthened through supportive environmental factors. The study further contributes to the academic literature by exploring how fostering a positive organizational culture and integrating technology can amplify students' readiness for change, presenting valuable insights for educational institutions to develop adaptive, forward-thinking learning environments.

## **2. Theory and Hypotheses Development**

### **2.1. Resilience, Organizational Culture, and Technological Adaptation**

Carver & Scheier (2023) postulated that optimism is associated with envisioning positive outcomes in the future. Optimists approach challenging but manageable obstacles by focusing on solutions and maintaining their goals through problem-solving and strategic planning (Carver & Scheier, 2023). Optimistic individuals are more likely to exhibit resilience in the face of adversity, even if their progress may be gradual [13]. Miranda & Cruz (2022) emphasized optimism supports students in managing academic challenges, while Dawson & Pooley (2013) highlighted that higher levels of optimism correlate with increased resilience among students. Similarly, Danesh & Shahnazari (2020), Derakhshan *et al.*, (2022), Yu *et al.*, (2022), and Yun *et al.*, (2018) have examined how resilience relates to motivation and academic performance. Fernandez *et al.* (2019) argue that resilience should be studied alongside other interacting variables, and numerous studies have confirmed its critical role in helping individuals manage stress in academic environments, particularly when interacting with organizational culture and technological adaptation. Firstly, organizational culture frequently appears as a central theme in empirical studies on organizational resilience. Spee (2020) examined how the University of Redlands responded to challenges and highlighted the necessity for a culture that

promotes resilience and supports positive change. Similarly, Paunescu & Argatu (2020) emphasized the crucial role of organizational culture, particularly in shaping resilience strategies. Organizations that cultivate a resilience-oriented culture acknowledge that adversity can arise unexpectedly, prompting them to enhance risk awareness and prioritize long-term survival proactively [23].

Technological adaptations, as previous suggestions and logical assumptions drawn from cognitive studies like Gantt (1998), can be argued that humans have limited retention capacity, which significantly depends on their interaction with their environment, and emphasize the importance of moving away from traditional lecture-based teaching towards models that foster higher retention rates. Studies have shown a positive relationship between using information and communication technologies, increased student motivation, and improved academic performance [25], [26]. In Indonesia, AI continues to be regarded as highly significant, particularly among educators and technology developers who seek to integrate learning strategies into educational settings [27]. [28] have explored various aspects, including its usability, challenges, and emerging opportunities in AI in higher education. One prominent AI tool utilized is ChatGPT, which university students and lecturers have widely adopted to improve work efficiency and deliver comprehensive learning materials [29], [30]. Based on the discussion, the relationship between resilience, organizational culture, and technological adaptations is analyzed through the following hypotheses:

- H1 Resilience has a positive influence on organizational culture
- H2 Resilience has a positive influence on technical adaptation

## 2.2. Self-efficacy, Organizational Culture, and Technological Adaptation

Self-efficacy theory, a core component of Bandura's social cognitive theory, has been recognized as one of his most significant contributions to academic achievement, learning, and motivation [31], [32]. Bandura (2001) noted that students' behavior is often best predicted by perceptions of their abilities. According to Bandura (1997), self-efficacy affects how students feel, think, and behave. Self-efficacy theory suggests that it is one's confidence in one's capability to plan and execute a specific course of action to solve a problem or complete a task [33]. Therefore, student self-efficacy refers to the belief in their ability to learn and perform tasks at a certain level. High self-efficacy in students fosters skill development, capacity building, and resilience by enhancing motivation, commitment to tasks, perseverance, and resilience, particularly in the face of challenges [34]. Nasa (2014) argued that students' abilities offer a way to explain and predict their emotions, thoughts, and behaviors and organize and carry out actions needed to achieve specific objectives. Students build academic self-efficacy by assessing and interpreting their performance, which involves self-evaluations of competence [10], [36]. Ansong *et al.*, (2019) suggested that students' self-efficacy tends to increase when they believe their academic efforts are successful but decreases when they perceive their efforts as inadequate. Consequently, students with high self-efficacy tend to excel in achieving their goals, including overcoming challenges and absorbing new information, achieving high performance, such as good grades, and outperforming their peers. When students believe they are skilled at something, they persist and remain dedicated, even in the face of failure [38]. Students must foster an understanding and embed the values of higher education organizational culture, both formally and informally, to grasp its vision and goals and see themselves as integral components of the organizational culture system. We focus on student readiness to change by sharing values and beliefs and guiding higher education toward success. Organizational culture also establishes guidelines, including principles, values, symbols, and respectful language used in communication [39]. It represents a set of shared beliefs and values developed within the organization and addresses external challenges through collective problem-solving. The culture is typically shaped by the organization's founders and further developed by teams as they learn to tackle external and internal adaptation challenges [40].

In contrast, the rapid pace of technological evolution will continue to drive future developments in today's high-tech world. Higher education productivity increasingly relies on integrating relevant technologies into their operations. These technological advancements have significantly transformed organizations, optimizing learning processes to be more efficient and streamlined. Earlier findings have demonstrated that using technology amplifies the effects of ICT. However, adaptation to new technology tends to be slow when it involves complex skills, high costs, and significant time commitments [41]. To remain competitive and sustain their existence, organizations must adapt their strategies, processes, structures, and cultures [42]. Selecting the appropriate model for planned change is crucial to ensure that the transformation process occurs

smoothly and that strategic objectives are achieved [43]. Numerous studies have investigated the influence of Information Technology on organizational services and performance [44], [45]. While these studies generally highlight IT's significant role in enhancing the quality and quantity of information, its potential for adoption and innovation remains uncertain [46]. Based on the discussion, the relationship between self-efficacy, organizational culture, and technological adaptation is analyzed through the following hypotheses:

- H3 Self-efficacy has a positive influence on organizational culture
- H4 Self-efficacy has a positive influence on technological adaptation

### **2.3. Critical Thinking, Organizational Culture, and Technological Adaptation**

Critical thinking is widely recognized as an essential competency in the 21st century. Recent labor market analyses indicate a rising demand for jobs that emphasize soft skills [47]. Adult learning is often described as an educational process outside formal systems [48]. Adult education, adult learning, and lifelong learning are sometimes used interchangeably, though they can be interpreted in distinct ways [48]. Given adulthood's typically complex schedules and responsibilities, a key feature of adult learning is its flexible time and location, allowing adult learners to participate in educational activities alongside their employment and other adult roles [49]. As an internal process, or one that occurs within the learner, adult learning can be viewed as a transformative or change-oriented process driven by learning activities, with selectiveness and self-directedness being central characteristics of the adult learner [48], [50]. Critical thinking teaching and learning differ from traditional educational environments and audiences in non-formal education settings. These differences are observable in at least two areas: the cognitive development of adult learners [49], [51], [52] and the external conditions of learning, such as the diversity and availability of learning activities, schedules, degree of isolation while studying, and study modalities like online or offline learning. According to Garrison (1991), socioeconomic factors in adulthood shape the methodology of organizing adult education, particularly impacting self-directed learning versus collaborative learning. These socioeconomic factors include roles, responsibilities, and economic conditions associated with adulthood [48], [53].

Given the critical role of critical thinking, it is evident that it not only enhances individual decision-making and problem-solving abilities but also fosters a culture of innovation and adaptability within organizations. A transformative process can lead to a more resilient organizational culture characterized by continuous improvement and a willingness to embrace change [54]. As organizations increasingly integrate advanced technologies into their operations, critically assessing and adapting these changes becomes paramount. Critical thinkers are more likely to engage with new technologies thoughtfully, evaluating their implications and potential applications within their organizational context. This proactive engagement not only aids in transitions during technological shifts but also cultivates a workforce better equipped to leverage technology for enhanced productivity and innovation [55]. Based on the literature, the following hypotheses are proposed

- H5 Critical thinking has a positive influence on organizational culture
- H6 Critical thinking has a positive influence on technological adaptation

### **2.4. Organizational Culture as Moderator**

Resilience is essential for achieving emotional stability and social success [56], and it is described as "a process of interactive adaptation that aids in overcoming adversity" [57]. According to Vinkers et al., (2020), resilience is crucial for managing stress and maintaining equilibrium. Resilience has a role in handling stress and uncertainty, which are common in academic environments, particularly when facing massive changes and ensuring the readiness to change. Prior studies have explored the importance of resilience in academics [59], particularly its role in supporting psychological and social well-being [60] and its strong connection to managing stress [61]. Furthermore, Dohaney et al., (2020) highlighted key factors in developing or hindering resilience, such as support systems, community, leadership, and strategic planning in academic institutions. Self-efficacy reflects an individual's belief in their ability to succeed in specific situations and is influenced by the organizational culture of higher education. A supportive organizational culture creates an environment that encourages students to take risks and engage in self-exploration. When students perceive their educational environment as encouraging and supportive, their confidence in their abilities will likely increase, positively influencing their readiness to adapt to new situations and challenges [32], [36]. Support systems,

community, leadership, and strategic planning within academic institutions play critical roles in developing self-efficacy and fostering an environment conducive to change [62]. An organizational culture emphasizing inquiry, reflection, and open dialogue enhances students' critical thinking skills, making them more adaptable and prepared for change [4], [51]. In an educational culture that values critical thinking, students will likely engage more deeply with the material, enhancing their ability to navigate change thoughtfully and proactively. This deep engagement fosters essential thinking skills and contributes to their readiness to embrace the challenges of transitions in their academic and professional lives. Therefore, to understand organizational culture as moderate to readiness for change, the following hypotheses are presented:

- H7 Organizational culture moderates the relationship between resilience and readiness for change
- H8 Organizational culture moderates the relationship between self-efficacy and readiness for change
- H9 Organizational culture moderates the relationship between critical thinking and readiness for change

## 2.5. Technological Adaptation as Moderator

Technological adaptation is how individuals, organizations, or educational institutions adjust to and integrate new technologies into their existing practices and systems [63]. This process involves the practical use of technology and the ability to modify behaviors, develop new skills, and embrace changes that technology brings. Technological adaptation emphasizes how students and educators leverage digital tools and resources to enhance learning outcomes, foster collaboration, and improve educational experiences. A strong focus on technological adaptation can enhance students' resilience by providing them with the necessary tools and resources to cope with academic pressures and changing environments [64]. When students are adept at using technology, they can better manage stress and uncertainty, increasing their readiness to change. Integrating technology into educational practices fosters an environment where students can adapt to new challenges and develop essential skills for future success [65]. Technological adaptation also significantly enhances self-efficacy by providing students with opportunities to engage with new learning tools and resources that empower them to take ownership of their education [66]. When students are confident in their technology use, they are more likely to feel competent in navigating academic challenges and adapting to new situations. As a result, this heightened self-efficacy can increase readiness for change, enabling students to embrace new learning environments and experiences. In an era of technological advancements rapidly changing the educational landscape, adapting to technology is crucial for fostering critical thinking skills [4]. Technological adaptation in higher education encourages inquiry, collaboration, and reflective thinking, which are vital for developing critical thinking abilities [51], [53]. From the explanation above, we propose the following hypothesis to determine whether technological adaptation moderates

- H10 Technological adaptation moderates the relationship between resilience and readiness for change
- H11 Technological adaptation moderates the relationship between self-efficacy and readiness for change
- H12 Technological adaptation moderates the relationship between critical thinking and readiness for change

## 2.6. Psychological Empowerment as a Mediator

Rappaport (1987) proposed that empowerment embodies a belief in individuals' inherent ability to influence their destiny and actively participate in their community. Similarly, Conger & Kanungo (1988), drawing on Bandura's theory, characterized empowerment as enabling individuals to enhance their sense of self-efficacy within an organizational context. They further described empowerment as a form of intrinsic motivation, aligning with Thomas & Velthouse (1990), who defined it as an increase in inherent task motivation. Empowerment can be understood in two distinct ways: first, as a psychological concept emphasizing personal agency and control, and second, in a broader context encompassing social influence, political authority, and legal rights [67]. Maynard *et al.*, (2012) identified two primary dimensions of empowerment: structural, which pertains to organizational systems and frameworks, and psychological, which focuses on individual perceptions. Psychological empowerment relates to personal experiences, while structural empowerment addresses organizational mechanisms (Spreitzer, 1995). In line with structural empowerment through psychological empowerment (Spreitzer, 1995), we argue that organizational culture of higher educational

institutions with psychological empowerment for final-year students will foster their confidence, competence, and motivation for post-campus transitions and resilient individuals.

Organizational culture, mainly through a clan culture, emphasizes collaboration, teamwork, and empowerment and significantly influences employees' behaviors, attitudes, and values, subsequently impacting organizational performance and effectiveness [71]. Organizational member are also crucial in shaping organizational culture, as their values, attitudes, and behaviors can reinforce or challenge the existing culture. Furthermore, the role of technology is becoming increasingly important in shaping organizational culture, as it can change how employees communicate, collaborate, and work. Finally, the history and ownership of an organization can also influence its culture, as the values and traditions of the organization's founders and leaders may continue to shape organization's culture long after they have left. Similarly, the ownership structure of an organization can influence its culture, with private companies prioritizing profitability and growth while nonprofit organizations prioritize social impact and community involvement [71]. Organizational culture determinants are complex and multifaceted, and various factors can influence employees' values, behaviors, and attitudes. This relationship highlights the importance of creating a supportive environment where technological integration is paired with efforts to empower students psychologically, fostering a more adaptable and resilient student body. This study proposes the following hypothesis to determine the mediating role of psychological empowerment

- H13 Psychological empowerment mediates organizational culture to readiness for change
- H14 Psychological empowerment mediates technological adaptation to readiness for change

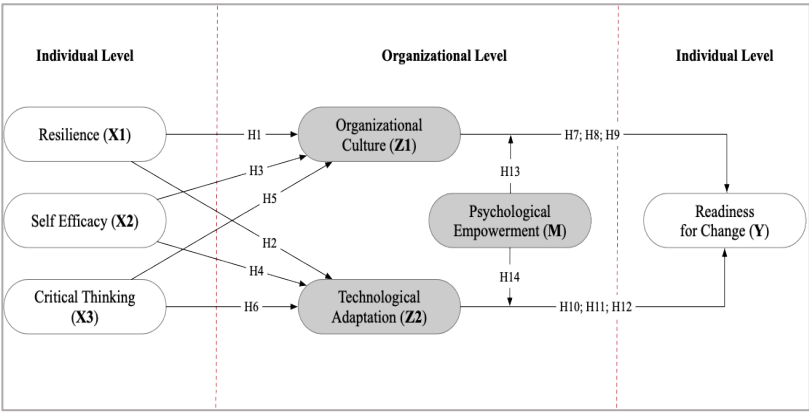


Figure 1. Conceptual Framework

3. Method

This study employs a quantitative approach to quantify or measure data, typically involving statistical analysis [72]. This study aims to examine the relationships between variables based on objective theories. After collecting data through surveys, the data is grouped and analyzed using model testing with confirmatory factor analysis (CFA), specifically applying Multi-level CFA (MCFA). The study utilizes random purposive sampling, combining random selection with deliberate judgment to select samples that meet specific criteria or characteristics relevant to the research objectives [73].

The study was conducted at three different universities in Indonesia, and data was collected through Google Forms and hard-copy surveys. Data collection was conducted for three months, from August to October 2024, to ensure a diverse sample and comprehensive understanding of the variables under study. A total of 330 respondents were initially collected for analysis, comprising 135 final-year students and 195 higher education members. However, to enhance the variability of the results, there were two rounds of data collection, we distributed the questionnaire again in February 2025 to a new sample of 460 respondents, consisting of 255 final-year students and 205 higher education members. Final-year students were given

questions to assess their resilience, self-efficacy, critical thinking, and readiness for change during their university studies, and these were measured at individual-level analysis. Population selection of final-year in higher education is based on the following considerations: (1) Consistency with the aim of study to explore resilience and self-efficacy impact on students' readiness for change [74] (2) significance to psychological constructs, as resilience and self-efficacy offer meaningful perspectives on strengthening students' adaptability [75], and (3) facilitating students in acquiring fundamental competencies necessary for both their professional careers and personal development [76], [77]. Members of higher education institutions (HEI) are provided with questions to assess organizational culture, psychological empowerment, and technological adaptation to gain insights into the dynamics that influence student readiness for change. Respondent characteristics are presented below

| Respondent Characteristic | Total Respondents<br>(n = 460) |     | Final-year Students<br>(n = 255) |     | Higher education members (n = 205) |     |
|---------------------------|--------------------------------|-----|----------------------------------|-----|------------------------------------|-----|
| Gender                    |                                |     |                                  |     |                                    |     |
| Male                      | 167                            | 36% | 77                               | 30% | 90                                 | 44% |
| Female                    | 293                            | 64% | 178                              | 70% | 115                                | 56% |
| Age Group                 |                                |     |                                  |     |                                    |     |
| 18 – 24 Years             | 345                            | 75% | 167                              | 65% | 178                                | 87% |
| 25 – 30 Years             | 115                            | 25% | 88                               | 35% | 27                                 | 13% |

Table 1. Demographic Characteristics of Respondents

3.1. Measurements

Appendix A lists all the items used in this study and the sources. A questionnaire is divided into two sections: individual-level and organizational-level. The individual-level questionnaire consists of 30 questions, scored using a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The example item, *"I am confident in my ability to adapt to new challenges in my academic and professional life, " examines resilience through self-belief, persistence, anxiety, and uncertainty control."* Self-efficacy is measured in three dimensions by Schwarzer (1995), with an example statement item: *"I am confident that I can overcome any challenges I may face during my transition to the workforce or further studies."* Critical thinking skills were assessed using a pilot critical thinking assessment tool. This assessment tool consists of selected and constructed-response items and was designed to reflect the four critical thinking dimensions proposed by Liu *et al.*, (2014). An item representing essential thinking is, *"I can accurately interpret information and identify key points related to my transition to the workforce or further studies."* Additionally, Wang *et al.*, (2023) have prioritized primary constructs and the selection of four key constructs for readiness for change in education contexts; they are personal efficacy, personal valence, personal commitment, and personal leadership. Readiness for change is evaluated with an item such as, *"I believe I can successfully adapt to new environments and situations after graduation."* Meanwhile, questionnaire for organizational level consists of 22 items. Organizational culture was measured by employing the questionnaire adopted from Quinn (2011), which includes five items, with an example item to measure: *"The leadership in this institution actively models behaviors that promote change readiness and adaptability among students."* We used a 5-item scale of technology adaptation derived from Schillewaert *et al.*, (2005), with items such as, *"The institution regularly shares updates and information about new technological tools and platforms that are available for student use."* Finally, the instrument applied for psychological empowerment was proposed by Spreitzer (1995) —meaning, competence, and impact, with example statement items, *"Students view the changes they face as meaningful steps toward achieving their career aspirations and educational goals."*

3.2. Multi-level Confirmatory Factor Analysis (MCFA)

In Confirmatory Factor Analysis (CFA), data utilized for analysis are presumed to be independent. In contrast, Multi-level Confirmatory Factor Analysis (MCFA) treats parameters as random components that fluctuate across higher-level units [83]. MCFA specifically decomposes the covariance matrix into two components: a pooled-within-cluster covariance matrix (e.g., measurement day) and a between-cluster covariance matrix (e.g., respondent data) to model the hierarchical nature of the responses appropriately (Kim *et al.*, 2016; Muthén, 1994). The pooled-within-cluster covariance matrix represents how item responses co-vary due to individual-level influences. In contrast, the between-cluster covariance matrix captures variations in the average response to each item across individuals. Consequently, MCFA estimates both within-cluster and between-cluster covariance matrices, as distinct models are specified for each analytical level (Muthén, 1994). Muthén (1994) outlined a systematic step approach for conducting MCFA. First, a standard CFA is performed using the total sample covariance matrix. Second, the Intraclass Correlation Coefficient (ICC) is calculated for each item to evaluate between-group variability, determining the proportion of variance attributable to differences between individuals. Third, CFA is applied to the pooled-within covariance matrix, followed by a separate CFA on the between-group covariance matrix in the last step.

4. Result and Discussion

4.1. Classical Assumption Test

4.1.1. Normality Test

The normality test results using the Kolmogorov-Smirnov test indicate that all variables in this study—Resilience, Self-Efficacy, Critical Thinking, Organizational Culture, Technological Adaptation, Psychological Empowerment, and Readiness for Change—exhibit a distribution that approximates normality. This conclusion is based on the Asymp. Sig. (2-tailed) values obtained for each variable, all of which exceed the 0.05 significance threshold. Since all significance values exceed 0.05, it can be concluded that the data for each variable meet the assumption of normality [85], [86]. Consequently, subsequent analyses can employ parametric statistical methods, such as Structural Equation Modeling (SEM) or linear regression, without requiring data transformation or alternative approaches to address non-normal distributions.

| Variables                     | Kolmogorov-Smirnov Statistic | Asymp. Sig. (2-tailed) |
|-------------------------------|------------------------------|------------------------|
| Resilience (X1)               | 1.023                        | 0.2                    |
| Self-Efficacy (X2)            | 1.056                        | 0.185                  |
| Critical Thinking (X3)        | 1.034                        | 0.175                  |
| Organizational Culture (Z1)   | 1.067                        | 0.16                   |
| Technological Adaptation (Z2) | 1.089                        | 0.14                   |
| Psychological Empowerment (M) | 1.012                        | 0.15                   |
| Readiness for Change (Y)      | 1.078                        | 0.13                   |

Table 2. Normality Test

4.1.2. Multicollinearity Test

Based on the analysis of the Variance Inflation Factor (VIF) and Tolerance (Table 3), there is no indication of multicollinearity issues among the variables in this study. All VIF values are below 10, and Tolerance values exceed 0.1, indicating that there are no strong linear relationships among the independent variables that could distort SEM analysis [85], [86]. Therefore, the model can proceed to SEM without the need to address multicollinearity concerns.

| Variables                     | Tolerance | VIF   |
|-------------------------------|-----------|-------|
| Resilience (X1)               | 0.712     | 1.405 |
| Self-Efficacy (X2)            | 0.685     | 1.46  |
| Critical Thinking (X3)        | 0.698     | 1.432 |
| Organizational Culture (Z1)   | 0.621     | 1.61  |
| Technological Adaptation (Z2) | 0.64      | 1.563 |
| Psychological Empowerment (M) | 0.725     | 1.38  |
| Readiness for Change (Y)      | 0.69      | 1.449 |

Table 3. Multicollinearity Test

4.2. Internal Structure Across Level

Before conducting the MCFA, a CFA was performed on the total covariance matrix (Step 1). The results demonstrated a good model fit, confirming the suitability of proceeding with the multilevel analysis. The statistical analysis indicates that the correlated four-factor model provides the best fit to the data compared to alternative models. This model yielded  $\chi^2 = 685.30$ ,  $df = 200$ ,  $CFI = 0.94$ ,  $TLI = 0.93$ ,  $RMSEA = 0.04$ , and  $SRMR = 0.03$ – $0.04$ , demonstrating a strong model fit. In contrast, the one-factor and three-factor models exhibited significantly lower fit, with CFI values below 0.92 and RMSEA exceeding 0.05, suggesting that these models do not adequately capture the data structure. While the multilevel model also showed a reasonable fit, it remained inferior to the correlated four-factor model, reinforcing its suitability for analysis. The weak metric invariance model maintained an acceptable fit ( $CFI = 0.94$ ,  $TLI = 0.93$ ,  $RMSEA = 0.04$ ), whereas the strong metric invariance model demonstrated a substantial decline in fit ( $CFI = 0.65$ ,  $TLI = 0.63$ ,  $RMSEA = 0.08$ ). These results indicate that the correlated four-factor model is the most appropriate representation of the studied variables. This model serves as a robust foundation for examining the effects of resilience, self-efficacy, critical thinking, organizational culture, technological adaptation, and psychological empowerment on readiness for change. Table 4 displays the fit indices for all tested models.

| Models                      | $\chi^2$ | df  | CFI  | TLI  | RMSEA | SRMR | AIC       | BIC       |
|-----------------------------|----------|-----|------|------|-------|------|-----------|-----------|
| Step 1: Total Model         | 780.25   | 100 | 0.94 | 0.93 | 0.05  | 0.03 | 95,210.32 | 95,524.10 |
| Step 3: Within-Group Model  | 675.8    | 100 | 0.93 | 0.91 | 0.05  | 0.03 | 61,325.42 | 61,537.83 |
| Step 4: Between-Group Model | 940.4    | 100 | 0.89 | 0.87 | 0.12  | 0.04 | 9,850.23  | 10,009.65 |

|                                      |          |     |      |      |      |         |           |           |
|--------------------------------------|----------|-----|------|------|------|---------|-----------|-----------|
| Step 5:<br>Multilevel<br>Model       | 685.3    | 200 | 0.94 | 0.93 | 0.04 | .03-.04 | 86,721.56 | 87,256.89 |
| One-Factor<br>Model                  | 1,990.1  | 210 | 0.78 | 0.74 | 0.07 | .06-.10 | 89,134.24 | 89,600.75 |
| Three-Factor<br>Model                | 835.45   | 204 | 0.91 | 0.9  | 0.05 | .04-.06 | 87,012.68 | 87,512.19 |
| Second-Order<br>Model                | 700.78   | 202 | 0.94 | 0.93 | 0.04 | .03-.05 | 86,768.13 | 87,280.41 |
| Weak Metric<br>Invariance<br>Model   | 710.62   | 210 | 0.94 | 0.93 | 0.04 | .03-.05 | 86,742.89 | 87,208.56 |
| Strong Metric<br>Invariance<br>Model | 3,120.55 | 230 | 0.65 | 0.63 | 0.08 | .11-.18 | 90,420.37 | 90,793.14 |

**Table 4.** Model Fit Indices for Total, Within-Group, Between-Group, and Multilevel Analyses

In Step 2, the variability of individual items was assessed by calculating the Intraclass Correlation Coefficient (ICC) for each item. ICC (1) aims to assess the homogeneity of variables between groups. Bliese & Castro (2000) suggest ICC (1) value in a range of 0.05–0.20 is sufficient to use multi-level models. An ICC (1) value more excellent than 0.25 indicates substantial differences between groups, making multi-level analysis highly appropriate.

| Variables                     | ICC1 | ICC2 | RWg  | P-Value |
|-------------------------------|------|------|------|---------|
| Resilience (X1)               | 0.55 | 0.79 | 0.70 | 0.00    |
| Self-efficacy (X2)            | 0.51 | 0.76 | 0.66 | 0.00    |
| Critical thinking (X3)        | 0.47 | 0.72 | 0.64 | 0.01    |
| Organizational culture (Z1)   | 0.59 | 0.74 | 0.72 | 0.00    |
| Technological adaptation (Z2) | 0.49 | 0.73 | 0.64 | 0.01    |
| Psychological empowerment (M) | 0.53 | 0.77 | 0.68 | 0.00    |
| Readiness for change (Y)      | 0.56 | 0.71 | 0.70 | 0.00    |

**Table 5.** Correlation Coefficient ICC (1), ICC (2) and RWg

According to study in Table 5, calculated ICC (1) values for each variable at individual level range from 0.47 to 0.59, thus supporting multi-level analysis. LeBreton & Senter (2008) recommend group reliability values of ICC (2) > 0.70 for good stability of group means. ICC (2) values up to 0.70 indicates each variable has a good reliability level between the sample groups. RWg is employed to assess consistency of responses within groups. James *et al.*, (1984) recommend a value of  $\geq 0.70$  as a minimum threshold for good agreement, while LeBreton & Senter (2008) indicate RWg values in a range of 0.51 - 0.69 can still be considered moderate agreement, but caution is needed in interpretation. The data processing results show values greater than 0.6, ranging from 0.64 to 0.72, thus supporting aggregation in multi-level model calculations. Therefore, based on the ICC (1), ICC (2), and RWg values for each variable, along with P-Values, all less than 0.05, the data at

the individual level supports multi-level model analysis. Steps 3 and 4 involved separately examining the factor structures at the within-group and between-group levels, within-group analysis as presented below:

| Hypotheses | Path                                         | Estimate | S.E. | Est/ S.E. | P-value |
|------------|----------------------------------------------|----------|------|-----------|---------|
| H1         | Resilience → Organizational culture          | 0.70     | 0.06 | 11.67     | 0.00    |
| H2         | Resilience → Technological adaptation        | 0.68     | 0.07 | 9.71      | 0.00    |
| H3         | Self-efficacy → Organizational culture       | 0.75     | 0.05 | 15.00     | 0.00    |
| H4         | Self-efficacy → Technological adaptation     | 0.72     | 0.06 | 12.00     | 0.00    |
| H5         | Critical thinking → Organizational culture   | 0.78     | 0.04 | 19.50     | 0.00    |
| H6         | Critical thinking → Technological adaptation | 0.70     | 0.06 | 11.67     | 0.00    |

**Table 6.** Path Analysis Results

The results, summarized in Table 6, highlight the significance of these paths.

**H1** Analysis reveals a strong positive relationship between resilience and organizational culture, with an estimated 0.70 ( $p < 0.05$ ).

**H2** Analysis indicates a significant positive relationship between resilience and technological adaptation is 0.68 ( $p < 0.05$ ).

**H3** A strong relationship between self-efficacy and organizational culture shows a robust estimate of 0.75 ( $p < 0.05$ ).

**H4** The analysis also indicates a significant positive relationship between self-efficacy and technological adaptation, with an estimated 0.72 ( $p < 0.05$ ).

**H5** The relationship between critical thinking and organizational culture has an estimate of 0.78 ( $p < 0.05$ ), which indicates a significant positive relationship

**H6** Critical thinking to technological adaptation is estimated at 0.70 ( $p < 0.05$ ), indicating a significant but weaker relationship than the other paths.

Multi-level analysis was conducted on 205 higher education members. Data processing was employed using *MPlus* 8.3. The complete results of the multi-level analysis are presented below:

| Hypotheses | Path                                                                      | Estimate | S.E. | Est/ S.E. | P-value |
|------------|---------------------------------------------------------------------------|----------|------|-----------|---------|
| H7         | Organizational culture moderates resilience → Readiness for change        | 0.75     | 0.06 | 12.50     | 0.00    |
| H8         | Organizational culture moderates self-efficacy → Readiness for change     | 0.72     | 0.07 | 10.29     | 0.00    |
| H9         | Organizational culture moderates critical thinking → Readiness for change | 0.70     | 0.06 | 11.67     | 0.00    |

|     |                                                                             |      |      |       |      |
|-----|-----------------------------------------------------------------------------|------|------|-------|------|
| H10 | Technological adaptation moderates resilience → Readiness for change        | 0.73 | 0.06 | 12.17 | 0.00 |
| H11 | Technological adaptation moderates self-efficacy → Readiness for change     | 0.71 | 0.07 | 10.14 | 0.00 |
| H12 | Technological adaptation moderates critical thinking → Readiness for change | 0.69 | 0.07 | 9.86  | 0.00 |

**Table 7.** Moderation Analysis Results

Multi-level analysis explored how organizational culture and technological adaptation moderate relationships among resilience, self-efficacy, and critical thinking concerning readiness for change among final-year students. The results of analysis presented in Table 5, provide essential insights into moderating effects of organizational culture and technical adaptation.

**H7** Result indicates organizational culture significantly moderates relationship between resilience and readiness for change, with an estimated 0.75 ( $p < 0.05$ ).

**H8** Relationship between self-efficacy and readiness for change is also significantly moderated by organizational culture, with an estimated 0.72 ( $p < 0.05$ ).

**H9** Analysis shows that critical thinking positively influences readiness for change with the moderation of organizational culture (estimate 0.70,  $p < 0.05$ ).

**H10** Results indicate that technological adaptation also moderates the relationship between resilience and readiness for change, with an estimate of 0.73 ( $p < 0.05$ ).

**H11** The relationship between self-efficacy and readiness for change, moderated by technological adaptation, is estimated at 0.71 ( $p < 0.05$ ).

**H12** The relationship between critical thinking and readiness for change, moderated by technological adaptation, is estimated at 0.69 ( $p < 0.05$ ).

**4.3. R-Square**

R-squared explains how dependent variable (output) can be predicted from model's independent variables (input). The R-squared value ranges from 0 to 1, with 1 indicating independent variables can explain all variability in dependent variable and 0 indicating that no variability in dependent variable can be explained by independent variables [90]. The results of R-squared are as follows

| Observed Variables                                            | Estimate | S.E.  | Est/ S.E. | P-value |
|---------------------------------------------------------------|----------|-------|-----------|---------|
| Readiness for Change<br>(H7; H8; H9; H10; H11; H12; H13; H14) | 0.912    | 0.018 | 50.667    | 0.00)   |

**Table 8.** Estimates of Observed Variables for Readiness for Change

The R-squared value for readiness for change is 0.912, indicating that 88.9% of variability in readiness for change can be explained by resilience, self-efficacy, critical thinking, organizational culture, technological adaptation, and psychological empowerment. The remaining 8.8% is influenced by other variables not examined in this study.

4.4. Mediation Effect on Psychological Empowerment

The Sobel test examined mediation effects of psychological empowerment on relationships between organizational culture and readiness for change. The results of the Sobel test are summarized in the table below.

| Hypotheses | Path                                                 | Estimate | S.E. | Est/ S.E. | P-value |
|------------|------------------------------------------------------|----------|------|-----------|---------|
| H13        | Organizational culture → Psychological empowerment   | 0.75     | 0.07 | 10.71     | 0.00    |
|            | Psychological empowerment → Readiness to Change      | 0.72     | 0.08 | 9.00      | 0.00    |
|            | Sobel Test                                           | 0.70     | 0.06 | 11.67     | 0.00    |
| H14        | Technological adaptation → Psychological empowerment | 0.71     | 0.09 | 7.89      | 0.00    |
|            | Psychological empowerment → Readiness to Change      | 0.70     | 0.10 | 7.00      | 0.00    |
|            | Sobel Test                                           | 0.69     | 0.08 | 8.63      | 0.00    |

Table 9. Sobel Test

**H13** The Sobel test result ( $\beta = 0.70$ ,  $p < 0.001$ ) further confirms the mediating role of psychological empowerment in this relationship, highlighting its critical function in fostering adaptability.

**H14** The Sobel test result ( $\beta = 0.69$ ,  $p < 0.001$ ) confirms the mediation effect, demonstrating that psychological empowerment bridges the link between technological adaptation and readiness for change.

4. Discussion

This study examined relationship between resilience, self-efficacy, and critical thinking for readiness for change among final-year students in three HEI in Indonesia. Furthermore, organizational culture and technological adaptation are moderating, and psychological empowerment mediates. The results showed a significant relationship between resilience, self-efficacy, and critical thinking for organizational culture, supporting hypotheses 1, 3, and 5. The findings are in line with studies that observe the relationship between resilience, self-efficacy, and critical thinking for organizational culture [91], [92], [93], [94], [95]. The findings indicate that students with a positive outlook are more inclined to exert control over their environment and demonstrate greater confidence in their ability to address and overcome challenges. Maintaining a positive perspective on life and the future enhances resilience, fostering a readiness to confront adversity and navigate difficult situations. The findings further indicated that students' perspectives on life and capacity to address and manage challenges are crucial [96]. This suggests that final-year students exhibit a sense of self-satisfaction, the ability to form meaningful connections that align with their needs, and a perception of themselves as growing and evolving individuals. Additionally, these students may possess explicit purposes and aspirations, such as fostering creativity, enhancing efficiency, or attaining emotional stability in the future, all of which shape their approach to managing difficult situations. Meanwhile, [93] argue organizational culture is an artifact that reflects the beliefs and values shared by organizational members, with the deepest level of culture being the basic assumptions members rely on to adapt to their

environment. Organizational culture works as a cohesive force, uniting members with the institutional system while fostering positive and innovative work behaviors [97].

The findings indicate a significant relationship between resilience, self-efficacy, and critical thinking to technological adaptation, supporting hypotheses 2, 4, and 6. In this modern era, the rapid advancement of technology compels academics to adapt promptly. One approach to adaptation involves digitalizing learning processes by integrating technology into teaching and learning activities. Adaptability is an individual's capacity to make "appropriate cognitive, behavioral, and/or affective adjustments in the face of uncertainty and novelty" [98]. [98] argue that trait-like capacity represents a specific form of general self-regulation of cognition, behavior, and affect, which becomes critical when individuals encounter uncertainties and novel situations that disrupt routines and impose new circumstances, as observed in the modern era. This study defines resilience as the capacity to adjust effectively, overcome obstacles, and maneuver through various circumstances [99]. [100] demonstrated that intrinsic and extrinsic motivation can predict psychological resilience, with self-efficacy acting as a mediator. Similarly, a study on Southeastern University undergraduate students revealed self-efficacy's mediating role in the relationship between adverse life changes and resilience [101]. According to [102], self-efficacy significantly predicts academic success and resilience among college students. We argue that critical thinking, the capacity to think clearly and rationally while evaluating logical connections between ideas, is a necessary cognitive skill for resilience and self-efficacy. Critical thinking involves analyzing arguments, assessing evidence, and making reasonable inferences based on that evidence. Its key components include analysis, which consists of breaking down complex information into manageable parts; evaluation, which assesses the credibility and validity of sources; and inference, which entails concluding logical reasoning [103]. Students with high levels of resilience and self-efficacy remain engaged and persevere when faced with the demands of change. These traits have proven critical factors in various positive outcomes, including enhanced critical thinking, increased achievement motivation, improved academic performance, and compelling technological adaptation.

The findings highlight the moderating effects of organizational culture and technology adaptation on the relationships between resilience, self-efficacy, critical thinking, and readiness for change, validating hypotheses 7, 8, 9, 10, 11, and 12. Organizational culture is characterized as a complex set of values, beliefs, assumptions, and symbols that define how a firm conducts its business [104]. Students' abilities, such as resilience and problem-solving approaches, will likely develop and transform through this socialization process. As discussed earlier, resilience and self-efficacy in final-year students are demonstrated by their ability to overcome challenges, effectively utilize resources within their educational setting, and exhibit determined efforts to achieve their objectives, supported by their critical thinking skills in adapting to changes [96], [102]. According to the interactive perspective, resilience in individuals is shaped by both personal and organizational factors. Meanwhile, technology adaptation refers to how individuals integrate information and communication technology into their tasks [105]. Furthermore, technology adaptation encompasses understanding how users accept and utilize technology effectively [64], [65]. [106] emphasize the importance of organizations communicating information technology's advantages, ease of use, and adaptability to target users to influence their IT adaptation behavior positively. Building on prior studies, we posit that sufficient technological adaptation within higher education institutions, along with accessible information, significantly impacts individuals' ability to readiness for change to modern technology. This aligns with [106], who underscore the role of human factors—such as skills, technical expertise, training, attitudes, and education—in shaping technology adaptation. We contend that the selection of technology should go beyond merely adopting the latest innovations (technology adoption); instead, HEI must cultivate technology adaptation to effectively engage with and address the needs of stakeholders, particularly final-year students, to readiness for change in the job market.

Psychological empowerment is conceptualized as a form of intrinsic motivation expressed through four cognitive dimensions: (a) meaning (the value of work), (b) competence (an individual's belief in their ability to perform their tasks), (c) self-determination (the ability to make decisions concerning the organization), and (d) impact (the effect of their work on organizational outcomes) [107]. The findings of this study confirm the acceptance of hypotheses H13 and H14, indicating that psychological empowerment acts as a mediator between organizational culture and technological adaptation in higher education institutions, influencing final-year students' readiness for change. These results are consistent with [108], who found a relationship between psychological empowerment and performance. This alignment is associated with the "meaning" dimension of psychological empowerment. Moreover, when individuals are confident in their competence to manage a situation (the second dimension of psychological empowerment), they perceive the task as a

challenge rather than a threat or stress [109]. Regarding self-determination, [108] suggested that a perceived lack of autonomy can create a sense of restriction, resulting in elevated stress levels, a conclusion supported by the present study. In other words, when autonomy, competence, and relatedness are fulfilled within an organization, members tend to exhibit higher levels of commitment and motivation. Education is widely acknowledged as a vital component of the knowledge economy, and its quality assessment is critical for promoting sustainable societal development. Consequently, HEI are continually faced with the challenge of ensuring and certifying the quality of their educational offerings while complying with regulatory authorities' standards. In this regard, over the past decade in Indonesia, several legal reforms, redesigns, and methodologies for evaluating higher education quality have been introduced to enhance the education system and ensure its standards. However, adopting new evaluation models has led to significant organizational shifts and increased demands on faculty, who must embrace new roles and adapt their capacities to meet emerging challenges. As observed in other educational contexts, these transformations have added further burdens to their professional performance, increasing stress levels.

## 5. Conclusion

This study employs a quantitative approach to explore the relationships between resilience, self-efficacy, critical thinking, and readiness for change among final-year students in HEI in Indonesia. Through CFA and Multi-level CFA, the research involved 460 respondents, including 255 final-year students and 205 higher education members. The study highlights the significant role of resilience, self-efficacy, and critical thinking in fostering student readiness for change, with organizational culture and technological adaptation as moderating factors. The findings align with existing research, demonstrating that students with higher resilience, self-efficacy, and critical thinking are more adaptable to change, especially in a rapidly evolving technological landscape. Additionally, the study underscores the importance of psychological empowerment in mediating the effects of organizational culture and technological adaptation on students' readiness for change. Psychological empowerment, characterized by meaning, competence, self-determination, and impact, is crucial in enhancing students' engagement and motivation, influencing their ability to adapt to change. The research also emphasizes the need for HEI to cultivate an environment that promotes technological adaptation and psychological empowerment, as these factors are essential for preparing students for future challenges in the workforce. These findings contribute valuable insights for educational institutions aiming to enhance curricula and support mechanisms that foster critical skills for students' personal and professional growth.

### 5.1. Limitation

To the best of the author's knowledge, this is the first national empirical study providing a specific role of psychological empowerment in higher education institutions, where resilience, self-efficacy, and critical thinking are often directly associated with drastic changes in organizational structure, policies, and educational practices in technology era. However, the findings should not be generalized to all dimensions of variables or other organizations due to certain research limitations. First, population included only final-year students and higher education members, with a sample size of 460 respondents (255 students and 205 higher education members). While this sample size is sufficient for statistical analysis, it may not fully capture the diversity of experiences across all higher education settings. Second, the study utilized random purposive sampling, which combines random selection with deliberate judgment to meet specific research objectives, potentially introducing selection bias. Third, the geographical scope of the research was confined to three universities in Indonesia, which may limit the applicability of findings to other regions or countries with different cultural, political, and economic contexts. Moreover, the study employed a cross-sectional design, collecting data during a specific three-month period from August to October 2024. This approach may not account for temporal variations in the relationships between variables, such as resilience, self-efficacy, critical thinking, and readiness for change. Data collection methods, including surveys via Google Forms and hard copies, also rely on self-reported measures, which could introduce response biases. Despite these limitations, the study utilized robust quantitative methods, including MCFA, to examine relationships between individual- and organizational-level variables, thereby providing valuable empirical insights. Nevertheless, future research should consider expanding the scope to include non-academic staff, students from diverse disciplines,

and universities with varying institutional characteristics. Longitudinal studies could also offer a more comprehensive understanding of these relationships' temporal dynamics. These steps would enhance the generalizability and depth of knowledge of the studied constructs.

## 5.2. Implication

This study aligns with [110], emphasizing self-efficacy, resilience, and critical thinking in equipping final-year students to adapt to change. It introduces an innovative model that incorporates key variables affecting self-efficacy, resilience, and critical thinking, with organizational culture and technological adaptation as moderating factors and psychological empowerment as mediators for readiness for change among final-year students in Indonesia. This model enriches theoretical and facilitates practical application for studies and practitioners. However, while this study offers a systematic contribution to advancing theoretical knowledge, it also identifies opportunities for further investigation and refinement. From a practical perspective, prior research on self-efficacy and resilience often overlooks essential elements of human adaptation and growth, favoring a focus on potential over development. This gap highlights the need for a shift in approach. The findings of this study aim to address the challenges Indonesian students face by providing practical recommendations for support. Self-efficacy, resilience, and critical thinking are pivotal for educational psychology and carry significant implications for assessment, intervention, consultation, research, and training. As these abilities can be developed and taught, it becomes imperative for university leaders and policymakers to implement initiatives that strengthen students' capacity to overcome challenges. Prioritizing workshops and seminars to promote understanding of these skills is crucial.

Programs like self-efficacy training grounded in social cognitive theory provide practical strategies to enhance students' confidence and adaptability. Likewise, resilience-building initiatives, like the "Road to Resilience" program by the American Psychological Association, employ techniques such as cultivating relationships, setting and pursuing goals, exercising self-control, maintaining a positive outlook, and fostering self-belief, offering a comprehensive framework for skill development. For counselors, educators, and practitioners, this study underscores the need to design targeted programs that enhance self-efficacy and resilience, particularly for final-year students facing adjustment difficulties. The findings advocate expanding counseling services and offering customized support to meet students' needs. Additionally, the insights generated by this research serve as valuable resources for academics, researchers, and university administrators. This study also highlights the potential for future research further to explore self-efficacy, resilience, and associated factors, facilitating the identification of new findings that can be broadly applied across diverse student cohorts.

## 5.3. Future Research Direction

We aim to develop a conceptual framework addressing readiness for change system enhancement and large-scale educational transformation. Insights gained from this conceptual framework and empirical evidence will enhance our understanding of institutional and systemic improvement and readiness for change in an interconnected global context. Several critical questions remain open for discussion and future research:

- Do the proposed core constructs for individual and organizational readiness dimensions sufficiently capture the viable conceptualization of higher education systems' readiness for change?
- Are organizational and system readiness distinct or overlapping constructs? Should system readiness be considered an independent construct, or is it embedded within organizational readiness for change?
- How can we design robust instruments to measure and explore the interaction between individual and organizational readiness in diverse cultural contexts? How can we ensure methodologically sound research to establish legitimate cross-cultural knowledge connections? Are educators and higher education systems adequately prepared for change?

Applying cultural and cross-cultural perspectives presents clear advantages in articulating and connecting global knowledge bases. The primary aim of this conceptual paper is to introduce a framework for assessing the readiness for change, mainly focusing on final-year students. It also seeks to test the framework's application to evaluate and enhance readiness for change across diverse settings. This framework will be a foundation for facilitating institutional and systemic improvement discussions while guiding future research directions. Assessing readiness profiles for change across various HEland systems is essential to

identifying strengths and weaknesses at individual, organizational, and systemic levels. Additionally, it is crucial to investigate how these factors influence the capacity to achieve systemic readiness for change. Rigorous and consistent qualitative and quantitative data collection methodologies across different cultural and geographic contexts will enable collaborative researchers to build large datasets and compare findings. Readiness profiles will provide empirical evidence to empower educators and institutional leaders to progress and build momentum for change. The strengths and weaknesses identified at individual, institutional, and systemic levels warrant further exploration. Triangulated findings and their interpretation will offer valuable insights into strategies for achieving systemic readiness for change. Validated multi-level frameworks and measurement tools can serve as diagnostic and developmental resources for higher education institutions. Ultimately, the goal is to assess, identify, and enhance the overall readiness of higher education systems to embrace change.

## References

- [1] F. Luthans and C. M. Youssef, 'Emerging Positive Organizational Behavior', *Journal of Management*, vol. 33, no. 3, pp. 321–349, Jun. 2007, doi: 10.1177/0149206307300814.
- [2] A. S. Masten, 'Global Perspectives on Resilience in Children and Youth', *Child Development*, vol. 85, no. 1, pp. 6–20, Jan. 2014, doi: 10.1111/cdev.12205.
- [3] A. Bandura, *Self-efficacy: The exercise of control*. Macmillan, 1997.
- [4] P. A. Facione, 'Critical thinking: What it is and why it counts', *Insight assessment*, vol. 1, no. 1, pp. 1–23, 2011.
- [5] A. A. Aji, J. A. Hamid, A. Hassan, and R. M. Rasdi, 'Effect of organizational cultures on lecturers psychological empowerment and organizational commitment: structural equation modeling approach', *IOSR Journal of Humanities and Social Science*, vol. 22, no. 2, pp. 71–82, 2017.
- [6] E. H. Schein, *Organizational Culture and Leadership*, 5th edition. New Jersey: John Wiley & Sons, Inc., 2017.
- [7] S. T. Hannah, B. J. Avolio, F. Luthans, and P. D. Harms, 'Leadership efficacy: Review and future directions', *The leadership quarterly*, vol. 19, no. 6, pp. 669–692, 2008.
- [8] G. Westerman, D. Bonnet, and A. McAfee, *Leading digital: Turning technology into business transformation*. Harvard Business Press, 2014. Accessed: Oct. 25, 2024. [Online].
- [9] G. M. Spreitzer, 'Psychological, empowerment in the workplace: dimensions, measurement and validation.', *Academy of Management Journal*, vol. 38, no. 5, pp. 1442–1465, Oct. 1995, doi: 10.2307/256865.
- [10] A. Bandura, 'Social Cognitive Theory: An Agentic Perspective', *Annu. Rev. Psychol.*, vol. 52, no. 1, pp. 1–26, Feb. 2001, doi: 10.1146/annurev.psych.52.1.1.
- [11] M. Jiang, H. Wang, and M. Li, 'Linking empowering leadership and organizational citizenship behavior toward environment: The role of psychological ownership and future time perspective', *Frontiers in psychology*, vol. 10, p. 2612, 2019.
- [12] C. S. Carver and M. F. Scheier, 'Optimism', in *Encyclopedia of Quality of Life and Well-Being Research*, F. Maggino, Ed., Cham: Springer International Publishing, 2023, pp. 4849–4854. doi: 10.1007/978-3-031-17299-1\_2018.
- [13] C. R. Snyder, D. B. Feldman, H. S. Shorey, and K. L. Rand, 'Hopeful choices: A school counselor's guide to hope theory', *Professional School Counseling*, vol. 5, no. 5, p. 298, 2002.
- [14] J. O. Miranda and R. N. C. Cruz, 'Resilience mediates the relationship between optimism and well-being among Filipino university students', *Curr Psychol*, vol. 41, no. 5, pp. 3185–3194, May 2022, doi: 10.1007/s12144-020-00806-0.
- [15] M. Dawson and J. A. Pooley, 'Resilience: The role of optimism, perceived parental autonomy support and perceived social support in first year university students', 2013, Accessed: Dec. 23, 2024. [Online]. Available: <https://ro.ecu.edu.au/ecuworks2013/418/>

- [16] J. Danesh and M. Shahnazari, 'A structural relationship model for resilience, L2 learning motivation, and L2 proficiency at different proficiency levels', *Learning and Motivation*, vol. 72, p. 101636, 2020.
- [17] A. Derakhshan, J.-M. Dewaele, and M. A. Noughabi, 'Modeling the contribution of resilience, well-being, and L2 grit to foreign language teaching enjoyment among Iranian English language teachers', *System*, vol. 109, p. 102890, 2022.
- [18] M. Yu, H. Wang, and G. Xia, 'The review on the role of ambiguity of tolerance and resilience on students' engagement', *Frontiers in Psychology*, vol. 12, p. 828894, 2022.
- [19] S. Yun, P. Hiver, and A. H. Al-Hoorie, 'Academic buoyancy: exploring learners' everyday resilience in the language classroom', *Studies in Second Language Acquisition*, vol. 40, no. 4, pp. 805–830, 2018.
- [20] J. R. Fernandez, F. Llamas-Salguero, and M. Gutiérrez-Ortega, 'Revisión bibliográfica y evolución del término resiliencia', *Revista Educativa Hekademos*, 2019.
- [21] J. C. Spee, 'Transformation and Resilience at the University of Redlands', *Journal of Management Inquiry*, vol. 29, no. 2, pp. 139–144, Apr. 2020, doi: 10.1177/1056492619866262.
- [22] C. Paunescu and R. Argatu, 'Critical functions in ensuring effective business continuity management. Evidence from Romanian companies', *Journal of Business Economics and Management*, vol. 21, no. 2, pp. 497–520, 2020.
- [23] T. Andersson, M. Cäker, S. Tengblad, and M. Wickelgren, 'Building traits for organizational resilience through balancing organizational structures', *Scandinavian Journal of Management*, vol. 35, no. 1, pp. 36–45, 2019.
- [24] P. Gantt, 'Maximizing multimedia for training purposes', *The Technology Source*, 1998.
- [25] E. Callaway, 'iTunes university'better than the real thing', *New Scientist*, 2009.
- [26] D. Fonseca, N. Martí, E. Redondo, I. Navarro, and A. Sánchez, 'Relationship between student profile, tool use, participation, and academic performance with the use of Augmented Reality technology for visualized architecture models', *Computers in human behavior*, vol. 31, pp. 434–445, 2014.
- [27] H. Jo, 'From concerns to benefits: a comprehensive study of ChatGPT usage in education', *Int J Educ Technol High Educ*, vol. 21, no. 1, p. 35, Jun. 2024, doi: 10.1186/s41239-024-00471-4.
- [28] H. U. Rahiman and R. Kodikal, 'Revolutionizing education: Artificial intelligence empowered learning in higher education', *Cogent Education*, vol. 11, no. 1, p. 2293431, Dec. 2024, doi: 10.1080/2331186X.2023.2293431.
- [29] Helmiatin, A. Hidayat, and M. R. Kahar, 'Investigating the adoption of AI in higher education: a study of public universities in Indonesia', *Cogent Education*, vol. 11, no. 1, p. 2380175, Dec. 2024, doi: 10.1080/2331186X.2024.2380175.
- [30] M. Pradana, H. P. Elisa, and S. Syarifuddin, 'Discussing ChatGPT in education: A literature review and bibliometric analysis', *Cogent Education*, vol. 10, no. 2, p. 2243134, Dec. 2023, doi: 10.1080/2331186X.2023.2243134.
- [31] F. Pajares, 'Albert Bandura: biographical sketch'. 2004.
- [32] D. H. Schunk, 'Self-Efficacy and Academic Motivation', *Educational Psychologist*, vol. 26, no. 3–4, pp. 207–231, Jun. 1991, doi: 10.1080/00461520.1991.9653133.
- [33] J. S. Eccles and A. Wigfield, 'Motivational Beliefs, Values, and Goals', *Annu. Rev. Psychol.*, vol. 53, no. 1, pp. 109–132, Feb. 2002, doi: 10.1146/annurev.psych.53.100901.135153.
- [34] S. Vermeiren, D. Duchatelet, and D. Gijbels, 'Assessing students' self-efficacy for negotiating during a role-play simulation of political decision-making. Taking student characteristics and simulation features into account', *Studies in Educational Evaluation*, vol. 72, p. 101124, 2022.
- [35] G. Nasa, 'Academic self-efficacy: a reliable predictor of educational performances Prof. Hemant Lata Sharma', *British Journal of Education*, vol. 2, no. 3, pp. 57–64, 2014.

- [36] E. L. Usher and F. Pajares, 'Sources of self-efficacy in mathematics: A validation study', *Contemporary educational psychology*, vol. 34, no. 1, pp. 89–101, 2009.
- [37] D. Ansong, S. R. Eisensmith, M. Okumu, and G. A. Chowa, 'The importance of self-efficacy and educational aspirations for academic achievement in resource-limited countries: Evidence from Ghana', *Journal of adolescence*, vol. 70, pp. 13–23, 2019.
- [38] W. Crain, *Theories of development: Concepts and applications*. Routledge, 2015.
- [39] W. A. Umrani, S. M. M. Shah, P. A. Memon, and A. H. Samo, 'Organizational culture and business performance: An empirical investigation in the Pakistani context', *International Journal of Academic Research in Economics and Management Sciences*, vol. 6, no. 1, pp. 93–107, 2017.
- [40] V. O. Akpa, O. U. Asikhia, and N. E. Nneji, 'Organizational culture and organizational performance: A review of literature', *International Journal of Advances in Engineering and Management*, vol. 3, no. 1, pp. 361–372, 2021.
- [41] T. B. Long, V. Blok, and I. Coninx, 'Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy', *Journal of cleaner production*, vol. 112, pp. 9–21, 2016.
- [42] L. S. Keong and O. Dastane, 'Building a sustainable competitive advantage for Multi-Level Marketing (MLM) firms: An empirical investigation of contributing factors', *Journal of Distribution Science*, vol. 17, no. 3, pp. 5–19, 2019.
- [43] M. Igbaria and M. Tan, 'The consequences of information technology acceptance on subsequent individual performance', *Information & management*, vol. 32, no. 3, pp. 113–121, 1997.
- [44] R. Beckley, M. A. Elliott, and J. M. Prickett, 'Closing the gap: information technology & the nonprofit sector', *Nonprofit world*, vol. 14, pp. 36–42, 1996.
- [45] J. G. McNutt and K. M. Boland, 'Electronic Advocacy by Nonprofit Organizations in Social Welfare Policy', *Nonprofit and Voluntary Sector Quarterly*, vol. 28, no. 4, pp. 432–451, Dec. 1999, doi: 10.1177/0899764099284004.
- [46] R. S. Mano, 'Information Technology, Adaptation and Innovation in Nonprofit Human Service Organizations', *Journal of Technology in Human Services*, vol. 27, no. 3, pp. 227–234, Aug. 2009, doi: 10.1080/15228830903093239.
- [47] V. Indrasiene et al., *Critical thinking in higher education and labour market*. Peter Lang International Academic Publishers, 2021.
- [48] K. Rubenson, 'Adult education overview', 2010.
- [49] C. P. Dwyer and A. Walsh, 'An exploratory quantitative case study of critical thinking development through adult distance learning', *Educational Technology Research and Development*, vol. 68, no. 1, pp. 17–35, 2020.
- [50] S. B. Merriam, 'Adult education-adult learning, instruction and program planning', *International Encyclopedia of Education*, pp. 12–17, 2010.
- [51] S. Brookfield, 'Adult cognition as a dimension of lifelong learning', in *Lifelong Learning*, Routledge, 2019, pp. 89–101.
- [52] E. K. Kallio, *Development of adult thinking: Interdisciplinary perspectives on cognitive development and adult learning*. Routledge, 2020.
- [53] D. R. Garrison, 'Critical thinking and adult education: a conceptual model for developing critical thinking in adult learners', *International Journal of Lifelong Education*, vol. 10, no. 4, pp. 287–303, Oct. 1991, doi: 10.1080/0260137910100403.
- [54] K. Cameron and R. E. Quinn, 'Diagnosing and Changing Organizational Culture: Based on the Competing Values Framework.', 1999.
- [55] M. A. Almaiah et al., 'Measuring institutions' adoption of artificial intelligence applications in online learning environments: integrating the innovation diffusion theory with technology adoption rate', *Electronics*, vol. 11, no. 20, p. 3291, 2022.

- [56] J. C. Zagalaz, I. López Manrique, M. B. San Pedro Veledo, M. L. Zagalaz Sanchez, and C. Gonzalez Gonzalez de Mesa, 'The importance of the phoenix bird technique (resilience) in teacher training: CD-RISC scale validation', *Sustainability*, vol. 12, no. 3, p. 1002, 2020.
- [57] S. H. Ameis, M.-C. Lai, B. H. Mulsant, and P. Szatmari, 'Coping, fostering resilience, and driving care innovation for autistic people and their families during the COVID-19 pandemic and beyond', *Molecular Autism*, vol. 11, no. 1, p. 61, Dec. 2020, doi: 10.1186/s13229-020-00365-y.
- [58] C. H. Vinkers *et al.*, 'Stress resilience during the coronavirus pandemic', *European Neuropsychopharmacology*, vol. 35, pp. 12–16, 2020.
- [59] J. Cleland, J. McKimm, R. Fuller, D. Taylor, J. Janczukowicz, and T. Gibbs, 'Adapting to the impact of COVID-19: Sharing stories, sharing practice', *Medical Teacher*, vol. 42, no. 7, pp. 772–775, Jul. 2020, doi: 10.1080/0142159X.2020.1757635.
- [60] W. D. Killgore, E. C. Taylor, S. A. Cloonan, and N. S. Dailey, 'Psychological resilience during the COVID-19 lockdown', *Psychiatry research*, vol. 291, p. 113216, 2020.
- [61] E. Giovannini, P. Benczur, F. Campolongo, J. Cariboni, and A. R. Manca, 'Time for transformative resilience: the COVID-19 emergency', Joint Research Centre, 2020. Accessed: Oct. 23, 2024. [Online]. Available: <https://ideas.repec.org/p/ipt/iptwpa/jrc120489.html>
- [62] J. Dohaney, M. de Róiste, R. A. Salmon, and K. Sutherland, 'Benefits, barriers, and incentives for improved resilience to disruption in university teaching', *International Journal of Disaster Risk Reduction*, vol. 50, p. 101691, 2020.
- [63] T. Jajuri, S. Hashim, M. N. Ali, and S. M. S. Abdullah, 'The implementation of Science, Technology, Engineering and Mathematics (STEM) activities and its effect on student's academic resilience', *Asia Pacific Journal of Educators and Education*, vol. 34, pp. 153–166, 2019.
- [64] E. Vaquero, A. Urrea, and A. Mundet, 'Promoting resilience through technology, art and a child rights-based approach', *Revista de cercetare si interventie sociala*, vol. 45, p. 144, 2014.
- [65] L. K. Kalyani, 'The role of technology in education: Enhancing learning outcomes and 21st century skills', *International Journal of Scientific Research in Modern Science and Technology*, vol. 3, no. 4, pp. 05–10, 2024.
- [66] Y. Zhang, 'The effect of educational technology on EFL learners' self-efficacy', *Frontiers in Psychology*, vol. 13, p. 881301, 2022.
- [67] J. Rappaport, 'Terms of empowerment/exemplars of prevention: Toward a theory for community psychology', *American J of Comm Psychol*, vol. 15, no. 2, pp. 121–148, Apr. 1987, doi: 10.1007/BF00919275.
- [68] J. A. Conger and R. N. Kanungo, 'The Empowerment Process: Integrating Theory and Practice', *The Academy of Management Review*, vol. 13, no. 3, p. 471, Jul. 1988, doi: 10.2307/258093.
- [69] K. W. Thomas and B. A. Velthouse, 'Cognitive Elements of Empowerment: An "Interpretive" Model of Intrinsic Task Motivation', *AMR*, vol. 15, no. 4, pp. 666–681, Oct. 1990, doi: 10.5465/amr.1990.4310926.
- [70] M. T. Maynard, L. L. Gilson, and J. E. Mathieu, 'Empowerment—Fad or Fab? A Multilevel Review of the Past Two Decades of Research', *Journal of Management*, vol. 38, no. 4, pp. 1231–1281, Jul. 2012, doi: 10.1177/0149206312438773.
- [71] D. A. Alkhodary, 'Exploring the Relationship between Organizational Culture and Well-Being of Educational Institutions in Jordan', *Administrative Sciences*, vol. 13, no. 3, Art. no. 3, Mar. 2023, doi: 10.3390/admsci13030092.
- [72] N. K. Malhotra, *Marketing research: an applied prientation*. Pearson, 2020.
- [73] N. Rai and B. Thapa, 'A Study on Purposive Sampling Method in Research', *Kathmandu: Kathmandu School of Law*, vol. 5, 2015.
- [74] M. Siddique, M. S. Ali, N. Nasir, T. H. Awan, and A. Siddique, 'Resilience and self-efficacy: A correlational study of 10th grade chemistry students in Pakistan', *Multicultural Education*, vol. 7, no. 9, pp. 210–222, 2021.

- [75] C. Chen, Y. Shen, Y. Zhu, F. Xiao, J. Zhang, and J. Ni, 'The Effect of Academic Adaptability on Learning Burnout Among College Students: The Mediating Effect of Self-Esteem and the Moderating Effect of Self-Efficacy', *PRBM*, vol. Volume 16, pp. 1615–1629, May 2023, doi: 10.2147/PRBM.S408591.
- [76] E. Ahdhianto, H. Marsigit, and Y. Nurfauzi, 'Improving fifth-grade students' mathematical problem-solving and critical thinking skills using problem-based learning', *Universal Journal of Educational Research*, vol. 8, no. 5, pp. 2012–2021, 2020.
- [77] L.-A. Hanna, S. Clerkin, M. Hall, R. Craig, and A. Hanna, 'The resilience of final-year pharmacy students and aspects of the course they found to be resilience-building', *Pharmacy*, vol. 10, no. 4, p. 84, 2022.
- [78] R. Schwarzer, 'Generalized self-efficacy scale', *Measures in health psychology: A user's portfolio. Causal and control beliefs/Nfer-Nelson*, 1995,
- [79] O. L. Liu, L. Frankel, and K. C. Roohr, 'Assessing Critical Thinking in Higher Education: Current State and Directions for Next-Generation Assessment', *ETS Research Report Series*, vol. 2014, no. 1, pp. 1–23, 2014, doi: 10.1002/ets2.12009.
- [80] T. Wang, D. F. Olivier, and P. Chen, 'Creating individual and organizational readiness for change: conceptualization of system readiness for change in school education', *International Journal of Leadership in Education*, vol. 26, no. 6, pp. 1037–1061, Nov. 2023, doi: 10.1080/13603124.2020.1818131.
- [81] R. E. Quinn, *Diagnosing and Changing Organizational Culture: Based on the Competing Values Framework*. Jossey-Bass, 2011.
- [82] N. Schillewaert, M. J. Ahearne, R. T. Frambach, and R. K. Moenaert, 'The adoption of information technology in the sales force', *Industrial marketing management*, vol. 34, no. 4, pp. 323–336, 2005.
- [83] E. S. Kim, R. F. Dedrick, C. Cao, and J. M. Ferron, 'Multilevel Factor Analysis: Reporting Guidelines and a Review of Reporting Practices', *Multivariate Behavioral Research*, pp. 0–0, Oct. 2016, doi: 10.1080/00273171.2016.1228042.
- [84] B. O. Muthén, 'Multilevel Covariance Structure Analysis', *Sociological Methods & Research*, vol. 22, no. 3, pp. 376–398, Feb. 1994, doi: 10.1177/0049124194022003006.
- [85] J. F. Hair, 'Multivariate data analysis: An overview', *International encyclopedia of statistical science*, pp. 904–907, 2011.
- [86] J. F. Hair, M. Sarstedt, L. Hopkins, and V. G. Kuppelwieser, 'Partial least squares structural equation modeling (PLS-SEM): An emerging tool in business research', *European business review*, vol. 26, no. 2, pp. 106–121, 2014.
- [87] P. D. Bliese and C. A. Castro, 'Role clarity, work overload and organizational support: Multilevel evidence of the importance of support', *Work & Stress*, vol. 14, no. 1, pp. 65–73, Jan. 2000, doi: 10.1080/026783700417230.
- [88] J. M. LeBreton and J. L. Senter, 'Answers to 20 questions about interrater reliability and interrater agreement', *Organizational Research Methods*, vol. 11, no. 4, pp. 815–852, Oct. 2008, doi: 10.1177/1094428106296642.
- [89] L. R. James, R. G. Demaree, and G. Wolf, 'Estimating within-group interrater reliability with and without response bias.', *Journal of Applied Psychology*, vol. 69, no. 1, p. 85, 1984.
- [90] J. S. Beer and K. N. Ochsner, 'Social cognition: A multi level analysis', *Brain research*, vol. 1079, no. 1, pp. 98–105, 2006.
- [91] D. J. Emerson, J. F. Hair, and K. J. Smith, 'Psychological Distress, Burnout, and Business Student Turnover: The Role of Resilience as a Coping Mechanism', *Res High Educ*, vol. 64, no. 2, pp. 228–259, Mar. 2023, doi: 10.1007/s11162-022-09704-9.
- [92] M. R. Kinanthi, N. Grasiawaty, and Y. Tresnawaty, 'Resiliensi pada mahasiswa di Jakarta: Menilik peran komunitas', *Jurnal Persona*, vol. 9, no. 2, pp. 249–268, 2020.

- [93] F. Olan, S. Liu, I. Neaga, H. Chen, and F. Nakpodia, 'How cultural impact on knowledge sharing contributes to organizational performance: Using the fsQCA approach', *Journal of Business Research*, vol. 94, pp. 313–319, 2019.
- [94] J. Southworth, 'Bridging critical thinking and transformative learning: The role of perspective-taking', *Theory and Research in Education*, vol. 20, no. 1, pp. 44–63, Mar. 2022, doi: 10.1177/14778785221090853.
- [95] T. Yunita, 'Self-Efficacy, Organizational Culture and Quality of Innovation Related to Student Sharing Knowledge', *INQUISITIVE: International Journal of Economic*, vol. 1, no. 2, Art. no. 2, Jun. 2021, doi: 10.35814/inquisitive.v1i2.2279.
- [96] F. Sabouripour, S. Roslan, Z. Ghiami, and M. A. Memon, 'Mediating role of self-efficacy in the relationship between optimism, psychological well-being, and resilience among Iranian students', *Frontiers in psychology*, vol. 12, p. 675645, 2021.
- [97] S. K. Khan, M. A. Memon, and T. Ramayah, 'Leadership and innovative culture influence on organisational citizenship behaviour and affective commitment: The mediating role of interactional justice', *International journal of business and society*, vol. 19, no. 3, pp. 725–747, 2018.
- [98] A. J. Martin, H. G. Nejad, S. Colmar, and G. A. D. Liem, 'Adaptability: How students' responses to uncertainty and novelty predict their academic and non-academic outcomes.', *Journal of Educational Psychology*, vol. 105, no. 3, p. 728, 2013.
- [99] Y. Wu, Z. Sang, X.-C. Zhang, and J. Margraf, 'The relationship between resilience and mental health in Chinese college students: a longitudinal cross-lagged analysis', *Frontiers in psychology*, vol. 11, p. 108, 2020.
- [100] M. Ghasem and M. Hosseinchari, 'Psychological resilience and intrinsic–Extrinsic motivation: The mediating role of self-efficacy', 2012, Accessed: Dec. 24, 2024. [Online]. Available: <https://www.sid.ir/filesserver/jf/78113913306>
- [101] J. A. Cody, 'The roles of stress appraisal and self-efficacy in fostering resilience to improve psychosocial outcomes following negative life events among college students: A multiple mediation analysis', 2013
- [102] W. E. Hudson, *The relationship between academic self-efficacy and resilience to grades of students admitted under special criteria*. The Florida State University, 2007. Accessed: Dec. 24, 2024. [Online]. Available:
- [103] S. Prakong, 'The Role of Critical Thinking in Enhancing Students' Problem-Solving Abilities in Higher Education', *Journal of Education, Humanities, and Social Research*, vol. 1, pp. 10–16, Dec. 2024, doi: 10.70088/scx8x622.
- [104] J. B. Barney, 'Organizational Culture: Can It Be a Source of Sustained Competitive Advantage?', *The Academy of Management Review*, vol. 11, no. 3, p. 656, Jul. 1986, doi: 10.2307/258317.
- [105] G. DeSanctis and M. S. Poole, 'Capturing the Complexity in Advanced Technology Use: Adaptive Structuration Theory', *Organization Science*, vol. 5, no. 2, pp. 121–147, May 1994, doi: 10.1287/orsc.5.2.121.
- [106] D. M. H. Kee and M. R. B. Rubel, 'Technology adaptation is on its way: the role of high involvement work practice', *IJBIR*, vol. 25, no. 1, p. 35, 2021, doi: 10.1504/IJBIR.2021.115011.
- [107] I. Jácome and S. Chi6n, 'Psychological Empowerment and Job Stress in Higher Education Institutions in Ecuador', *PRBM*, vol. Volume 15, pp. 3297–3312, Nov. 2022, doi: 10.2147/PRBM.S381342.
- [108] A. M. S. Mostafa, 'The mediating role of positive affect on the relationship between psychological empowerment and employee outcomes: A longitudinal study', in *Evidence-based HRM: A global forum for empirical scholarship*, Emerald Publishing Limited, 2017, pp. 266–282. Accessed: Dec. 24, 2024.

- [109] L. Blaique, H. Ismail, T. P. Corbin Jr, and H. Aldabbas, 'Enhancing learning organizations through employee resilience: Investigating the mediating influence of psychological empowerment', *Journal of Workplace Learning*, 2024,
- [110] A. Bandura, 'Social foundations of thought and action', *Englewood Cliffs, NJ*, vol. 1986, no. 23–28, p. 2, 1986.



# Model Checking Access Control Protocol for Spreadsheets

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## ABSTRACT

Spreadsheets are one of the most used software systems in business and academia. Since the first introduction of electronic spreadsheets for personal computers in 1979, spreadsheets have significantly evolved. With recent technological advancements and new features added, spreadsheets have become powerful computing platforms capable of complex analysis and modelling. However, numerous publications over the years described cases of spreadsheet errors. In focus of this research paper are spreadsheet errors caused by unauthorized access and modifications of spreadsheets in multi-user environments. Specifically, this paper is structured around formal verification of the novel ABAC4S (Attribute Based Access Control for Spreadsheets) protocol designed for prevention or detection of unauthorized modifications to spreadsheets in multi-user environments. We utilized a model checking approach to verify ABAC4S protocol rules for correctness.

**Keywords:** Spreadsheets, Spreadsheet Errors, Attribute Based Access Control Protocol, Unauthorized Spreadsheet Modifications, Model Checking

## 1. Introduction

Spreadsheets are widely used and can be considered as the most successful end-user programming systems. End-user programming systems allow end-users to build and execute powerful computer programs without the use of traditional programming languages and supporting development tools. It has been estimated that the number of end-user programmers outnumber traditional software programmers [1]. Spreadsheets are used in almost all companies in the US and Europe [2]. Modern enterprises use spreadsheets to support key processes such as capacity planning, financial reporting, stakeholder analysis, risk management, performance calculation, data transformation, cash-flows analysis, time-series transformations and simulations [3]. Despite their great success and importance, numerous publications over the years have described the importance of spreadsheet errors as well as the extent to which it has caused significant financial and reputational risks to individuals and organizations [4]. The European Spreadsheet Risk Interest Group (EuSpRIG), a non-profit and voluntary organization maintains a list of horror stories that illustrate problems with uncontrolled usage of spreadsheets [5].

In focus of this research paper are spreadsheet errors caused by unauthorized access and modifications of spreadsheets in multi-user environments. Specifically, this paper is structured around formal verification of the novel ABAC4S (Attribute Based Access Control for Spreadsheets) protocol designed for prevention or detection of unauthorized modifications to spreadsheets in multi-user environments. In [6], we have introduced Attribute Based Access Control conceptual model for spreadsheets. Herein we will provide thorough model checking of ABAC4S protocol and verify it for correctness. The remainder of this paper is organized as follows.

Section 2 provides a summary of related work in the field of automated detection of spreadsheet errors and controlled access for spreadsheet users in modern enterprises. In Section 3, the research methodology is presented structured around model checking of the proposed ABAC4S protocol. Afterwards, in Section 4, the ABAC4S protocol is presented with descriptions of model components and protocol rules. In Section 5, a brief introduction to model checking concepts is presented. In Section 6, formal verification of the proposed ABAC4S protocol with a symbolic model checker is provided. In Section 7, research results are discussed within the context of the overall spreadsheet research. Finally, in Section 8, the conclusions and reflections on research and verification procedures conducted are provided with proposals for future research opportunities.

## **2. Related Work**

The tremendous success of spreadsheets and impact of spreadsheet errors triggered significant interest of the research community. In the following a critical review of the literature focused on taxonomy of spreadsheet errors, automated detection of spreadsheet errors, and controlled access for spreadsheet users in modern enterprises is provided.

### **2.1. Taxonomy of spreadsheet errors**

Understanding types of spreadsheet errors is an important aspect of spreadsheet research and key to effective detection and prevention of spreadsheet errors.

Early studies listed types of errors detected without classification of spreadsheet errors. Brown and Gould [7] conducted reviews and experiments with volunteers experienced with spreadsheet use and development. As a part of the experiment, volunteers had to complete three tasks and create three different spreadsheets according to the instructions. Authors measured time required to complete the tasks, accuracy and visual appearance of final solution. An interesting part of this experiment was the use of a key logger [8] that recorded keystrokes of participants during the experiment and allowed insights to user behavior during completion of given tasks. Regardless of the limited number of participants, the experiment identified errors in formulae, mistyping, rounding and logical errors.

Galetta et al. [9] introduced two classes of spreadsheet errors. Authors distinguished between domain errors and device errors. The domain refers to the spreadsheet application area (e.g., accounting), while the device refers to the spreadsheet technology itself. For example, a mistake in logic due to a misunderstanding of depreciation is a domain error, but entering the wrong reference in the depreciation function SLN is a device error. Authors conducted an experiment with thirty accounting experts and thirty students to seek up to two errors introduced in each of six spreadsheets used during experiment. While accounting experts performed better in detection of domain errors, students demonstrated comparable performance in detection of device errors.

In one of the first attempts to offer a complete classification of errors, Panko and Halverson distinguished between quantitative and qualitative errors [10]. Quantitative errors are related to the current version of the spreadsheet, while qualitative errors refer to risky practices that might lead to an error in later stages of a spreadsheet's lifecycle. Panko and Halverson further divided quantitative errors into three subcategories: (i) mechanical errors, due to mistakes in typing or pointing, (ii) logic errors, due to choosing the wrong function or creating the wrong formula, and (iii) omission errors, due to misinterpreting the situation to be modeled. In critics to the above presented classification, Powell et al. [11] noted that this proposed classification does not take into account context of spreadsheet use and how each error was committed.

The taxonomy of errors developed by Rajalingham et al. [12] is one of the first attempts that introduced different spreadsheet user roles. This taxonomy is focused on user-generated errors and differentiates between developer and end-user errors. End-users are further classified as data inputter and interpreter. However, the given taxonomy classifies quantitative accidental errors as omission, alteration or duplication, without taking into consideration the possible errors caused by unauthorized changes in multi-user environments.

In recent years, researchers identified the need to relate types and occurrences of spreadsheet errors with the quality of the spreadsheets. Intuitively, a higher incidence of spreadsheet errors suggests that the overall quality of spreadsheet is low. O'Beirne presented an overview of information quality and data quality within the context of spreadsheets [13]. The author presented a comprehensive list of information quality attributes in the context of spreadsheet programs. In addition, the author presented checks and control procedures for spreadsheet information and quality processes.

Further refinement in spreadsheet quality research provided a set of domain specific metrics, used to measure concrete spreadsheet characteristic [14]. The presented quality model for spreadsheets is based on

the widely accepted ISO/IEC 9126 international standard for software product quality [15]. Authors provided a comprehensive analysis of ISO/IEC 9126 standard and mapped relevant quality attributes to spreadsheets.

## 2.2. Automated detection of spreadsheet errors

An automated method to infer data types from a spreadsheet was presented by Erwig and Burnett [16]. The proposed method for inferring types from spreadsheets is based on the concrete notion of units instead of the abstract concept of types. Authors used header information given by spreadsheets to derive units. In continuation of the presented concept around units, Ahamd et al. developed a type system for statically detecting spreadsheet errors [17]. The authors named the proposed model “unit checking” and presented a collection of rules that help identify weaknesses in spreadsheets that are likely to be errors. This model also relies on the concept of the header that defines common units for grouped cells. The working prototype based on the proposed model was developed for a specific version of Microsoft Excel spreadsheet application using the UCheck tool [18]. Authors validated performance of the UCheck tool in an experiment conducted with high school teachers [19]. Results of this experiment indicated that the tool effectively supports users in error correction.

High incidents of spreadsheet errors have led to a series of commercial software packages. Nixon and O'Hara provided structured assessments of several commercial auditing tools [20]. The test was designed to identify the success of software tools in detecting different types of errors, to identify how the software tools assist the auditor and to determine the usefulness of the tools. The assessment conducted by Nixon and O'Hara included the built-in auditing tool in Microsoft Excel spreadsheet [20]. Excel's built-in formula auditing tool supports visualization of spreadsheet formulas and error checking generated as result of formula evaluation.

In addition to research related to automated error detection, important to note is the work of Abraham and Erwig related to automation of spreadsheet testing [21]. The authors followed the original concept of mutation testing for general purpose programming languages and developed mutation operators for spreadsheets that allow generation of test cases.

Spreadsheets allow users to arrange data and metadata freely in a human readable format. To extract their content with automated tools, data practitioners need to perform manual inspections and data preparations. Mondrian system assists users with detection of multiregion layout templates in spreadsheets [36]. Mondrian comprises an automated approach to detect multiple data regions and an algorithm to compute layout similarity and identify templates with potential spreadsheet errors.

Recent spreadsheet research is focused on the application of large language models to improve spreadsheets quality. A team of researchers from Microsoft Corporation developed the FLAME language model for spreadsheet formulae [22]. FLAME uses the Microsoft Excel specific formula tokenizer and other techniques to achieve competitive performance with a substantially smaller model (60 million parameters) and training dataset, compared to other large language models such as Codex. Researchers used a training dataset of 972 million formulas extracted from a corpus of 1,8 million Excel workbooks. FLAME was evaluated on three different tasks for Excel formulas: last-mile repair, autocompletion and syntax reconstruction. The presented FLAME language model outperformed larger language models, such as Codex-Davinci (175 billion parameters), Codex-Cushman (12 billion parameters), and CodeT5 (220 million parameters), in 6 out of 10 experimental settings [22].

## 2.3. Access control for spreadsheets

Access control and authorization are key components of information technology systems in multi-user environments. Korman et al. evaluated existing access control models in the context of different business scenarios [23]. They also provided a unified metamodel capable of expressing access policies for all evaluated models. In [6] we have conducted an evaluation of common access control models, as well as their suitability for spreadsheet use in multi-user environments. Below is a summary of ABAC (Attribute Based Access Control) model advantages for spreadsheet applications, while detailed evaluation is provided in [6]:

- The ABAC model is based on dynamic attributes, where object attributes fit to the proposed model of spreadsheet resources and corresponding attributes.
- A hierarchy of spreadsheet resources can be modelled with ABAC conditions and access rules determinations. This property prevents conflicts in access resolutions and simplifies prototype implementation.
- Deployment opportunities for ABAC with spreadsheets are flexible and allow early prototype implementation as a corrective access control system. This minimizes impact on users and generally accepted spreadsheet user interface.

- Complexity of the ABAC model for spreadsheets depends on the number of spreadsheet resource attributes.
- The dynamic nature of modern cloud-powered spreadsheets and extensions to spreadsheet formula language fits nicely to ABAC's dynamic attribute concept. Potential new functionalities and modules added in cloud-powered spreadsheet can be integrated within existing ABAC concepts.

The National Institute of Standards and Technology (NIST) published a guideline with definitions for the ABAC model [24]. The guideline provides definitions and considerations for using ABAC to improve information sharing and design of systems, while maintaining control of that information. The concepts and terminology for ABAC presented in that document have been instrumental for the design and verification of ABAC4S protocol presented in this paper.

### 3. Research Methodology

The research methodology in this paper follows the Design Science Research approach [35]. We started our research journey with comprehensive literature review to understand existing knowledge base. We followed a focused approach on work related to taxonomy of spreadsheet errors and automated methods applied to detection and prevention of spreadsheet errors as described in Section 2.

Based on the existing knowledge base and literature review conducted, we identified research opportunities to address unauthorized spreadsheet changes and errors in multi-user environments. Aligned with the Design Science Research approach and requirements to control user interaction with spreadsheets in multi-user environments, we formulated our first research goal:

- RG1 – Develop formal description of access control protocol capable of controlling user's interaction with spreadsheets in multi-user environments.

In search of the appropriate access control protocol, we further investigated the concept of spreadsheets represented as collection of resources [6]. The first research goal is the basis for the second research goal, in that it provides specification of the access control protocol that can be formally verified. The next step in our research is to evaluate access control properties with a model checking tool, which leads to our second research goal:

- RG2 – Evaluate correctness property of the proposed access control protocol with model checking approach.

To address the second research goal further, we used NuSMV model checker to verify correctness property of the proposed access control protocol [25]. The selection of the NuSMV model checker has been primarily driven by the richness of supported SMV language and its capability to specify hierarchical SMV modules that correspond to the natural hierarchy of spreadsheet resources.

Even though presented research methodology is structured around two formulated research goals, we followed iterative research through experimentation and simulation to refine outcomes of the conducted research. Initial results of the model verification and provided counterexamples were instrumental for access protocol improvements and protocol rules redesign. Appendices, if included, follow the main text. Each appendix should be lettered, e.g., "Appendix A". To properly format appendix title, use Heading Unnumbered style from the styles menu.

### 4. ABAC4S

ABAC4S protocol is designed to control unauthorized activities on spreadsheets in multi-user environments. The core idea of the proposed protocol revolves around spreadsheet representation as a collection of resources [6]. In modern cloud-based spreadsheets, resources are building blocks manipulated with a native spreadsheet formula language or custom computational modules constructed with external programming languages. Spreadsheet resources and their attributes are bound by ABAC4S rules and allow granular control of resource states during a spreadsheet's lifecycle. The ABAC4S protocol specification consists of five distinct parts [27]:

1. The *Service* to be provided by the protocol
2. The *Assumptions* about the environment in which the protocol is executed
3. The *Vocabulary* of data flows used to implement the protocol
4. The *Encoding* (format) of each data flows in the vocabulary
5. The *Procedure rules* guarding the consistency of data flows and correctness of *Service* to be provided by the protocol

4.1. ABAC4S Protocol Service Specification

The ABAC4S protocol is defined on the conceptual level of modern cloud-based spreadsheets and is agnostic from specific commercial implementations of spreadsheets. In addition, ABAC4S protocol specifications provided in this paper are based on set-oriented data structures and data flows suitable for translation to model checking tools and verification of correctness for protocol rules.

4.2. Assumptions about ABAC4S Protocol Environment

The environment in which the protocol is executed consists of the ABAC4S conceptual model and four generic user roles typically found in multi-user environments: developer, tester, analyst and manager. The ABAC4S protocol is not restricted to only 4 specified users and can be easily extended to unlimited number of user roles depending on specific deployment needs. Four generic user roles are selected to limit the complexity of the model and prevent state space explosion during model checking. The ABAC4S protocol definition in this paper focuses on accurate and complete specification of data flows and procedure rules, while implementation for protocol execution on commercial spreadsheets is left for specific deployment scenarios.

4.3. ABAC4S Protocol Vocabulary

The spreadsheet conceptual model is visually presented in Figures 1 and 2, followed with the model of ABAC4S access rules for spreadsheets presented in Figure 3. Detailed description of spreadsheet conceptual model is provided in original paper [6].

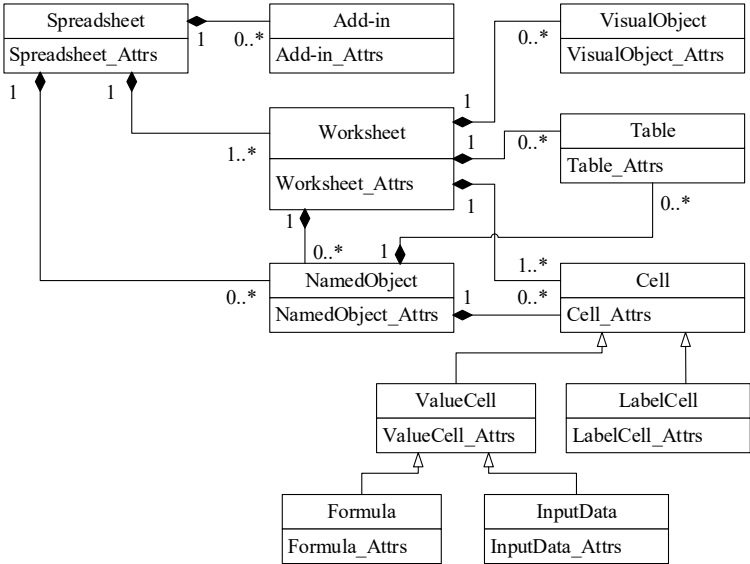


Figure 1. Metamodel of spreadsheet resources and associated attributes [6].

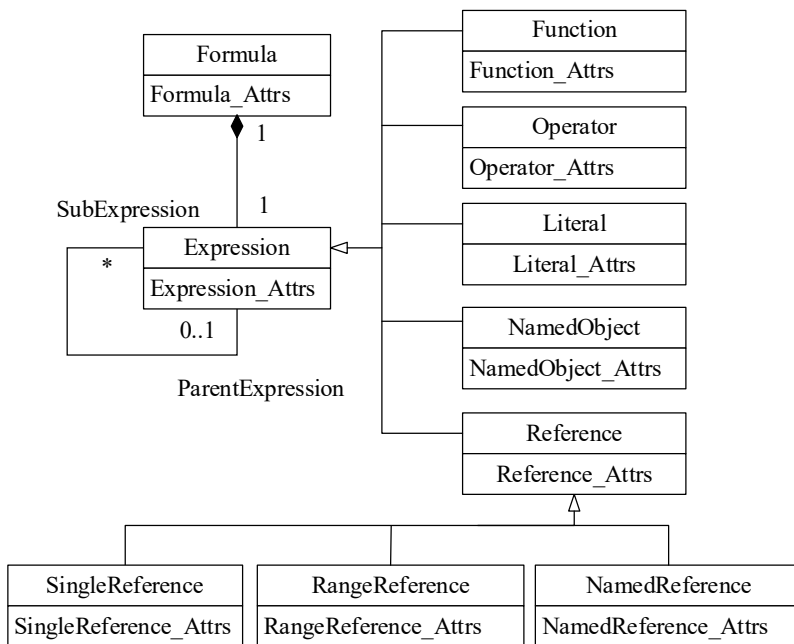


Figure 2. Spreadsheet formula metamodel [6].

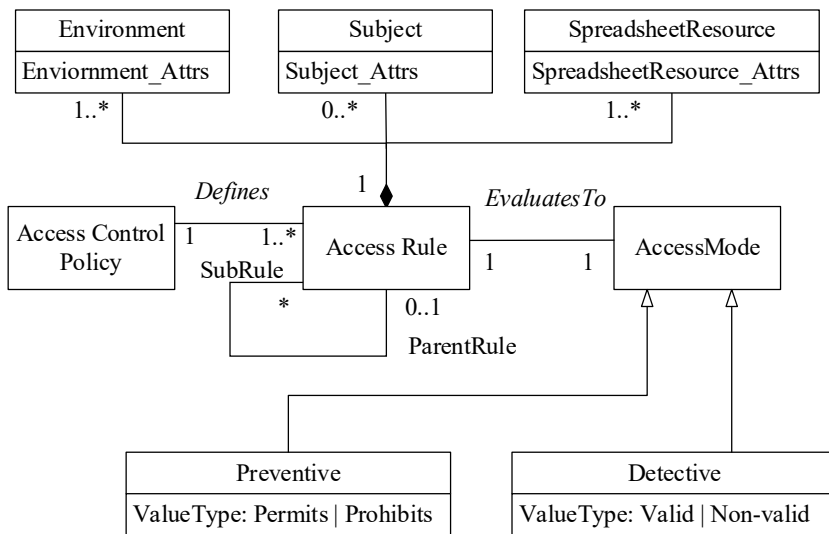


Figure 3. ABAC4S access rules for spreadsheets [6].

Spreadsheet stages during lifecycle phases are modelled with finite sequence of state transitions as follows:

$$S_0 \xrightarrow{\Delta S_0(MU)} S_1 \xrightarrow{\Delta S_1(MU)} S_2 \xrightarrow{\Delta S_2(MU)} \dots, S_e. \quad (1)$$

where  $S_0$  is the initial state of the spreadsheet ("first creation"),  $S_e$  is the final state of spreadsheet ("end of lifecycle"),  $\Delta S_j(MU)$  are transitions between spreadsheet states caused by modifications  $M$  of user  $U$  on spreadsheet resources  $SR$ .

$$U \in [developer, tester, analyst, manager]. \quad (2)$$

Modifications  $M$  are determined by comparing affected spreadsheet resource at states  $S_{j+1}$  and  $S_j$ . Transitions  $\Delta S_j(MU)$  are modeled as triplets with the following structure:

$$\Delta S_j(MU) = (U, M, SR_j). \quad (3)$$

In the proposed ABAC4S protocol vocabulary, access rules are modelled as quadruples with the following structure:

$$(U, A, SR, E). \quad (4)$$

$A$  is a set of actions that user might perform on spreadsheet resource represented with following enumerated list:

$$A \in [CREATE, READ, UPDATE, DELETE]. \quad (5)$$

These actions are usually denoted with the CRUD acronym. The proposed ABAC4S protocol is not limited to four CRUD actions, and if needed in specific deployment scenarios, the number of actions could be reduced or extended.

$SR$  represents a set of spreadsheet resources and corresponding resource attributes on which user  $U$  can perform action  $A$ .

$E$  are dynamic environmental conditions, independent of the users and the spreadsheet resources that may be used as attributes at decision time to influence an access decision. Examples of environmental conditions include time, location, threat level, or temperature [6].

#### 4.4. ABAC4S Protocol Encoding

For the ABAC4S protocol definition presented herein, we denoted spreadsheet transitions and access rules as abstract set-oriented data structures. This will allow us to express procedure rules with a specific order of evaluation between sets and model hierarchies between spreadsheet resources with set compositions. Abstract data structures presented in the protocol definition can be transformed into programming language data structures or encoded to other formats like XML (eXtensible Markup Language) or JSON (JavaScript Object Notation) messages during specific implementation scenarios.

#### 4.5. ABAC4S Protocol Rules

The procedure rules for the ABAC4S protocol are defined as follows:

Rule 1 – Priority of Actions

Actions assigned to users are evaluated in the following order:

$$DELETE > CREATE > UPDATE > READ. \quad (6)$$

Delete action has the highest priority. For example, if the access rule permits the user to delete a specific spreadsheet resource, the user is also allowed to create, update, and read the corresponding spreadsheet resource.

Rule 2 – Access Rule Inheritance

All spreadsheet's resources inherit access rules applicable to their parents.

Rule 3 – Spreadsheet Valid State

Spreadsheet is in valid state  $S_{j+1}$ , iff Rule 1 (Priority of actions) and Rule 2 (Access Rule Inheritance) are satisfied for all affected spreadsheet resources during spreadsheet state transition from  $S_j$  to  $S_{j+1}$ .

## 5. Model Checking

Model checking is a model-based verification procedure designed to automatically verify properties of finite state systems [26], [28]. The core principle behind a model checking procedure is exhaustive exploration of states to verify whether a given system model satisfies certain properties.

Transition state machines are used in model checking to represent the behavior of the system. A common method for representing transition state machines are Kripke structures. A Kripke structure  $M$  is represented as an ordered sequence of four objects:

$$M = (S, I, R, L). \quad (7)$$

$S$ : finite set of states

$I$ : set of initial states  $I \subseteq S$

$R$ : transition relation  $R \subseteq S \times S$

$L$ : interpretation function  $L: S \rightarrow 2^{AP}$

For each state  $s \in S$  there is a possible successor state  $s' \in S$  specified with transition relation  $R$ . The interpretation function  $L$  labels each state with Atomic Propositions ( $AP$ ) which are Boolean variables and the evaluations of expressions in that state [26]. A finite path  $\pi$  from some state  $s \in S$  is a sequence of states  $\pi = s_0, s_1, \dots, s_n$  such that  $s_0 = s$  and  $R(s_i, s_{i+1})$  holds for all  $0 \leq i < n$  [26].

Emerson and Clarke introduced model checking [29] and Computational Tree Logic (CTL) as a combination of linear temporal logic and branching-time logic [30]. In model checking, temporal logic is used to express system specifications (properties) denoted as  $\phi$ . CTL combines path quantifiers and temporal operators to describe events associated with single computation path.

CTL path quantifiers are as follows:

- $A$  – for All paths from a certain state on
- $E$  – there Exists at least one single path from a certain state

CTL temporal operators are as follows:

- $X\phi$  –  $\phi$  holds neXt time
- $F\phi$  –  $\phi$  holds sometime in the Future
- $G\phi$  –  $\phi$  holds Globally in the future
- $p U \phi$  –  $\phi$  holds Until  $\phi$  holds

CTL allows modeling complex behavior of the systems, where temporal operator must always be preceded by a path quantifier. Figure 4, adapted from [31] visually represents the meaning of CTL path and temporal operators.

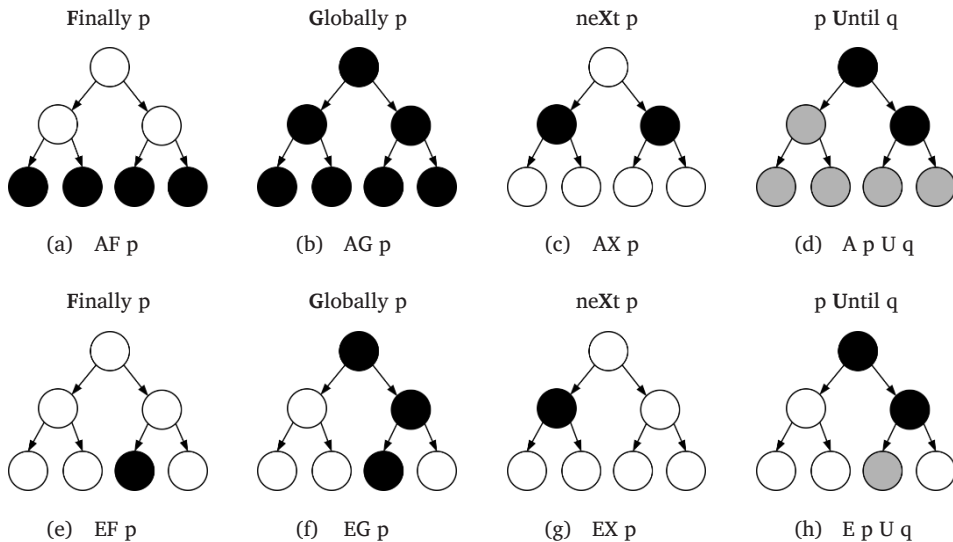


Figure 4. CTL path and temporal operators [31].

In practical model checking applications, system model  $M$  is described semantically with a Kripke structure and the specifications (properties) are described with formulae  $\phi$  in the applicable form of temporal logic. The decision procedure conducted by a model checker tool decides whether  $M \models \phi$ . Operator  $\models$  meaning is “specification  $\phi$  is satisfied by structure  $M$ ”.

## 6. Model Checking the ABAC4S Protocol

We performed model checking of the proposed ABAC4S protocol for spreadsheets with the NuSMV symbolic model checker [25]. Original SMV model checking tool has been developed at the Carnegie Mellon University [32]. NuSMV is a modern variant of original SMV symbolic model checker with compatible SMV language syntax and advanced architecture that allows textual construction of hierarchical models and verification of very large number of states [33].

The system model is a transition system with a set of states and transition relations that specifies the behavior of the system. In SMV language, a system is defined as a module, beginning with the keyword `MODULE`. The module consists of an encapsulated collection of declarations (such as `VAR`, `INIT`, `ASSIGN`, etc.) that depend on the nature of the analyzed problem and specific parameters. A module’s state variables declaration begins with the keyword `VAR`. In general, model checker tools are limited to only few data types and the SMV language allows for Boolean values, enumeration of constants, or other modules for constructing hierarchical models. The set of initial states can be specified with simple logical statements or conjunctions of equations associated with the initial state of the system. The transition relation of a module starts with the keyword `ASSIGN` and may be limited to single statement or complex set of equations. An assignment statement is structured as the next step evaluation, where the right-hand side allows the construction of complex expressions built with Boolean operators, integer arithmetic and case constructs with conditions.

The main challenge during the modeling of the spreadsheet conceptual model with the SMV language has been the abstraction of the provided model (Figures 1 and 2) with suitable SMV constructs. We represented each spreadsheet resource with a corresponding SMV module. The hierarchy of SMV modules follows the natural hierarchy of spreadsheet resources defined in the spreadsheet conceptual model (Figures 1 and 2).

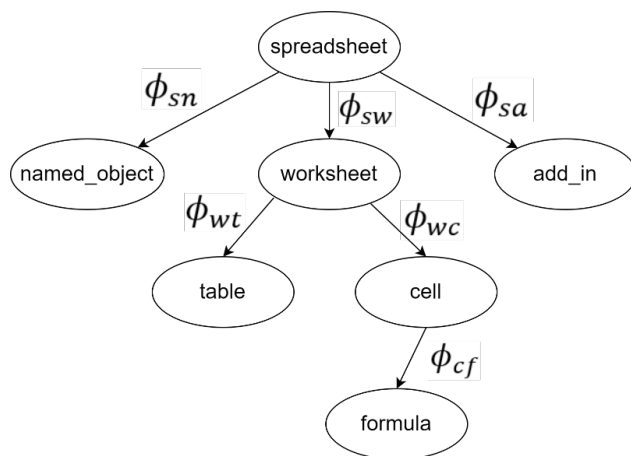


Figure 5. Hierarchy of spreadsheet resources as SMV language modules.

In addition, we wanted to explore all possible access role assignments and evaluate ABAC4S protocol for all combinations of four defined user roles and CRUD actions. In such a scenario, correct protocol behavior should detect potential conflicts and defined priority of actions and access inheritance rules should ensure correct resolution of detected conflicts in the consecutive model state. Below is the hierarchical model of spreadsheet resources specified in SMV.

```
MODULE spreadsheet_t()
VAR
    role:{developer,tester,analyst,manager};
    a:{create,read,update,delete};
    add_in:add_in_t();
    named_object:named_object_t();
    worksheet:worksheet_t();

MODULE add_in_t()
VAR
    role:{developer,tester,analyst,manager};
    a:{create,read,update,delete};

MODULE named_object_t()
VAR
    role:{developer,tester,analyst,manager};
    a:{create,read,update,delete};

MODULE worksheet_t()
VAR
    role:{developer,tester,analyst,manager};
    a:{create,read,update,delete};
    table:table_t();
    cell:cell_t();

MODULE table_t()
VAR
    role:{developer,tester,analyst,manager};
    a:{create,read,update,delete};

MODULE cell_t()
VAR
    role:{developer,tester,analyst,manager};
    a:{create,read,update,delete};
    formula:formula_t();

MODULE formula_t()
VAR
    role:{developer,tester,analyst,manager};
    a:{create,read,update,delete};

MODULE main
VAR
    spreadsheet:spreadsheet_t();
```

As listed in the above specifications, we utilized the capability of SMV language and build hierarchical modules that correspond to the natural hierarchy of spreadsheet resources. The above modules represent all possible state transitions  $\Delta S_j(MU)$  for each spreadsheet resource, assigned users and CRUD actions. To prevent state space explosion, we abstracted and simplified each spreadsheet resource to a bare minimum. For example, an additional two attributes on module `spreadsheet_t()` can be added with an enumerated list of constants, and a next case assignment for added attributes sharing the same structure with simplified model specification.

```
MODULE spreadsheet_t()
VAR
    attributes:{spreadsheet_attribute1,spreadsheet_attribute2};
    role:{developer,tester,manager};
    a:{create,read,update,delete};
    add_in:add_in_t();
    named_object:named_object_t();
    worksheet:worksheet_t();
```

Transitions to new states are modeled in SMV with next-case statements within the `ASSIGN` language construct. ABAC4S protocol rules for priority of actions and access rule inheritance are specified with a

complex conjunction statement from relevant spreadsheet resource properties. As visually represented in Figure 5, there are six conjunction statements ( $\phi_{sn}, \phi_{sw}, \phi_{sa}, \phi_{wt}, \phi_{wc}, \phi_{cf}$ ) that correspond with the hierarchical representation of spreadsheet resources. In order to correctly specify both protocol rules for priority of actions and access rule inheritance, the correct transition to the next state for the hierarchically lowest spreadsheet resource (formula) should be evaluated as a composition of all statements on the path to the root spreadsheet resource ( $\phi_{cf}, \phi_{wc}, \phi_{sw}$ ). Due to complexity of specifications and limited space in this publication, a fragment of SMV code for  $\phi_{sw}$  next-case conjunction statement that specify logic for priority of actions and access inheritance protocol rules is listed below. The complete SMV protocol specification can be fetched from author's GitHub repository at [34].

```

next(spreadsheet.worksheet.a) :=
  case
    spreadsheet.role=spreadsheet.worksheet.role) & \
    (spreadsheet.a=read) & (spreadsheet.worksheet.a in \
    update,create,delete}): read;

    (spreadsheet.role=spreadsheet.worksheet.role) & \
    (spreadsheet.a=update) & (spreadsheet.worksheet.a in \
    read,create,delete}): update;

    (spreadsheet.role=spreadsheet.worksheet.role) & \
    (spreadsheet.a=delete) & (spreadsheet.worksheet.a in \
    read,create,update}): delete;

    (spreadsheet.role=spreadsheet.worksheet.role) & \
    (spreadsheet.a=create) & (spreadsheet.worksheet.a in \
    read,update,delete}): create;

  TRUE : spreadsheet.worksheet.a;
esac;

```

After finalization of model construction and formal specification of the spreadsheet conceptual model and ABAC4S protocol rules, we conducted model checking with the NuSMV model checker. We utilized NuSMV in interactive mode, and executed CTL temporal logic property checks in NuSMV built-in shell.

CTL temporal logic specification with the following structure has been used to verify correctness of protocol rules for priority of actions and access inheritance:

$$AG (p \rightarrow AF q). \quad (8)$$

The CTL temporal logic specification above should be interpreted as “for all execution paths globally, when condition  $p$  occurs it is always followed by condition  $q$ ”. If we apply the above generic CTL specification i.e. for the table spreadsheet resource, the specific CTL syntax is as follows:

```

check_ctlspec -p "AG \
(((spreadsheet.role=spreadsheet.worksheet.role) & \
(spreadsheet.worksheet.role= \ spreadsheet.worksheet.table.role) & \
(spreadsheet.a=read) & (spreadsheet.worksheet.a=read) & \
(spreadsheet.worksheet.table.a in {update,create,delete})) \
-> AF spreadsheet.worksheet.table.a=read)"

```

As a result of the above CTL temporal logic specification check, the NuSMV model checker confirms that the above specification is satisfied by given model:

```

NuSMV >
-- specification AG (((((spreadsheet.role = spreadsheet.worksheet.role &
spreadsheet.worksheet.role = spreadsheet.worksheet.table.role) & spreadsheet.a =
read) & spreadsheet.worksheet.a = read) & spreadsheet.worksheet.table.a in
(update union create) union delete) -> AF spreadsheet.worksheet.table.a = read)
is true
NuSMV >

```

NuSMV model checker evaluates the above CTL specification to true, thus formally verifying correct conflict resolution and correct behavior of two protocol rules in case of a table spreadsheet resource. Appropriate CTL specifications for other spreadsheet resources follow the same generic structure, however conjunction statements are growing in complexity for hierarchically lower spreadsheet resources due to longer evaluation path to the root spreadsheet resource.

## 7. Discussion

Spreadsheet related research is a rich knowledge base with great scientific contributions. Many authors addressed the need to control spreadsheet errors as described in Section 2.2. Results of our research focused on unauthorized spreadsheet changes and errors in multi-user environments could usefully be combined with unit errors detection in spreadsheet [18], other commercial spreadsheet auditing tools [20] and modern large language models to improve spreadsheet quality [22]. Additional strength of the proposed ABAC4S protocol is result of our user-centric approach followed during ABAC4S protocol development and specification. This approach permits organizations to retain investment in their spreadsheets. The negative side of our approach is the requirement to document organizational dynamics and user roles in the format suitable for ABAC4S protocol.

To address our first research goal, we developed the novel ABAC4S protocol specifications based on spreadsheet representation as collection of resources. Defined protocol addresses the need identified to control user's interaction with spreadsheets on granular level of spreadsheet resources. We utilized set-oriented data structures and data flows for modeling transitions between spreadsheet states.

To address our second research goal, we converted defined ABAC4S protocol specifications to SMV language and conducted model checking to verify correctness of the protocol rules. During model construction, we used abstraction and refinement of model characteristics to reduce model complexity and prevent state space explosion during verification with model checking tools. We designed modules to represent all possible state transitions for each spreadsheet resource with associated users and actions as described in Section 4.3. Thus, we ensured that the model covers all possible realistic scenarios where users in multi-user environments might have roles of various complexities. We overcome various challenges with model abstraction and state space explosion associated with the model checking tools. Even though we reduced the number of allowed actions and number of user roles to four, the model checking tool must explore  $16^7$  (more than 268 million) possible states. To illustrate the importance of appropriate model abstraction and its impact to the state space explosion, if we increased the number of modeled actions and user roles to five, possible explorable state would grow to  $25^7$ . This small increase in the model complexity resulted in a more than 22 times larger model state space.

## 8. Conclusion

In this study, we presented results of research structured around model checking of novel ABAC4S protocol for spreadsheets. To our best knowledge, application of the model checking technique in verification of spreadsheet related research problems brings new perspective in spreadsheet research. We provided modeling guidelines and insights into how to convert ABAC4S protocol specifications to the language accepted by the model checking tool. Model checking confirms correctness of the defined ABAC4S protocol rules and appropriate resolution in case a conflict of access rights is detected. We will explore opportunities to further automate generation of machine-readable user's roles and implement developed ABAC4S protocol in various multi-user environments.

## References

- [1] C. Scaffidi, M. Shaw, and B. A. Myers, "Estimating the numbers of end users and end users programmers", In Proc. of VL/HCC '05, pp. 207-214, 2005.
- [2] L. Bradley and K. McDaid, "Using Bayesian Statistical Methods to Determine the Level of Error in Large Spreadsheets", Proceedings of the International Conference on Software Engineering, pp. 351-354., 2009.
- [3] T. Reschenhofer and F. Matthes, "A Framework for the Identification of Spreadsheet Usage Patterns", Proceedings of the European Conference on Information Systems, 2015.

- [4] K. Rajalingham, D. Chadwick, B. Knight, and D. Edwards, "Quality Control in Spreadsheets: A Software Engineering-Based Approach to Spreadsheet Development," *Proc. 33rd Hawaii Int'l Conf. System Sciences*, pp. 1-9, 2000.
- [5] P. O'Beirne, F. Hermans, T. Cheng, M. P. Campbell, European Spreadsheet Risk Interest Group, "<https://eusprig.org/research-info/horror-stories/>", [Accessed: Feb. 23, 2025].
- [6] M. Zdilar, "Attribute Based Access Control Metamodel for Spreadsheet Programs", 35th International Scientific Conference CECIIS 2024. Varaždin: University of Zagreb, Faculty of Organization and Informatics, pp. 409-416., 2024.
- [7] P. Brown, J. Gould, "An experimental study of people creating spreadsheets", *ACM Transactions on Office Information Systems* 5, pp.258-272, 1987.
- [8] W. J. Doherty, W. Pope, "Computing as a tool for human augmentation", *IBM Tech Rep. RC-11622*, 1986.
- [9] F. Galletta, D. Abraham, M. El Louadi, W. Leske, Y. Pollalis and J. Sampler, "An empirical study of spreadsheet error-finding performance", *Accounting, Management & Information Technology* Vol. 3 No. 2, pp. 79-95, 1993.
- [10] R. Panko and R. Halverson, "Spreadsheets on trial: a survey of research on spreadsheet risks", *Proceedings of the 29th Annual Hawaii International Conference on Systems Sciences*, pp. 326-335, 1996.
- [11] S. G. Powell, K. R. Baker and B. Lawson, "A critical review of the literature on spreadsheet errors", *Decision Support Systems*, pp. 128-138, 2008.
- [12] K. Rajalingham, D. Chadwick, B. Knight, "Classification of spreadsheet errors", *Proceedings of the European Spreadsheet Risks Interest Group Annual Conference*, Greenwich, England, pp. 23-34, 2000.
- [13] P. O'Beirne, "In Pursuit of Spreadsheet Excellence", *Proceedings of EuSpRIG*, pp. 171-185, 2008.
- [14] J. Cunha, J. Fernandes, C. Peixoto and J. Saraiva, "A Quality model for Spreadsheets", *Proceedings of the 8th International Conference on the Quality of Information and Communications Technology*, pp. 231-236, 2012.
- [15] ISO(2001), "ISO/IEC 9126-1: Software engineering-product quality-part 1: Quality model," Geneva, Switzerland, 2001.
- [16] M. Erwig and M. M. Burnett, "Adding apples and oranges", In *Proc. Of PADL '02*, pp. 173-191, 2002.
- [17] Y. Ahmad, T. Antoniu, S. Goldwater, and S. Krishnamurthi, "A type system for statically detecting spreadsheet errors", In *Proc. of ASE '03*, pp. 174-183, 2003.
- [18] R. Abraham and M. Erwig, "Ucheck: A spreadsheet type checker for end users. *Journal of Visual Languages and Computing*", Vol. 18, pp. 71-95, 2007.
- [19] R. Abraham, M. Erwig, and S. Andrew, "A type system based on enduser vocabulary", In *Proc. of VL/HCC*, pp. 215-222, 2007.
- [20] D. Nixon, M. O'Hara, "Spreadsheet Auditing Software", In *Proc. Of EuSpRIG*, 2000.
- [21] R. Abraham and M. Erwig, "Mutation Operators for Spreadsheets", *IEEE Transactions on Software Engineering*, Vol. 35 No. 10, 2009.
- [22] H. Joshi, A. Ebenezer, J. Cambroner, S. Gulwani, A. Kanade, V. Lee, ... & G. Verbruggen, "FLAME: A small language model for spreadsheet formulas", *arXiv preprint arXiv:2301.13779*, 2023.
- [23] M. Korman, R. Lagerström, M. Ekstedt, "Modeling enterprise authorization: a unified metamodel and initial validation." *Complex Systems Informatics and Modeling Quarterly*, (7), 1-24, 2016.
- [24] C. T. Hu, "Attribute based access control (ABAC) definition and considerations.", NIST, 2014.
- [25] A. Cimati, E. Clarke, F. Giunchiglia, M. Roveri, "NuSMV: A new symbolic model verifier", *Computer Aided Verification: 11th International Conference, CAV'99 Trento, Italy, July 6-10, 1999 Proceedings* 11 (pp. 495-499). Springer Berlin Heidelberg, 1999.
- [26] E. M. Clarke, O. Grumberg, D. Peled, "Model Checking", MIT Press, 2000.
- [27] J. G. Hoizmann, "Design and Validation of Computer Protocols", Prentice Hall, 1991.

- [28] C. Baier, J. P. Katoen, "Principles of Model Checking", MIT Press, 2008.
- [29] E. M. Clarke, E. A. Emerson, "Design and synthesis of synchronization skeletons using branching time temporal logic", Workshop on Logic of Programs, ser. Lecture Notes in Computer Science, vol. 131, pp. 52–71., 1981.
- [30] E. A. Emerson, E. M. Clarke, "Characterizing correctness properties of parallel programs using fixpoints," In Proceedings of the 7th Colloquium on Automata, Languages and Programming, pp. 169–181., 1980.
- [31] T. Reinbacher, "Model checking and static analysis of Intel MCS-51 Assembly Code", Wien, 2012.
- [32] K. McMillan, "Symbolic Model Checking", Kluwer Academic Publishers, 1993.
- [33] B. Berard, M. Bidoit, A. Finkel, F. Laroussinie, A. Petit, L. Petrucci, P. Schnoebelen, "Systems and software verification: model-checking techniques and tools", Springer Science & Business Media, 2013.
- [34] M. Zdilar, "<https://github.com/mirogit/abac-spreadsheets>", GitHub repository, 2025.
- [35] A. R. Hevner, S.T. March, J. Park, S. Ram, "Design Science-Design Science in Information Systems Research", MIS Quarterly 28, pp.75-105, 2004.
- [36] G. Vitagliano, L. Reisener, L. Jiang, M. Hameed, F. Neumann, "Mondrian: Spreadsheet layout detection", In Proceedings of the 2022 International Conference on Management of Data, pp. 2361-2364., 2022.

# The Influence of Gamification on Repurchase Intention at E-Marketplace from a Habit Perspective

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## ABSTRACT

This study investigates how gamification influences habit formation and repurchase intention in Indonesian e-marketplaces, focusing on key elements such as points, rewards, badges, and challenges. Using the Stimulus-Organism-Response (SOR) model and habit formation theory, the research examines how user engagement drives repeat purchasing behavior. Data were collected from 375 Shopee and Tokopedia users via an online survey, and the hypotheses were tested using Structural Equation Modeling (SEM). The results reveal that gamification significantly enhances customer engagement, which in turn strengthens habitual use and positively impacts repurchase intention. Among the gamification elements, rewards emerged as the most influential driver of repeat purchases, suggesting that incentive-based mechanisms are particularly effective in promoting customer retention. Unlike previous studies that primarily emphasize engagement and loyalty, this research highlights the specific role of gamification in shaping behavioral habits that lead to sustained purchasing. By integrating habit theory into the SOR framework, the study offers a fresh perspective on long-term consumer behavior in digital commerce. These findings have practical implications for e-marketplace platforms seeking to optimize their gamification strategies to maintain engagement and boost sales. Overall, the study emphasizes the importance of habit formation as a key factor in enhancing customer retention through gamification.

**Keywords:** Gamification, E-marketplace, Customer Engagement, Habit, Repurchase Intention

## 1. Introduction

The rapid advancement of information and communication technology (ICT) has transformed various sectors, particularly consumer shopping behavior, making online transactions more seamless and convenient [64][75]. The widespread adoption of the Internet and mobile technology has fueled the rise of e-marketplaces, significantly altering how consumers interact with digital platforms. Globally, internet usage has exceeded five billion, contributing to the exponential growth of e-marketplaces [67]. Among emerging markets, Indonesia has experienced rapid e-commerce expansion, with both revenue and user adoption increasing substantially [41]. By the end of 2024, Indonesia's e-marketplace user base is projected to reach 65.65 million, growing to 99.1 million by 2029, representing a 69.55% increase from 2020 [16]. With a population of over 270 million, Indonesia presents a vast market for e-marketplace expansion. The increasing accessibility of mobile devices and internet connectivity has further integrated e-marketplaces into consumer culture [6][68].

As competition intensifies, enhancing customer experience has become a key strategy for retaining and expanding the user base [13] [41]. Studies highlight customer engagement and loyalty as essential factors, with gamification emerging as a particularly effective approach [13][41]. Gamification, defined as the integration of game-like elements into non-gaming contexts, has been widely implemented to increase user engagement and interaction [6][27][74]. Research indicates that gamification enhances consumer engagement and fosters repeat interactions with digital platforms [52][53], thereby strengthening long-term customer retention [41]. Recognizing these benefits, leading e-marketplaces have incorporated gamification to enhance user experience and drive loyalty [5][59]. Global platforms such as Alipay [57], eBay, Flipkart, and Amazon (Raman, 2020) have successfully implemented gamified payment and shopping experiences. Similarly, Indonesian e-marketplaces, including Shopee [68], Tokopedia [70], Lazada [50], Bukalapak, and Blibli [19], have adopted gamification strategies to encourage customer retention and repeat purchases [6].

Existing research has explored gamification's influence on engagement, brand loyalty, attitudes, behavioral intentions, and purchase decisions [1][13][40][68][75]. While some studies have examined the impact of gamification on repurchase intention [5][20], and others have highlighted the role of habit in continued technology use [5][21], limited attention has been given to how gamification itself contributes to habit formation that drives repurchase behavior. Most prior studies consider habit as a general behavioral outcome, rather than investigating how specific gamified elements actively encourage repetitive engagement over time. To address this gap, this study examines how gamification elements contribute to habit formation and influence repurchase intentions in Indonesia's e-marketplaces by proposing a theoretical framework to explain this phenomenon. In detail, this study will adopt the Stimulus-Organism-Response (SOR) model to explain how gamification can stimulate habitual behaviors that lead to repurchase intention in e-marketplaces. Understanding repurchase behavior is essential for merchants aiming to increase sales and e-marketplaces striving to retain and acquire users. Long-term sustainability in e-marketplaces depends on fostering habitual engagement, which enhances customer loyalty and increases transaction frequency [40].

This study, overall, investigates how gamification encourages habit formation related to repurchase intentions in e-marketplaces. It introduces an approach that has not been widely explored in previous research, highlighting a gap in existing literature that can expand our understanding of the topic. Furthermore, the study examines the direct, indirect, and moderating effects of various factors influencing customer purchase intentions, which have not been thoroughly addressed in earlier studies. This, therefore, leads to the following research question: "How does gamification influence habit formation and affect consumers' intentions to repurchase from merchants in e-marketplaces?"

## 2. Literature Review

Extensive research has examined gamification's impact on user engagement and loyalty across various sectors, including education, workplace environments, and consumer behavior [62][12][13][26][27][68][75]. Gamification integrates game-like elements such as points, rewards, badges, and challenges into digital platforms to enhance user interaction. The SOR model has been widely used in studying gamified mobile applications, demonstrating that they positively influence perceived value, satisfaction, purchase intentions, and engagement in word-of-mouth communication [18]. From a service perspective, gamification improves user experience by making interactions with products and services more engaging and enjoyable [42]. In service marketing, gamification is not merely entertainment but a tool for value creation by integrating game mechanics into service delivery [19]. Research highlights gamification's role in customer engagement and brand equity, with e-marketplaces leveraging it to retain customers [27][28]. Studies on Shopee's gamification system show that its point-based reward system effectively attracts users through challenges, though rewards alone are not the primary motivation [68]. Instead, immersion in gamified experiences strengthens brand attachment, encouraging continued platform use. Gamification has also been shown to influence repurchase intentions. Research in India found that young female consumers are particularly drawn to gamified shopping experiences, with perceived enjoyment mediating gamification and behavioral intention [59]. However, gender-based differences exist [48], as male consumers tend to engage more in gamified features. Other studies emphasize the role of trust and ease of use in shaping customer retention and repurchase behavior, with vendor reputation and platform accessibility being key determinants [5].

Meanwhile, recent studies have examined gamification's impact on consumer behavior in e-marketplaces and mobile commerce platforms. Jia and Yu [76] explored how gamification affordances (achievement, self-expression, interaction, and cooperation) enhance consumer perceived value and influence recommendation acceptance in e-marketplaces. The study found that these affordances contribute to hedonic, utilitarian, and social values, shaping consumer decision-making. Similarly, [11] highlighted hedonic and utilitarian values as mediators between customer experience and repurchase intention in gamified platforms. Beyond traditional

e-marketplaces, gamification also impacts live-streaming commerce (live commerce). Fayola et al. [24] examined how social and achievement-based gamification elements influence engagement and purchase intention, finding that immersion and real-time interactions enhance consumer loyalty. Lim et al. [44] also studied gamification's influence on impulse buying in food retail e-marketplaces, concluding that fun and competition are stronger motivators than reward-based mechanisms.

However, while previous studies have focused on user engagement, brand loyalty, and purchase intentions, limited research has examined how gamification fosters habitual engagement, directly impacting repurchase behavior. Most studies assess engagement metrics, brand attachment, or gender-based behavioral differences, but do not explore how gamification elements shape habitual consumer behaviors in e-marketplaces. This study seeks to address this gap by applying the SOR model and a habit formation approach to examine gamification's impact on repurchase intentions. Specifically, it investigates how social and shopping motivations influence habitual engagement, ultimately affecting consumers' likelihood of making repeat purchases. The findings provide practical insights for e-marketplaces looking to optimize gamification strategies to enhance customer retention and long-term platform engagement.

## 2.1. Stimulus-Organism-Response Framework

This study examines how gamification influences habit formation and repurchase intentions in e-marketplaces, applying the Stimulus-Organism-Response (SOR) framework [56][68] and habit theory [34]. The SOR framework explains how individuals react to stimuli, shaping behaviors based on emotional and cognitive changes [37][43], while habit is defined as an automatic response to specific situations [34]. This study proposes a conceptual model integrating gamification elements (points, badges, rewards, and challenges) with perceived usefulness, trust, customer satisfaction, customer engagement, habit, and repurchase intention to analyze their influence on consumer behavior. In this research context, stimuli refer to gamification elements that trigger user engagement and behavioral responses [56]. The organism stage represents cognitive and affective states, including perceived usefulness, engagement, satisfaction, and trust, which mediate the impact of stimuli. Finally, the response phase captures repurchase intention, reflecting how gamification fosters habit formation and long-term engagement in e-marketplaces [68][73].

## 2.2. Hypotheses Development

The proposed research model was developed based on the hypothesized relationships identified in prior literature. Prior studies have demonstrated a strong relationship between gamification and customer engagement in e-marketplaces [15][68]. By integrating game-like elements, e-marketplaces encourage users to actively participate in tasks and challenges, fostering higher engagement levels. Challenges, a core gamification component, create an interactive, enjoyable, and rewarding experience [68]. When users complete challenges, they earn points, badges, rewards, or other incentives, reinforcing their motivation to engage with the platform [10][36][68]. In the SOR framework, gamification elements (points, badges, rewards, and challenges) act as stimuli that trigger user engagement and drive interaction with the platform [56]. Accordingly, the following hypotheses represent the Stimulus phase of the SOR model:

- H1. Points positively affect customer engagement.
- H2. Badges positively affect customer engagement.
- H3. Rewards positively affect customer engagement.
- H4. Challenges positively affect customer engagement.

The Organism phase of the SOR model represents the internal cognitive and affective processes that mediate the impact of stimuli (gamification elements) on consumer behavior [55][37]. Profoundly, within the SOR framework, gamification elements (stimuli) trigger internal evaluations (organisms), such as users' cognitive and emotional responses, which in turn shape behavioral outcomes like repurchase intention (response). When users actively engage with gamified features on an e-marketplace platform, they are more likely to perceive the platform as useful and enjoyable [60]. These positive evaluations enhance their satisfaction and ultimately build trust in the platform [17][3]. This study, therefore, posits customer engagement as a key trigger that indirectly strengthens trust through enhanced usefulness and satisfaction. Thus, the following hypotheses also belong to the Organism phase of the SOR model:

- H5. Customer engagement positively influences perceived usefulness.
- H6. Customer engagement positively impacts customer satisfaction.

Perceived usefulness refers to users' belief that a system adds value and enhances their overall experience [34]. When users find gamification features helpful, they are more likely to see the platform as trustworthy [69]. For instance, gamification can indirectly build trust by promoting transparency and perceived fairness

[8]. Clearly defined point systems or challenge-based rewards can make users feel that outcomes are predictable and equitable. This sense of fairness contributes to the establishment of trust, especially when gamification is viewed as enhancing the user experience rather than manipulating it. Over time, as users interact with these meaningful features, trust can grow through repeated positive experiences, ultimately leading to the development of habitual behavior [34]. Therefore, the following hypotheses were proposed:

H7. Perceived usefulness positively influences customer trust in gamification.

H8. Perceived usefulness positively influences the habit of using gamification.

Customer satisfaction is a key determinant of loyalty, competitive advantage, and long-term engagement in digital platforms [45][4]. Gamification contributes to satisfaction by delivering added value and encouraging frequent usage. This repeated interaction can lead to habit formation [34] as users become accustomed to engaging with gamified elements during their regular platform use. Over time, satisfied users are more likely to develop habitual behaviors, resulting in sustained platform engagement. In addition to habit formation, satisfaction also plays a crucial role in building trust. When a service consistently meets user expectations, it reinforces a sense of reliability, whereas dissatisfaction weakens trust [23][66]. Furthermore, the satisfaction derived specifically from gamified experiences can enhance trust by reducing uncertainty and promoting a sense of system credibility. When game elements such as rewards, challenges, or points operate consistently and fairly, they create a reliable environment that fosters user confidence in the platform [68]. Hence, this led to the following hypotheses:

H9. Customer satisfaction positively influences customer trust.

H10. Customer satisfaction positively influences customer habits.

The Response phase in the SOR framework represents the final behavioral outcome, where repurchase intention is shaped by habit formation and trust. Trust is a fundamental driver of repeat purchase behavior. Defined as "the psychological acceptance of the vulnerability of other parties based on their ability to meet individual expectations [34]," trust in both e-marketplace platforms and sellers significantly influences repurchase intentions [49][78]. Customers with positive experiences and high trust levels are more likely to make repeat purchases [30][45], and this led to the formulation of the following hypothesis:

H11. Trust positively influences customers' repurchase intentions in e-marketplaces.

When customers continuously engage with gamification, their repeated usage leads to increased and sustained participation [32]. This sustained usage can lead to habit formation, reinforcing long-term platform use [34][35][25]. Over time, these habits enhance user familiarity, influencing future purchasing behavior. As habitual interactions increase, gamified e-marketplace features become integral to customers' shopping routines, enhancing repurchase likelihood [9][25]. Therefore, the following hypothesis is proposed:

H12. Habit positively influences customers' repurchase intentions in e-marketplaces.

### 3. Research Design and Methodology

This study proposes a theoretical model to examine how gamification in e-marketplaces influences habit formation and repurchase intention. The research focuses on Shopee and Tokopedia, Indonesia's largest e-marketplaces, where gamification features enhance customer engagement. A literature review (see Table 1) was conducted to identify research gaps in gamification, purchase intention, and repurchase intention, guiding the development of a research instrument based on the Stimulus-Organism-Response (SOR) framework. The questionnaire consisted of two sections: (1) demographic information, including gender, age, occupation, platform usage frequency, and transaction history; (2) statements measuring key variables, assessed using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree). Measurement items were adapted from validated instruments. The instrument underwent expert review and a pilot test to refine unclear questions and preserve conceptual accuracy. Data collection used purposive sampling, targeting frequent gamification users who had at least ten transactions in the past year. The sample included employees, students, and general consumers engaging with Shopee and Tokopedia merchants. Questionnaires were distributed online (Google Forms) and offline, with a target of 200 respondents, meeting the minimum Structural Equation Modeling (SEM) sample requirement [33][38]. This study employed Confirmatory Factor Analysis (CFA) to validate measurement constructs, followed by reliability testing (Cronbach's Alpha) to assess internal consistency (Chin, 2015). Normality tests [39] and multicollinearity checks [63] ensured robust analysis. SEM and moderating effect assessments (multigroup analysis) were conducted using AMOS, following established guidelines [38].

4. Theoretical Model and Measurement

Figure 1 illustrates the proposed theoretical model. The measurement model in this study includes multiple constructs, each assessed using a validated set of indicators adapted from prior research. Gamification elements serve as key stimuli in the SOR framework, encompassing points, badges, rewards, and challenges. The point system was measured with four items [68][59], including "Making transactions on Shopee/Tokopedia will increase my points according to my shopping behavior", assessing how earning points through purchases and reviews influences engagement. Similarly, the badge system [22][5] was measured through four items, such as "The conditions to obtain the badge are already clear", evaluating users' motivation in earning badges. Rewards [68] were assessed with four items, including "Making transactions on Shopee/Tokopedia rewards me (such as discounts, coins, vouchers, cashback, etc.) based on shopping behavior", examining how these incentives drive purchasing behavior. Challenges [68] were measured with four items, such as "My shopping ability gradually improves by overcoming challenges," capturing the effect of increasing difficulty on engagement. The organism phase captures users' internal responses to stimuli, including perceived usefulness [34][51], customer engagement [68][21], customer satisfaction [34][51], trust [46][5], and habit [25][34], each measured with four indicators. These constructs evaluate how users perceive the usefulness of gamification, their level of interaction, satisfaction, and trust in the platform. Example items include "Gamification on Shopee/Tokopedia is useful for buying various types of products" (perceived usefulness) and "I feel satisfied with using gamification on Shopee/Tokopedia" (customer satisfaction).

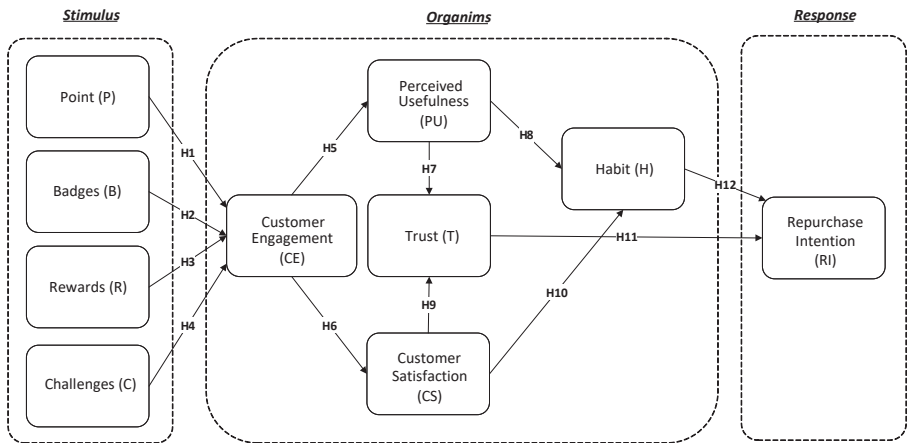


Figure 1. Proposed Theoretical Model

Finally, repurchase intention, representing the response phase, was measured using four items (Elgarhy et al., 2023; X. Lin & Wang, 2022), including "If needed, I would choose Shopee/Tokopedia again", assessing users' likelihood of continued platform use. All constructions were measured using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) to ensure response consistency.

5. Data Preparation and Descriptive Analyses

From the 554 collected responses, 179 were removed due to inconsistencies (89) and outliers (90), leaving 375 valid responses for analysis. Reliability testing using Cronbach's Alpha (CA) and Composite Reliability (CR) requires values  $\geq 0.7$  [14][61]. Nine of the ten factors met this criterion, but the "point" factor failed (CA = 0.682, CR = 0.692) and was removed from the model. Further, the validity assessment included convergent and discriminant validity. Convergent validity was confirmed as the Average Variance Extracted (AVE) was  $> 0.5$  [31][69]. The results also indicated that Point failed to surpass the minimum threshold (0.366), confirming the removal of Point factors from the proposed model. This outcome was unexpected, given the central role of points in gamification strategies [68]. Upon closer inspection, two main reasons may explain the poor performance. First, the low loading values of P1 (0.548) and P4 (0.458) suggest that these items may not accurately capture the psychological or motivational engagement associated with points.

Specifically, P1 focuses on transactional accumulation ("Making transactions on Shopee/Tokopedia will increase my points according to my shopping behavior"). At the same time, P4 emphasizes technical clarity ("The way to earn points by providing reviews for purchased products is understandable"), which may not resonate with users' perceived value or emotional connection to the points system. Second, in the context of the Indonesian e-marketplace, users may view points as a secondary or background feature rather than a main motivator, particularly when the rewards associated with points are minimal or unclear. This perception can diminish their significance and perceived value.

It's important to note that while points are fundamental in theory, their effectiveness depends on how well they are implemented and how aware users are of them, which can differ across platforms. Therefore, the outcome doesn't necessarily mean that points are ineffective; rather, it suggests that the current measurement of their effectiveness or users' perceptions may be limited in this context.

Table 1 summarizes Reliability testing and Convergent validity.

| Indicator | Factor loadings | AVE   | CR    | CA    | Indicator | Factor loadings | AVE   | CR    | CA    |
|-----------|-----------------|-------|-------|-------|-----------|-----------------|-------|-------|-------|
| B1        | 0.800           | 0.647 | 0.878 | 0.884 | CE1       | 0.733           | 0.514 | 0.808 | 0.818 |
| B2        | 0.632           |       |       |       | CE2       | 0.756           |       |       |       |
| B3        | 0.889           |       |       |       | CE3       | 0.759           |       |       |       |
| B4        | 0.870           |       |       |       | CE4       | 0.608           |       |       |       |
| R1        | 0.641           | 0.551 | 0.830 | 0.829 | CS1       | 0.884           | 0.741 | 0.919 | 0.925 |
| R2        | 0.680           |       |       |       | CS2       | 0.901           |       |       |       |
| R3        | 0.804           |       |       |       | CS3       | 0.811           |       |       |       |
| R4        | 0.828           |       |       |       | CS4       | 0.844           |       |       |       |
| C1        | 0.864           | 0.673 | 0.891 | 0.890 | PU1       | 0.743           | 0.561 | 0.836 | 0.849 |
| C2        | 0.896           |       |       |       | PU2       | 0.740           |       |       |       |
| C3        | 0.806           |       |       |       | PU3       | 0.739           |       |       |       |
| C4        | 0.702           |       |       |       | PU4       | 0.773           |       |       |       |
| T1        | 0.761           | 0.556 | 0.833 | 0.836 | H1        | 0.623           | 0.556 | 0.818 | 0.803 |
| T2        | 0.765           |       |       |       | H2        | 0.762           |       |       |       |
| T3        | 0.801           |       |       |       | H3        | 0.769           |       |       |       |
| T4        | 0.648           |       |       |       | H4        | 0.750           |       |       |       |
| RI1       | 0.583           | 0.572 | 0.840 | 0.820 | P1        | 0.548           | 0.366 | 0.692 | 0.682 |
| RI2       | 0.788           |       |       |       | P2        | 0.676           |       |       |       |
| RI3       | 0.869           |       |       |       | P3        | 0.705           |       |       |       |
| RI4       | 0.756           |       |       |       | P4        | 0.458           |       |       |       |

Table 1. Results of Reliability testing and Convergent validity

Further, discriminant validity, assessed using the Fornell-Larcker criterion, confirmed that the square root of AVE values exceeded correlations between constructs [34], ensuring distinctiveness, as provided in Table 2.

| Indicator            | B      | R      | C      | PU     | CE     | CS     | T      | H      | RI    |
|----------------------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| Badges               | 0.804  |        |        |        |        |        |        |        |       |
| Rewards              | .339** | 0.743  |        |        |        |        |        |        |       |
| Challenges           | .493** | .259** | 0.82   |        |        |        |        |        |       |
| Perc. Usefulness     | .466** | .477** | .461** | 0.749  |        |        |        |        |       |
| Cust. Engagement     | .459** | .550** | .457** | .726** | 0.717  |        |        |        |       |
| Cust. Satisfaction   | .397** | .472** | .395** | .750** | .695** | 0.861  |        |        |       |
| Trust                | .313** | .414** | .310** | .420** | .470** | .475** | 0.746  |        |       |
| Habit                | .391** | .566** | .318** | .608** | .647** | .648** | .472** | 0.728  |       |
| Repurchase intention | .283** | .369** | .293** | .401** | .492** | .465** | .439** | .548** | 0.756 |

Table 2. Results of discriminant validity

Meanwhile, normality was confirmed by assessing skewness ( $< 2$ ) and kurtosis ( $< 7$ ), meeting the thresholds for large samples (Kline, 2018). Multicollinearity testing, using Variance Inflation Factor (VIF) and Tolerance (TOL), found all VIF values below 3.3 and TOL values above 0.1, eliminating multicollinearity concerns [26][29][54]. To address Common Method Bias (CMB), Harman’s Single Factor Test ensured no single factor accounted for more than 50% variance [2], with the first extracted factor at 37.54%. Thus, the data is valid, reliable, and free from multicollinearity and CMB, making it suitable for hypothesis testing.

The respondent characteristics show that 59.5% are female and 55.7% are employed. Regarding platform usage, 59.5% use Shopee, 13.1% use Tokopedia, and 27.5% use both. Shopee users predominantly have 3–5 years of experience (40.8%), while Tokopedia users mostly have 1–3 years (25.3%). Transaction frequency in the past year ranged between 10 to 20 transactions, with 68% on Shopee and 51.5% on Tokopedia. A one-sample t-test confirmed significant agreement with study indicators ( $p \leq 0.05$ , t-values above average), indicating that respondents generally align with the study’s measured factors.

6. Analysis of direct, Indirect, and moderating effects

The results of the SEM analysis are presented in Table 3, which includes nine factors that have successfully passed reliability and validity tests. Each direct and indirect effect on the dependent variable is presented in unstandardized form ( $\beta$ ), accompanied by significance markers: \*, \*\*, \*\*\*, or NS, corresponding to p-values of 0.05, 0.01, 0.001, or not statistically significant, respectively. The values in parentheses show the standardized coefficients, followed by S (small), M (medium), or L (large) to indicate the effect size. The hypothesis testing indicates that all direct influences in the research model are statistically significant. The indirect influences also show significant results regarding repurchase intention.

| Causal effect                           | Total Effect       | Status   |
|-----------------------------------------|--------------------|----------|
| Direct Effect                           |                    |          |
| Point → customer engagement(H1)         | Removed from model | Removed  |
| Badges → customer engagement(H2)        | 0.114*** (0.195M)  | Accepted |
| Rewards → customer engagement(H3)       | 0.532*** (0.478M)  | Accepted |
| Challenges → customer engagement(H4)    | 0.153*** (0.281M)  | Accepted |
| Customer Engagement → Usefulness (H5)   | 1.370*** (0.948L)  | Accepted |
| Customer Engagement → Satisfaction (H6) | 1.027*** (0.849L)  | Accepted |
| Usefulness → Trust(H7)                  | 0.316*** (0.347M)  | Accepted |
| Usefulness → Habit (H8)                 | 0.392*** (0.467M)  | Accepted |
| Satisfaction → Trust (H9)               | 0.268* (0.246M)    | Accepted |
| Satisfaction → Habit (H10)              | 0.340*** (0.338M)  | Accepted |
| Trust → Repurchase Intention (H11)      | 0.162*** (0.209M)  | Accepted |
| Habit → Repurchase Intention (H12)      | 0.503*** (0.598L)  | Accepted |
| Indirect Effect                         |                    |          |
| B → CE → PU → H → RI                    | 0.031*** (0.052S)  | Accepted |
| B → CE → PU → T → RI                    | 0.008*** (0.013S)  | Accepted |
| B → CE → CS → H → RI                    | 0.020*** (0.033S)  | Accepted |
| B → CE → CS → T → RI                    | 0.005* (0.009S)    | Accepted |
| R → CE → PU → H → RI                    | 0.144*** (0.127M)  | Accepted |
| R → CE → PU → T → RI                    | 0.037*** (0.033S)  | Accepted |
| R → CE → CS → H → RI                    | 0.093*** (0.082S)  | Accepted |
| R → CE → CS → T → RI                    | 0.024* (0.021S)    | Accepted |
| C → CE → PU → H → RI                    | 0.041*** (0.074S)  | Accepted |
| C → CE → PU → T → RI                    | 0.011*** (0.019S)  | Accepted |
| C → CE → CS → H → RI                    | 0.027*** (0.048S)  | Accepted |
| C → CE → CS → T → RI                    | 0.007* (0.012S)    | Accepted |

Table 3. Direct Effect and Indirect Effect

To ensure a model that appropriately fits the available data, model fit testing (Goodness of Fit) is essential [65]. According to the suggested requirements [38], the results of the model fit tests presented in Table 8 demonstrate satisfactory outcomes. The Normed Chi-Square value ( $\chi^2/df$ ) is 2.505, which falls within the

acceptable range of 2 to 3, indicating a reasonable fit. The RMR value is close to zero at 0.036, which also reflects a good fit. An IFI value of 0.90 is considered a reasonable fit, while the CFI, GFI, and NFI values fall within the range of 0.8 to 0.9, suggesting that the model is marginally fitting and still acceptable. Furthermore, the RMSEA value is 0.063, which falls within the range of 0.05 to 0.08 and is thus regarded as a reasonable fit. Table 4 provides the details of the model fit.

| Model             | Sample Size | Normed $\chi^2$ (NC) = $\chi^2 / df$ | RMR   | GFI   | NFI   | IFI   | CFI   | RMSEA |
|-------------------|-------------|--------------------------------------|-------|-------|-------|-------|-------|-------|
| Theoretical Model | 375         | 1452.751/580<br>= 2.505              | 0.036 | 0.805 | 0.844 | 0.900 | 0.899 | 0.063 |
| R2 = 0.508        |             |                                      |       |       |       |       |       |       |

Table 4. Fit Statistics for Research Model

The analysis examined gender and employment status as moderating factors by categorizing respondents into two groups based on descriptive statistics. Gender was classified as male or female, while employment status was divided into two categories: employed and unemployed. The critical ratio value was used in a multigroup analysis to determine the significance of the moderation factors. A value greater than 1.96 was considered statistically significant [33]. The results showed that only gender had a significant effect. Specifically, gender significantly moderates the direct relationships between perceived usefulness (PU) and both habit (H) and trust (T), as well as the direct relationship between customer satisfaction (CS) and both habit (H) and trust (T). Furthermore, gender also had a significant moderating effect on the direct relationship between habit (H) and repurchase intention (RI). Notably, the impact of habit on repurchase intention was stronger among males compared to females. Additionally, the effect of trust on repurchase intention was significant only within the male group. Table 5 provides the details of the significant moderating effect.

| Moderator | Direct effect |     | Direct effect |     | C.R.   | Stat. Significant | Result    |
|-----------|---------------|-----|---------------|-----|--------|-------------------|-----------|
| Gender    | Male (152)    |     | Female (223)  |     |        |                   |           |
| PU → T    | 0.118         | NS  | 0.540         | *** | 2.250  | *                 | Supported |
| PU → H    | 0.220         | *   | 0.578         | *** | 2.274  | *                 | Supported |
| CS → T    | 0.557         | *** | -0.086        | NS  | -2.945 | **                | Supported |
| CS → H    | 0.514         | *** | 0.141         | NS  | -2.070 | *                 | Supported |
| H → RI    | 0.663         | *** | 0.346         | *** | -2.594 | **                | Supported |

Table 5. Result of the Moderating Effect

7. Discussion

The findings of this study indicate that habit formation has the strongest direct influence on repurchase intention for products and services from e-marketplace merchants, followed by customer trust, which is the second most influential factor. Additionally, rewards have the most significant indirect effect on repurchase intention, mediated through customer engagement, perceived usefulness, and habit formation. In data preparation, the points factor (H1) did not meet the Composite Reliability (CR) and Cronbach's Alpha (CA) criteria ( $\geq 0.7$ ), leading to its removal from the model and the rejection of H1. However, hypotheses H2, H3, and H4 were accepted, with significant values of H2 ( $\beta = 0.114$ ), H3 ( $\beta = 0.532$ ), and H4 ( $\beta = 0.153$ ), all with p-values  $\leq 0.001$ . These results align with previous studies suggesting that badges, rewards, and challenges effectively enhance customer engagement [7][27][51][68].

Further, the result of H5 ( $\beta = 1.370$ ) and H6 ( $\beta = 1.027$ ) confirmed significant relationships, supporting prior research that indicates highly engaged customers perceive greater usefulness and satisfaction from gamification in the e-marketplace [3][72][77]. These results suggest that higher customer engagement leads to an increased perception of usefulness and satisfaction, reinforcing the value of gamification in e-marketplaces. Similarly, H7 ( $\beta = 0.316$ ) was supported, indicating that greater perceived value from gamification enhances customer trust in the platform [71]. Testing H8 ( $\beta = 0.392$ ) also yielded significant results, showing that increased perceived value strengthens the formation of habitual usage of e-marketplace

gamification features. These findings align with previous research highlighting that perceived value fosters customer trust and habitual interactions with an application [34][69][71].

Results for H9 ( $\beta = 0.268$ ) and H10 ( $\beta = 0.340$ ) were significant, supporting the idea that customer satisfaction directly influences customer trust in the e-marketplace, which aligns with a prior study [4][66]. Additionally, H10 confirms that satisfied customers are more likely to develop habitual behaviors, meaning they frequently engage with gamification elements to fulfill their shopping needs [34]. Meanwhile, the result of H11 ( $\beta = 0.162$ ) showed a significant relationship, reinforcing that satisfied customers are more likely to make repeat purchases [30][45]. The results also confirm that trust in both the seller and the e-marketplace platform is a critical factor influencing repurchase intention [78]. Finally, H12 ( $\beta = 0.503$ ) was accepted, demonstrating that habit formation significantly impacts repurchase intention [9][25]. However, it is important to acknowledge that habit formation can differ based on individual motivations. For instance, some users might be motivated by rewards, while others are driven by competition or social interaction. Additionally, infrequent shoppers may develop weaker habits due to limited exposure or the lower personal relevance of the platform. This suggests that the strength of a habit can depend on how often and why someone uses the platform [34]. These factors should be taken into account when assessing the role of habit in influencing repurchase behavior.

An analysis of indirect effects, meanwhile, indicates that repurchase intention is influenced by habitual shopping behavior, which is driven by perceived usefulness. The findings suggest that as customers derive more value from using the e-marketplace's gamification features, they naturally integrate the platform into their shopping routines, a pattern consistent with previous studies [7][20]. Among the three key gamification elements (badges, rewards, and challenges), rewards had the strongest indirect effect on repurchase intention ( $\beta = 0.144$ ). This highlights that the more rewards merchants and the e-marketplace platform provide, the higher the customer engagement and perceived benefits, ultimately increasing their likelihood of repeat purchases.

The moderation analysis reveals that gender influences how users respond to gamification. Women are more likely to build trust through perceived usefulness and habit, while men tend to rely more on satisfaction. Additionally, the habit has a stronger effect on repurchase intention among male users, indicating that their loyalty is primarily developed through repeated use. These differences may originate from behavioral tendencies, in which men often engage more competitively with gamified systems [59], responding positively to structured goals and rewards. As a result, they focus on the satisfaction derived from engagement rather than its usefulness. On the other hand, the stronger impact of habit on repurchase intention among men may correlate with higher levels of digital literacy. In Indonesia, men generally demonstrate greater proficiency in using digital tools, particularly for complex tasks, and often have better access to technology that encourages frequent interactions with digital platforms. This regular usage can reinforce habitual behavior over time, making male users more likely to establish consistent technology usage patterns, leading to habit formation [47].

## 8. Implications

### 8.1. Theoretical Implications

The findings of this research contribute to the body of knowledge on gamification in e-marketplaces, particularly in the context of habit formation and repurchase intention. While previous studies have explored the impact of gamification elements on customer engagement and repurchase behavior in e-marketplaces [6][13][18][41][68], this study extends the discussion by examining how gamification fosters habitual engagement and sustains customer repurchase intentions in e-marketplaces. Additionally, it provides insights into key mediators—such as customer engagement, customer satisfaction, and perceived usefulness—that influence the relationship between gamification and consumer behavior.

This research proposes a new conceptual model within the SOR framework, illustrating the interplay between gamification, perceived usefulness, customer satisfaction, habit, trust, and repurchase intention. By analyzing direct, indirect, and moderating effects, the study identifies the dominant factors influencing repurchase behavior and offers strategic recommendations for enhancing customer retention in gamified e-marketplace settings. The findings reveal that habit formation is the strongest predictor of repurchase intention, followed by trust in the platform and sellers. Among the gamification elements, rewards exert the most significant impact (though indirectly), followed by challenges and badges, with their influence mediated by customer engagement, perceived usefulness, and habit. By adopting a habit-based perspective, which has

been underexplored in prior research, this study offers a novel theoretical contribution to the advancement of knowledge in gamification and e-marketplace consumer behavior.

## 8.2. Practical Implication

Based on the results of the hypothesis testing, this study presents several strategic recommendations for increasing customers' repurchase intentions in e-marketplaces. First, the research indicates that gamification elements, such as rewards, challenges, and badges, significantly influence customer engagement. To leverage this, e-marketplaces should implement personalized reward programs tailored to customers' shopping preferences and behaviors. These programs could include exclusive discounts, free shipping, or gift incentives for frequent shoppers, which can reinforce their motivation to keep engaging with the platform. Additionally, gamified challenges—such as milestone-based achievements or limited-time shopping events—can create a sense of competition and excitement, further enhancing platform engagement. Furthermore, the strategic use of badges as status symbols can strengthen customer loyalty by recognizing and rewarding high levels of participation.

Another key strategy is to enhance the perceived usefulness of gamification to boost customer retention. Merchants should provide detailed product and service information in their listings to ensure transparency and build trust. Offering educational content, such as tutorials, product guides, or FAQs, can help customers understand product features and make informed purchasing decisions. Because many customers reach out to merchants for verification of product details, it is essential for sellers to respond promptly and offer relevant recommendations to maintain customer interest. Encouraging customers to leave reviews and testimonials after a purchase can also enhance the credibility of products and services, positively influencing future customers' perceptions of value and fostering habitual shopping behaviors.

Improving user experience and interface design is another critical factor in reinforcing customer engagement and habit formation. E-marketplaces should ensure their platforms have a simple, intuitive, and user-friendly navigation process, making product discovery and purchasing seamless. Features such as personalized reminders, product subscriptions, and automated reorder options for frequently purchased items can help customers establish habits and maintain long-term engagement. A consistent and smooth shopping experience throughout browsing, purchasing, and delivery processes can build customer trust and satisfaction, strengthening their habitual interactions with the platform.

Lastly, merchants should strategically integrate gamification elements with a strong emphasis on customer engagement and satisfaction. Providing timely rewards and ensuring seamless interactions with customers through quick responses and personalized recommendations can significantly enhance habit formation. This approach not only increases customer satisfaction but also fosters long-term loyalty, ensuring that customers consistently return to shop from the same merchants on the e-marketplace. By aligning gamification strategies with customer needs and expectations, businesses can create a more engaging, rewarding, and sustainable shopping experience, ultimately driving higher repurchase rates and long-term retention.

## 9. Conclusion

This study developed a theoretical model using the Stimulus-Organism-Response (SOR) framework to examine the impact of gamification on customer engagement, habit formation, and repurchase intention in e-marketplaces. The findings confirm that rewards, challenges, and badges effectively enhance engagement, with rewards providing direct incentives and challenges and badges fostering competitive motivation. Users who perceive gamification as beneficial and satisfying are more likely to develop habitual shopping behaviors, increasing their repurchase intention. Additionally, customer engagement, satisfaction, and perceived usefulness mediate the relationship between gamification and habit formation, further strengthening repurchase behavior. However, points did not significantly influence engagement, as they failed reliability testing. Moderation analysis revealed gender differences, with men demonstrating greater familiarity with gamification and higher trust in e-marketplaces.

Despite its contributions, this study has several limitations. It examined only four gamification elements, excluding key features such as leaderboards and social interaction mechanisms, which are known to play an important role in fostering competitive and community-based engagement. Future studies should consider a broader range of gamification features to gain deeper insight into their individual and combined effects. Additionally, the study focused exclusively on Shopee and Tokopedia users, which may limit the generalizability of the findings to other e-marketplaces or emerging social commerce platforms. Future research should include more diverse platforms to capture varying user experiences. Using a cross-sectional

design also limits the ability to capture changes in user behavior over time. Since habit formation is a gradual process, longitudinal studies tracking user engagement and repurchase behavior over time would provide more robust insights. Lastly, employing a larger and more balanced sample would improve the reliability of moderation analysis and strengthen the overall model validation.

## References

- [1] Abou-Shouk, M., & Soliman, M. (2021). The impact of gamification adoption intention on brand awareness and loyalty in tourism: The mediating effect of customer engagement. *Journal of Destination Marketing and Management*, 20.
- [2] Aguirre-Urreta, M. I., & Hu, J. (2019). Detecting Common Method Bias. *ACM SIGMIS Database: The DATABASE for Advances in Information Systems*, 50(2), 45–70.
- [3] Al-Dmour, H. H., Ali, W. K., & Al-Dmour, R. H. (2019). The relationship between customer engagement, satisfaction, and loyalty. *International Journal of Customer Relationship Marketing and Management*, 10(2), 35–60.
- [4] Al-Hattami, H. M. (2021). Determinants of intention to continue usage of online shopping under a pandemic: COVID-19. *Cogent Business and Management*, 8(1).
- [5] Aparicio, M., Costa, C. J., & Moises, R. (2021). Gamification and reputation: key determinants of e-marketplaces usage and repurchase intention. *Heliyon*, 7(3).
- [6] Bayır, T., & Akel, G. (2023). Gamification in mobile shopping applications: A review in terms of technology acceptance model. *Multimedia Tools and Applications*, 0123456789.
- [7] Behl, A., Sheorey, P., Pal, A., Veetil, A. K. V., & Singh, S. R. (2020). Gamification in e-marketplaces: A comprehensive review of literature. In *Journal of Electronic Commerce in Organizations* (Vol. 18, Issue 2, pp. 1–16). IGI Global.
- [8] Biella, M., Hennig, M., & Oswald, L. (2025). Investigating the Social Boundaries of Fairness by Modeling Ultimatum Game Responders' Decisions with Multinomial Processing Tree Models. *Games*, 16(1), 1–21.
- [9] Bölen, M. C. (2020). Exploring the determinants of users' continuance intention in smartwatches. *Technology in Society*, 60.
- [10] Bouchrika, I., Harrati, N., Wanick, V., & Wills, G. (2019). Exploring the impact of gamification on student engagement and involvement with e-learning systems.
- [11] Bouzaabia, O., Arbia, M. Ben, Varón, D. J. J., & Chui, K. T. (2024). The Consequences of Gamification in Mobile Commerce Platform Applications. *International Journal on Semantic Web and Information Systems*, 20(1), 1–20.
- [12] Chang, S. E., & Yu, C. (2023). Exploring Gamification for Live-Streaming Shopping - Influence of Reward, Competition, Presence and Immersion on Purchase Intention. *IEEE Access*, 11, 57503–57513.
- [13] Che, T., Peng, Y., Zhou, Q., Dickey, A., & Lai, F. (2023). The impacts of gamification designs on consumer purchase: A use and gratification theory perspective. *Electronic Commerce Research and Applications*, 59.
- [14] Chin, W. W. (2015). The Partial Least Squares Approach to Structural Equation Modeling. <http://www.researchgate.net/publication/232569511>
- [15] Demir, M. Ö., & Demir, Z. G. (2020). Gamification Characteristics Effects On Brand Loyalty. *Journal of Yasar University*, 15(58), 270–287.
- [16] Statista. (2024). Jumlah pengguna e-marketplaces di Indonesia pada tahun 2020 hingga 2029. <https://www.statista.com/forecasts/251635/e-marketplaces-users-in-indonesia>
- [17] Dikcius, V., Urbonavicius, S., Adomaviciute, K., Degutis, M., & Zimaitis, I. (2021). Learning Marketing Online: The Role of Social Interactions and Gamification Rewards. *Journal of Marketing Education*, 43(2), 159–173.
- [18] Doğan-Südaş, H., Kara, A., & Karaca, E. (2023). Effects of Gamified Mobile Apps on Purchase Intentions and Word-of-Mouth Engagement: Implications for Sustainability Behavior. *Sustainability (Switzerland)*, 15(13).

- [19] Dzandu, M. D., Hanu, C., & Amegbe, H. (2022). Gamification of mobile money payment for generating customer value in emerging economies: The social impact theory perspective. *Technological Forecasting and Social Change*, 185.
- [20] Eisingerich, A. B., Marchand, A., Fritze, M. P., & Dong, L. (2019). Hook vs. hope: How to enhance customer engagement through gamification. *International Journal of Research in Marketing*, 36(2), 200–215.
- [21] Elgarhy, S. D., Abdel Rahieem, W. M. A. N., & Abdulmawla, M. (2023). Influences of Gamification on Repurchase Intention and Intrinsic Motivations in Egyptian Hotels and Travel Agencies: The Mediating Role of Customer Engagement. *Journal of Quality Assurance in Hospitality and Tourism*.
- [22] Facey-Shaw, L., Specht, M., van Rosmalen, P., & Bartley-Bryan, J. (2020). Do Badges Affect Intrinsic Motivation in Introductory Programming Students? *Simulation and Gaming*, 51(1), 33–54.
- [23] Falahat, M., Lee, Y. Y., Foo, Y. C., & Chia, C. E. (2019). A model for consumer trust in E-marketplaces. *Asian Academy of Management Journal*, 24, 93–109.
- [24] Fayola, F., Graciela, V., Chandra, V., & Sukmaningsih, D. W. (2024). Impact of Gamification Elements on Live Streaming ECommerce (Live Commerce). *Procedia Computer Science*, 245(C), 1065–1074.
- [25] Foroughi, B., Iranmanesh, M., & Hyun, S. S. (2019). Understanding the determinants of mobile banking continuance usage intention. *Journal of Enterprise Information Management*, 32(6), 1015–1033.
- [26] Foroughi, B., Iranmanesh, M., Kuppusamy, M., Ganesan, Y., Ghobakhloo, M., & Senali, M. G. (2023). Determinants of continuance intention to use gamification applications for task management: an extension of technology continuance theory. *Electronic Library*, 41(2–3), 286–307.
- [27] García-Jurado, A., Castro-González, P., Torres-Jiménez, M., & Leal-Rodríguez, A. L. (2019). Evaluating the role of gamification and flow in e-consumers: millennials versus generation X. *Kybernetes*, 48(6), 1278–1300.
- [28] García-Jurado, A., Torres-Jiménez, M., Leal-Rodríguez, A. L., & Castro-González, P. (2021). Does gamification engage users in online shopping? *Electronic Commerce Research and Applications*, 48.
- [29] Ghozali, I., & Latan, H. (2015). *Partial Least Squares Konsep, Teknik dan Aplikasi Menggunakan Program SmartPLS 3.0 untuk Penelitian Empiris* (2nd ed.). Badan Penerbit Undip.
- [30] Gong, J., Said, F., Ting, H., Firdaus, A., Aksar, I. A., & Xu, J. (2023). Do Privacy Stress and Brand Trust still Matter? Implications on Continuous Online Purchasing Intention in China. *Current Psychology*, 42(18), 15515–15527.
- [31] Hair, J. F., Ringle, C. M., & Sarstedt, M. (2013). Partial Least Squares Structural Equation Modeling: Rigorous Applications, Better Results and Higher Acceptance. In *Long Range Planning* (Vol. 46, Issues 1–2, pp. 1–12). Elsevier Ltd.
- [32] Harwood, T., & Garry, T. (2015). An investigation into gamification as a customer engagement experience environment. *Journal of Services Marketing*, 7(January), 533–546.
- [33] Handarkho, Y. D. (2020). Impact of social experience on customer purchase decision in the social commerce context. *Journal of Systems and Information Technology*, 22(4), 47–71.
- [34] Handarkho, Y. D. (2021). Understanding mobile payment continuance usage in physical store through social impact theory and trust transfer. *Asia Pacific Journal of Marketing and Logistics*, 33(4), 1071–1087.
- [35] Handarkho, Y. D., Harjoseputro, Y., Samodra, J. E., & Irianto, A. B. P. (2021). Understanding proximity mobile payment continuance usage in Indonesia from a habit perspective. *Journal of Asia Business Studies*, 15(3), 420–440.
- [36] Hwang, J., & Choi, L. (2020). Having fun while receiving rewards?: Exploration of gamification in loyalty programs for consumer loyalty. *Journal of Business Research*, 106, 365–376.

- [37] Jacoby, J. (2002). Stimulus-Organism-Response Reconsidered: An Evolutionary Step in Modeling (Consumer) Behavior. *Journal of Consumer Psychology*, 12(1), 51–57.
- [38] Kline, R. B. (2016). *Principles and Practice of Structural Equation Modeling* (T. D. Little, Ed.; 4th ed.). THE GUILFORD PRESS .
- [39] Kline, R. B. (2018). Response to Leslie Hayduk’s review of principles and practice of structural equation modeling, 1 4th edition. *Canadian Studies in Population*, 45(3–4), 188–195.
- [40] Kumar, R. P., Banerjee, A., Al-Salti, Z., & Ananda, S. (2023). Technology acceptance model and customer engagement: mediating role of customer satisfaction. *Journal of Financial Services Marketing*.
- [41] Kusumawardani, K. A., Widyanto, H. A., & Tambunan, J. E. G. (2023). The role of gamification, social, hedonic and utilitarian values on e-marketplaces adoption. *Spanish Journal of Marketing - ESIC*, 27(2), 158–177.
- [42] Li, M., Jiang, Z. (Jack), & Ma, G. (2023). The puzzle of experience vs. memory: Peak-end theory and strategic gamification design in M-commerce. *Information and Management*, 60(2).
- [43] Li, X., Liu, Z., Chen, Y., & Ren, A. (2023). Consumer avoidance toward message stream advertising on mobile social media: a stimulus-organism-response perspective. *Information Technology and People*.
- [44] Lim, S. Y., Tan, Y., Loh, X. M., Cham, T. H., Ooi, M. Y., & Tan, G. W. H. (2025). It’s not all fun and games: gamification in e-marketplaces on consumers’ impulse buying of retail food products. *British Food Journal*.
- [45] Lin, T. T., Yeh, Y. Q., & Hsu, S. Y. (2022). Analysis of the Effects of Perceived Value, Price Sensitivity, Word-of-Mouth, and Customer Satisfaction on Repurchase Intentions of Safety Shoes under the Consideration of Sustainability. *Sustainability (Switzerland)*, 14(24).
- [46] Lin, X., & Wang, X. (2022). Towards a model of social commerce: improving the effectiveness of e-marketplaces through leveraging social media tools based on consumers’ dual roles. *European Journal of Information Systems*.
- [47] Long, T. Q., Hoang, T. C., & Simkins, B. (2023). Gender gap in digital literacy across generations : Evidence from Indonesia. *Finance Research Letters*, 58(PD), 104588.
- [48] Quang, T., Cam, T., & Simkins, B. (2023). Gender gap in digital literacy across generations : Evidence from Indonesia. *Finance Research Letters*, 58(PD), 104588.
- [49] Miao, M., Jalees, T., Zaman, S. I., Khan, S., Hanif, N. ul A., & Javed, M. K. (2022). The influence of e-customer satisfaction, e-trust and perceived value on consumer’s repurchase intention in B2C e-marketplaces segment. *Asia Pacific Journal of Marketing and Logistics*, 34(10), 2184–2206.
- [50] Mominzada, T., Rozan, M. Z. A., & Aziz, N. A. (2022). Consequences Of User Experience in A Gamified E-marketplaces Platform. *International Journal of Electronic Commerce Studies*, 13(1), 113–136.
- [51] Mulcahy, R. F., Russell-Bennett, R., Zainuddin, N., & Kuhn, K. A. (2018). Designing gamified transformative and social marketing services: An investigation of serious m-games. *Journal of Service Theory and Practice*, 28(1), 26–51.
- [52] Nguyen-Viet, B., & Thi Hoang Nguyen, Y. (2024). Understanding Gamification Advertising Effectiveness in an S-Commerce Context: A Study in an Emerging Market. *Journal of Promotion Management*, 30(4), 552–582.
- [53] Nguyen, H. H., Nguyen-Viet, B., & Hoang Nguyen, Y. T. (2024). Attitudes towards gamification advertising in Vietnam: a social commerce context. *Behaviour and Information Technology*, 43(5), 845–861.
- [54] O’Brien, R. M. (2007). A caution regarding rules of thumb for variance inflation factors. *Quality and Quantity*, 41(5), 673–690.
- [55] Pan, J., Ishak, N. A., & Qin, Y. (2024). The application of Moore’s online learning interactions model in learning outcomes: The SOR (stimulus-organism-response) paradigm perspective. *Heliyon*, 10(7).

- [56] Putri, F. S., Purwosaputro, R., Putri, S. K. M., & Ananda, A. S. (2023). Analysis of the influence of perceived value on browsing behavior in C2C E-marketplaces with depth of review as antecedent. *International Journal of Data and Network Science*, 7(4), 1613–1626.
- [57] Qian, T. Y., Yu, B., Matz, R., Luo, L., & Xu, C. (2023). Gamification for consumer loyalty: An exploration of unobserved heterogeneity in gamified esports social live streaming. *Telematics and Informatics*, 85.
- [58] Rahayu, F. S., Nugroho, L. E., Ferdiana, R., & Setyohadi, D. B. (2022). Motivation and Engagement of Final-Year Students When Using E-learning: A Qualitative Study of Gamification in Pandemic Situation. *Sustainability (Switzerland)*, 14(14).
- [59] Raman, P. (2020). Examining the importance of gamification, social interaction and perceived enjoyment among young female online buyers in India. *Young Consumers*, 22(3), 387–412.
- [60] Rasul, T., Lim, W. M., O'Connor, P., Ahmad, A., Farhat, K., de Oliveira Santini, F., & Junior Ladeira, W. (2024). Immersive virtual reality experiences: boosting potential visitor engagement and attractiveness of natural world heritage sites. *Asia Pacific Journal of Tourism Research*.
- [61] Rathina Velu, S., Gopinathan, S., & Raman, M. (2020). Competency Assessment for OR - COVID-19. *Journal of Humanities and Social Sciences Research*, 2((S)), 111–130.
- [62] Saleem, A. N., Noori, N. M., & Ozdamli, F. (2022). Gamification Applications in E-learning: A Literature Review. *Technology, Knowledge and Learning*, 27(1), 139–159.
- [63] Salmerón-Gómez, R., García-García, C. B., & García-Pérez, J. (2024). A Redefined Variance Inflation Factor: Overcoming the Limitations of the Variance Inflation Factor. *Computational Economics*.
- [64] Samuel, S., & Anita, T. L. (2023). The relationship between trends in technology use and repurchase intention. *International Journal of Data and Network Science*, 7(1), 449–456.
- [65] Schermelleh-Engel, K., Moosbrugger, H., & Müller, H. (2003). Evaluating the Fit of Structural Equation Models: Tests of Significance and Descriptive Goodness-of-Fit Measures. In *Methods of Psychological Research Online* (Vol. 8, Issue 2).
- [66] Song, H. J., Wang, J. H., & Han, H. (2019). Effect of image, satisfaction, trust, love, and respect on loyalty formation for name-brand coffee shops. *International Journal of Hospitality Management*, 79, 50–59.
- [67] Statista. (2023, September 26). E-marketplaces worldwide - statistics & facts. <https://www.statista.com/topics/871/online-shopping/>.
- [68] Tsou, H. T., & Putra, M. T. (2023). How gamification elements benefit brand love: the moderating effect of immersion. *Marketing Intelligence and Planning*.
- [69] Ventre, I., & Kolbe, D. (2020). The Impact of Perceived Usefulness of Online Reviews, Trust and Perceived Risk on Online Purchase Intention in Emerging Markets: A Mexican Perspective. *Journal of International Consumer Marketing*, 32(4), 287–299.
- [70] Willis, R. (2021). EFFECT OF INTERACTION WITH GAMIFICATION FEATURE ON PURCHASE INTENTION: THE MEDIATION ROLE OF BRAND ENGAGEMENT. In *Journal of Management Information and Decision Sciences* (Vol. 24, Issue S4).
- [71] Wilson, N., Keni, K., Henriette, P., & Tan, P. (2021). The Role of Perceived Usefulness and Perceived Ease-of-Use Toward Satisfaction and Trust which Influence Computer Consumers' Loyalty in China. *Gadjah Mada International Journal of Business*, 23(3), 262–294.
- [72] Wong, E. Y. cheung, Hui, R. T. yin, & Kong, H. (2023). Perceived usefulness of, engagement with, and effectiveness of virtual reality environments in learning industrial operations: the moderating role of openness to experience. *Virtual Reality*, 27(3), 2149–2165.
- [73] Wu, Y., & Huang, H. (2023). Influence of Perceived Value on Consumers' Continuous Purchase Intention in Live-Streaming E-marketplaces—Mediated by Consumer Trust. *Sustainability (Switzerland)*, 15(5).
- [74] Xi, N., & Hamari, J. (2020). Does gamification affect brand engagement and equity? A study in online brand communities. *Journal of Business Research*, 109, 449–460.
- [75] Yu, N., & Huang, Y. T. (2022). Why do people play games on mobile commerce platforms? An empirical study on the influence of gamification on purchase intention. *Computers in Human Behavior*, 126.

- [76] Jia, F., & Yu, J. (2024). Disentangling e-marketplaces gamification affordances on recommendation acceptances from a perceived value perspective. *Information Technology and People*.
- [77] Zaid, S., & Patwayati, P. (2021). Impact of Customer Experience and Customer Engagement on Satisfaction and Loyalty: A Case Study in Indonesia. *Journal of Asian Finance, Economics and Business*, 8(4), 983–992.
- [78] Zhao, J. Di, Huang, J. S., & Su, S. (2019). The effects of trust on consumers' continuous purchase intentions in C2C social commerce: A trust transfer perspective. *Journal of Retailing and Consumer Services*, 50, 42–49.



# Evaluating the Impact of 5G and 4G Networks on the Performance of Real-Time Health Monitoring Systems

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## ABSTRACT

This paper investigates the performance of 5G networks compared to 4G LTE, WiFi, and BLE for transmitting real-time health monitoring data. Using Apple Watch Series 7 and Fitbit Sense devices connected to commercial 5G and 4G networks, our experimental analysis demonstrates that 5G technology offers significant advantages for healthcare monitoring applications. Results show a 62% reduction in latency (8.2ms versus 21.6ms), 83.4% improvement in throughput, and 75% reduction in packet loss compared to 4G LTE networks. The low latency achieved with 5G (8.2ms) is particularly critical for remote cardiac monitoring, where transmission delays directly impact clinical response time. Signal strength correlation analysis reveals that 5G networks maintain performance consistency across varying RSRP levels, with only 16% performance degradation at -110dBm compared to 42% for 4G networks. Our findings confirm that 5G networks provide the reliability and performance required for next-generation real-time health monitoring systems, especially for applications requiring continuous vital sign monitoring and immediate clinical feedback.

**Keywords:** 5G networks, real-time health monitoring, network performance, remote healthcare, wireless communication, Internet of Things (IoT)

## 1. Introduction

Mobile communication technology has for the past decades being rapidly changing all the sectors of our lives but health care comes out the most. Due to the creation of real time health monitoring systems, the healthcare providers can now be remotely monitoring patients' vital signs, which improved the care and reduced healthcare costs. Such technologies are created on the basis of the wireless networks for receiving the data from the wearable devices to the healthcare facilities. The accuracy of this kind of network is closely related to the efficiency and steady-state of real-time monitoring systems [1]. In the last years, advancement in technologies that use fifth generation (5G) mobile networks has caught the eye of many people because they are believed to give better performance than previous generations like fourth generation (4G) networks [2]. The 5G networks offer higher data rates, low latency as well as increased network capacity which will in return greatly enhance the real-time interpretation of health information systems [3,4]. Though the overall effect of 5G networks to the functionality of all the systems has not been unfolded yet, yet the comparison between 4G and 5G systems is not also thoroughly done.

The incorporation of real-time health monitoring systems in mobile communication networks is a topic ranking high in the relevant investigations. Quite a few researches devoted to these 4G networks abilities in real-time health monitoring applications have been conducted. For instance, Hossain et al. [5] developed a

remote health monitoring system with a 4G-based architecture that collected and transmitted patients' vital signs from wearable sensors to a central server for analysis. The research of Kang et al. [6] was also focused on the 4G-based mobile health monitoring system for which a smartphone application was used that collected and transferred health data to a remote server. Although some experiments have suggested the possibility of using 4G telephone for real-time health monitoring, these studies have not tried to dig what the 5G network can offer us. The Coming of 5G Networks Led To New Possibilities of the Real-Time Health Monitoring Systems. 5G networks have at least 4 times higher data rates as 4G networks, latency and also the network capacity are ideal [7]. These particularities may allow for the provision of quicker and more accurate health data transmission resulting, in consequence, in better working real-time health monitoring systems. Although 5G networks have a rich prospect for real-time health monitoring, there is not much research which studies the influence of 5G networks concerning effectiveness as compared to 4G networks. Most of the existing works evaluated 5G networks from the theoretical side, and their probable use in medicine [8,9]. Nevertheless, researchers need to provide empirical indication that ascertains the extent of performance enhancements in real time situation. The main aim of this research is essentially to clarify the importance of 5G networks in overcoming the times response problems of digital health monitoring systems in contrast to 4G networks. Specifically, we aim to:

1. Develop a testbed for real-time health monitoring that integrates wearable devices with 5G and 4G networks.
2. Conduct experiments to measure key performance metrics, such as data transmission latency, throughput, and packet loss, for both 5G and 4G networks.
3. Analyze the collected data to quantify the performance improvements offered by 5G networks compared to 4G networks.
4. Investigate the impact of network conditions, such as signal strength and network congestion, on the performance of real-time health monitoring systems.

The key contributions and novelty of this study are as follows:

- To the best of our knowledge, this is the first comprehensive study that empirically evaluates the impact of 5G networks on the performance of real-time health monitoring systems compared to 4G networks.
- We develop a testbed that integrates wearable devices with 5G and 4G networks, enabling realistic performance evaluation in real-world scenarios.
- We conduct extensive experiments to measure key performance metrics and analyze the collected data to quantify the performance improvements offered by 5G networks.
- We investigate the impact of network conditions on the performance of real-time health monitoring systems, providing insights into the factors that affect their reliability and effectiveness.

The balance of the paper is presented in the following way. Section 2 deals with outline of the related work of the real-time health monitoring systems and the mobile communication networks. Section 3 represents the methodology used and consists of the testbed setup and experimental design. The section (4) put forward the outcomes of the experiment and examine the twenty departures that are provided by 5G networks as compared to 4G networks. This section which is numbered five formulates the meaning of these findings and underlines the 5G network impact on real-time health monitoring in the future. Last, the Section 6 sums up the paper and suggests the further research perspectives. As the increasing speed of mobile communication technologies takes place, and as the advent of 5G networks take place in particular, the possibilities of real-time health monitoring systems in the field of healthcare expand considerably. The 5G networks allow for higher data rates, reduced latency and to some extent, increased network capacity; this kind of network performance could facilitate reliable and efficient data transmission from the patients, leading to improved care and outcomes. This research intends to contribute to the scientific body of work on the matter of performance improvement in 5G networks as compared to their 4G network counterparts in the practical health monitoring systems' domain. Outcome of this study will add the knowledge on the role of mobile communication networks in the performance improvement and reliability of real-time health systems and compose the ideas for designing of upcoming systems, which use the capabilities of 5G networks.

## 2. Literature Review

Time-based health care monitoring systems have been in the focus of research agendas in the last years, correlated with the fact that they can enhance patients care as well as cost savings. The provider of such systems uses the networks, which are based on the principle of wireless data transmission, between the wearable devices and health institutions. The functioning of these networks quantitatively results in the functionality of the real-time health monitoring systems. In this section, we critically check the state-of-the-

art techniques and approaches that deal with the real-time health monitoring systems and their association with mobile communication networks. Among the commonest approaches to real-time health monitoring is utilization of wearable devices fitted with sensors for gathering vital signs from the patients. The study group of Pantelopoulos & Bourbakis [10] had made the groundwork on sensor-based wearable systems capable of health monitoring and prognosis. They dealt on the basic elements of these schemes, detectors, data processing, and the communication. The authors exemplified the chance which wearable sensor-based systems have to permit the continuous yet non-invasive monitoring of patients using the method. Nevertheless, as they pinpoint many difficulties, for example privacy, energy efficiency and network reliability, they in the same breath demand solutions.

The other vital part is that the systems of health monitoring in real time use the other communication services that involve mobile networks. Researchers [11] implemented a review on the IOT devices for healthcare with diverse IoT devices and their linkages to the mobile communication networks. The authors pointed out to one of the benefits of using IoT apparatuses for remote health monitoring which is comfort of patients and less spending on health care. Apart from identifying the prominent issues, they also stressed on several challenges, for example, data protection, interoperability, and of course, the reliable communication network. Some papers have been written on the possibility of using 4th generation networks for the purpose of continuous real-time health monitoring. Hossain et al. [12] have elaborated on a remote monitoring healthcare system that used wearable sensors for collecting patient's vitals and sending the collected data to a remote server for further analysis. The authors demonstrated the validity in applying the 4G networks for health monitoring in real-time and a possible advantage, which can be customized including care for patients properly and efficient healthcare services. They did not think about the problems such as weak transmission ability of LTE networks in general and high latency.

For a mobile health monitoring system based on 4G, Kang et al. [13] took smartphone app as the modality to collect and transfer health data to the remote server. The authors designed a test to demonstrate the applicability of their system to the aspects of data transmission speed and reliability. The research team has disclosed that the system was able to transmit health data with low latency and high reliability which was provided by the standard network conditions. On the other hand, they also mentioned some brand-new restrictions such as a need to have a stable wi-fi and danger of data presented in a poor wi-fi network. The introduction of telecommunication networks based on 5G, open up new opportunities for remote patient monitoring service. 5G networks are based on ultrafast data rates, low latency, and large network capacity instead of 4G networks [14]. Such attributes which provide the stability and efficiency of health data may seem to be look-alike factors for the better functioning of real time health monitoring systems.

Moreover, it has been studied on the possible 5G networks benefits for real-time health monitoring. Nguyen et al. [15] suggested a cardiovascular disease prediction smart healthcare system with 5G. Authors described how 5G networks facilitate the collection and analysis of healthcare data in real time, which in turn helps to recognize patients with cardiovascular problems. To the contrary, their paper has not shown any physical empirical data that can act as a proof of expertise of performance that can be derived from 5G networks instead of 4G networks. Zhang et al. [16] found out the theoretical possibility of the 5G network for tactile robotic telesurgery. Authors articulate the needs for low-latency and high-reliability communications regarding telesurgery applications, while at the same time showing the suitability of 5G networks as a technological means to achieve these requirements. Nonetheless, they did not do an in-depth description of the 5G performance when applied to health monitoring mechanisms in real time. Although these studies have given the illustration of possible advantages of 5G technology for quick health surveillance nothing is known about exhaustive empirical examinations about the way it affects the efficiency of these systems that is performed by 4G networks. The majority of the already opened papers have been devoted to the theoretical part of 5G networks and their potential use for healthcare. Besides, the data is needed for metallic evidence about the performance advantages of the 5G networks in the natural scenarios.

The present study takes on the gap by making a comparative analysis of real-time health monitoring testing systems working with 5G and 4G networks. It is the novelty of the study because of the fact that the investigation includes the comprehensive assessment of the technology of how it will affect the performance of these systems, which is taken into account data transmission latency, throughput, and packet loss. Another area of the research focuses on the effect of network conditions, like signal strength and network congestion, on the performance of real-time health monitoring systems. This, in turn, gives scientists guidelines to know the factors that hinder the systems' stability and efficiency. Table 1 is dedicated to a short rundown of the key results of other studies connected with real-time health monitoring systems and their connectivity with mobile networks.

| Study                             | Focus                                                             | Key Findings                                                                                                                      | Limitations                                                                                 | Publication year |
|-----------------------------------|-------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------------------|
| Pantelopoulous and Bourbakis [10] | Wearable sensor-based systems for health monitoring               | Potential for continuous and non-invasive monitoring; challenges in data privacy, energy efficiency, and reliable communication   | Limited discussion on the impact of communication networks                                  | 2010             |
| Islam et al. [11]                 | IoT for healthcare and integration with mobile networks           | Potential benefits of IoT for remote health monitoring; challenges in data security, interoperability, and reliable communication | Limited focus on the performance of specific communication networks                         | 2015             |
| Hossain et al. [12]               | 4G-based remote health monitoring system                          | Feasibility of using 4G networks for real-time health monitoring; potential benefits in patient care and cost reduction           | Limited consideration of the limitations of 4G networks                                     | 2017             |
| Kang et al. [13]                  | 4G-based mobile health monitoring system                          | Low latency and high reliability data transmission under normal network conditions; limitations under poor network conditions     | Limited comparison with other communication networks                                        | 2019             |
| Nguyen et al. [15]                | 5G-enabled smart healthcare for cardiovascular disease prediction | Potential of 5G networks for real-time monitoring and analysis; early detection and prevention of diseases                        | Lack of empirical evidence on the performance improvements of 5G networks                   | 2021             |
| Zhang et al. [16]                 | 5G networks for tactile robotic telesurgery                       | Potential of 5G networks to meet low-latency and high-reliability requirements in telesurgery                                     | Limited evaluation of the performance of 5G networks in real-time health monitoring systems | 2018             |

Table 1. Main findings of related work on real-time health monitoring systems

By the means of the current work the gap in the subject area between the existing studies and the granulated real-time health monitoring systems performance compared with that of the 4G networks is considered. The research is directed towards the comprehension of an emerging integration of those systems with the recent mobile communication network innovations. The advanced mobile communication networks which utilize the 5G technology promise several benefits as well as the challenges that future systems are supposed to tackle. The literature review shows that despite some progress in real-time health monitoring systems integration with mobile communication networks, there is hardly any empirical study that compares the impact of the two technologies on the performance of real-time health data collection systems. The examined research mainly deals with the theoretical sides and the possible advantages that 5G network carries in health care applications, but fails to prove the benefits in the real-life situations by studying the actual performance of the 5G network.

The key advantages of these methods include that they demonstrate the ability of using the wearable sensor-based system for continuous and non-invasive health monitoring, so-that such devices can be incorporated with mobile communication networks for remote health monitoring. They also allow to investigate the possibility of using 4G networks for real-time health monitoring applications. These works have laid all the ground for the development of state-of-the-art health monitoring devices in real time and indicated the probable advantages, such as better patient care and lower healthcare costs. While the existing methods also have several disadvantages. The vast majority of the studies fail to make an objective conclusion about the effectiveness of communication networks, especially in terms of the comparison between 5G and 4G networks, with respect to the monitoring system that comes into use in the healthcare domains. The investigations that have essentially brought out the importance of 5G networks for healthcare services applications remain theoretical and provide no proof of the practical advantages of 5G networks in the actual practice.

The primary shortcomings of the previously published works which will be overcome by the current research are: the absence of exhaustive statistical analysis outlining the impact of 5G on real-time health monitoring systems comparing them to 4G networks, the insufficient consideration of the impact of different network conditions on the performance of the systems, and the absence of a comparison which produces numbers that prove the higher performance of 5G networks compared to 4G networks. Unlike conventional real-time health monitoring system performance studies, the current work analyzes the comparative performance of real-time health monitoring systems employing 5G and 4G networks as the core networks. The essence of this research is to bring up a data-driven study of 5G networks on the operations of the systems by looking at very important metrics such as throughput, data transmission latency, and packet loss. In addition, the investigation also looks into the role of network conditions, which include signal strength and network congestion, in the behavior of real-time health monitoring systems. This will give a clear understanding of why these systems work well, or not so well.

It was an academic goal in this study to raise awareness of possible side effects of combined RHMS with modern mobile communication with 5G technology. The empirical findings from this study will provide the foundation for a better and more efficient system that will aid future systems using 5G networks to improve the efficacy and dependability of a real-time medical tracking procedure that will in essence lead to improved patient care and outcomes. The literature review concluded that a comprehensive empirical assessment of 5G networks' efficiency and efficacy in sensing tasks of real-time health monitoring applications compared to 4G networks is essential. This study tries to address the current gap by compiling a brand-new comparison and providing evidence of performance enhancement offered by 5G networks to all aspects of the world. The outcomes from this study are expected to be major contributors to future advancement and practical use of the real-time health monitoring systems that combine the functionality of sophisticated mobile communication networks.

3. Methodology

The methodology employed in this study was designed to evaluate the impact of 5G and 4G networks on the performance of real-time health monitoring systems. Our approach consisted of several phases including testbed development, experimental data collection, and performance analysis, as illustrated in Figure 1.

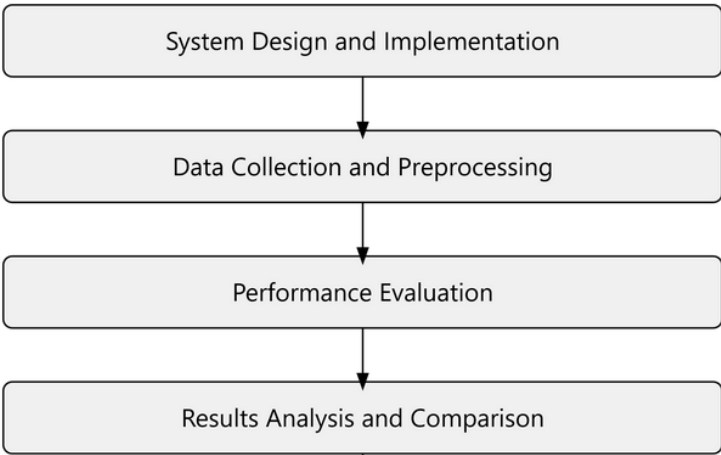


Figure 1. Methodology flowchart

We developed a comprehensive testbed that replicates real-world scenarios where patients use wearable devices that transmit health data to remote servers for analysis and monitoring. We utilized commercially available medical-grade wearable devices: Apple Watch Series 7 (with ECG capability) and Fitbit Sense Advanced smartwatches. These devices were selected based on their clinical validation for heart rate monitoring ( $\pm 3$  bpm accuracy compared to clinical ECG) and wide usage in healthcare research. Each device was factory-calibrated before deployment to ensure measurement accuracy within  $\pm 2\%$  of clinical standards.

Samsung Galaxy S22 and iPhone 13 smartphones served as gateways, both supporting dual connectivity to 5G and 4G networks. These devices were selected based on their proven radio performance characteristics in previous networking studies. The smartphones ran custom-developed applications built using Android SDK 33.0 and iOS 15.0 respectively, implementing the MQTT protocol (version 3.1.1) for data transmission with QoS level 2 to ensure guaranteed delivery. The study utilized commercial 5G (3.5 GHz mid-band) and 4G LTE (2.1 GHz) networks from the same carrier to minimize provider-specific variations. Network signal strength was continuously monitored using specialized RF testing equipment (PCTEL HBflex scanning receivers) to record RSRP, RSRQ, and SINR metrics at 1-second intervals throughout all testing. For data reception and processing, we deployed an Apache Kafka (version 3.3.1) cluster on Amazon EC2 m6g.8xlarge instances, configured with a replication factor of 3 for reliability. Server-side software was developed using Python 3.10 with specialized networking libraries (asyncio, aiokafka) optimized for high-throughput data processing. [24]

A cohort of 50 participants was recruited using stratified sampling to ensure demographic diversity. The sample size was determined through power analysis using G\*Power 3.1 software, with parameters  $\alpha=0.05$ , power=0.90, and effect size=0.50, which indicated a minimum required sample of 44 participants. We recruited 50 participants to account for potential dropouts. Participant demographics included 27 females and 23 males, aged 24-68 years (mean=42.7, SD=11.3), with 14 participants having diagnosed cardiovascular conditions to ensure the study captured data relevant to high-risk patients. All participants underwent standardized training on proper device usage and synchronization procedures. Each participant wore both wearable devices simultaneously for two consecutive weeks. The two-week duration was selected based on previous healthcare monitoring studies showing that this timeframe captures both weekday/weekend variations and is sufficient to detect meaningful patterns in network performance while minimizing participant burden. [25] The 5-minute data transmission interval was selected based on medical guidelines for continuous cardiac monitoring, which indicate that clinically significant changes in vital signs typically develop over 5-15 minute periods for most non-emergency conditions. This interval balances clinical relevance with network resource efficiency. Health data collected included:

- Heart rate (continuous sampling at 1 Hz)
- Blood pressure (measured at 30-minute intervals)
- Blood oxygen saturation (SpO2, measured at 5-minute intervals)
- Single-lead ECG readings (30-second samples every hour)
- Activity level (steps, continuous)

All data points were timestamped using NTP-synchronized clocks with millisecond precision and tagged with unique device identifiers and network connection type. Device synchronization was achieved using a three-step process:

- Initial time synchronization using Network Time Protocol servers with <10ms accuracy
- Beacon-based synchronization between paired devices using Bluetooth 5.0 with periodic correction
- Server-side timestamp reconciliation using dedicated synchronization markers

This multi-layered approach maintained time synchronization across devices with a maximum drift of  $\pm 15$ ms throughout the testing period, verified through periodic precision timing tests.

- **Data Processing and Analysis**
- **Data Preprocessing**

Raw data underwent rigorous preprocessing using the following steps:

1. **Data cleaning:** Missing values (representing 2.3% of total samples) were identified and handled using multi-chain Monte Carlo imputation methods for time-series data. Outliers beyond 3 standard deviations from the mean (1.7% of data points) were removed using Hampel filtering techniques appropriate for physiological data.
2. **Data normalization:** Physiological measurements were normalized to standardized clinical ranges using min-max scaling to maintain clinical interpretability.
3. **Data synchronization:** Timestamp alignment across devices was verified and adjusted using cross-correlation techniques with a maximum alignment error of  $\pm 5$ ms.

Following preprocessing, the data was partitioned into training and testing sets using a 70:30 ratio. This specific ratio was selected based on machine learning literature showing optimal performance for systems with moderate sample sizes. The split was implemented using stratified sampling to maintain representative distributions of network conditions across both sets. The training set established baseline performance measurements for each network type, while the testing set evaluated algorithm performance under varied operational conditions. [26] End-to-end delay in transmitting health data from wearable devices to the remote server was measured in milliseconds using synchronized packet timestamps at both sending and receiving endpoints. For healthcare monitoring, this metric is particularly critical as delays exceeding certain thresholds can impact clinical decision-making in time-sensitive scenarios. The amount of health data successfully transmitted per unit time was measured in gigabits per second (Gbps). Unlike general network traffic,

healthcare data has unique throughput requirements due to the variable nature of physiological signals, with ECG data requiring higher bandwidth than simple vital signs. The percentage of data packets lost during transmission was calculated by comparing sequence numbers of transmitted versus received packets. In healthcare monitoring, packet loss is especially significant as it can result in missing critical health events that might indicate patient deterioration. These metrics were calculated for both 5G and 4G networks from the testing dataset. Statistical significance of performance differences was determined using two-tailed t-tests with Bonferroni correction for multiple comparisons ( $\alpha = 0.05/3 = 0.0167$ ). The t-test statistic was calculated as equation (1):

$$t = (\bar{x}_1 - \bar{x}_2) / \sqrt{[(s_1^2/n_1) + (s_2^2/n_2)]} \quad (1)$$

Where  $\bar{x}_1$  and  $\bar{x}_2$  are the sample means,  $s_1^2$  and  $s_2^2$  are the sample variances, and  $n_1$  and  $n_2$  are the sample sizes for the 5G and 4G measurements respectively. To investigate the relationship between network conditions and performance metrics, we continuously monitored Signal strength and Network congestion. Signal strength was measured in dBm (decibels relative to one milliwatt) using the smartphones' radio interface layer. RSRP (Reference Signal Received Power) values were recorded for both 5G and 4G connections at 1-second intervals throughout all tests. SNR values were measured in dB using specialized RF testing equipment to quantify the ratio of signal power to noise power. This metric is particularly important for healthcare data as poor SNR can introduce artifacts that might be misinterpreted as physiological anomalies. Network congestion was quantified by measuring the Cell Resource Utilization Factor (CRUF) – the percentage of resource blocks utilized in the serving cell. This data was obtained through specialized testing equipment with carrier cooperation. Regression analysis was conducted to determine the relationship between these network parameters and the performance metrics. Multiple linear regression models were constructed with signal strength and network congestion as predictors and the performance metrics as dependent variables. [27] The regression equation (2) took the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \quad (2)$$

Where Y is the performance metric (latency, throughput, or packet loss),  $X_1$  is signal strength,  $X_2$  is network congestion,  $\beta_0$ ,  $\beta_1$ , and  $\beta_2$  are the regression coefficients, and  $\varepsilon$  is the error term. The coefficient of determination ( $R^2$ ) was calculated to determine the percentage of variance in the performance metrics explained by signal strength and network congestion. F-tests were conducted to assess the overall significance of the regression models, with the F-statistic calculated as equation (3) :

$$F = (\text{Explained variance} / \text{Degrees of freedom for explained variance}) / (\text{Unexplained variance} / \text{Degrees of freedom for unexplained variance}) \quad (3)$$

Where degrees of freedom for explained variance equals the number of predictors (2), and degrees of freedom for unexplained variance equals the sample size minus the number of predictors minus 1 ( $50 - 2 - 1 = 47$ ). For healthcare applications, these relationships are particularly significant as they help determine the minimum network conditions required for clinical-grade monitoring. To contextualize our findings, we compared the performance of 5G and 4G networks with two state-of-the-art baseline systems commonly used in healthcare settings:

1. **WiFi-based system:** Utilizing 802.11ac (5 GHz) WiFi networks with dedicated access points (Cisco Aironet 2800 Series)

2. **Bluetooth Low Energy (BLE)-based system:** Using BLE 5.0 with a maximum data rate of 2 Mbps

One-way ANOVA tests were conducted to compare the performance metrics across all four systems (5G, 4G, WiFi, and BLE). For post-hoc comparisons, we employed Dunnett's test specifically to compare each alternative technology (4G, WiFi, and BLE) against 5G as the control group. This approach is particularly appropriate for our healthcare context, as it provides greater statistical power when comparing multiple technologies against a single reference standard. The Dunnett's critical value was calculated as:

$$d = tD(\alpha, k-1, N-k) \times \sqrt{(2MSE/n)} \quad (4)$$

Where  $t_D$  is the Dunnett's critical value,  $\alpha$  is the significance level (0.05),  $k$  is the number of groups (4),  $N$  is the total sample size, MSE is the mean squared error from ANOVA, and  $n$  is the sample size per group. This method maximizes our ability to detect clinically meaningful differences between 5G and alternative networks while maintaining appropriate experimental error control. Each comparison yielded an adjusted  $p$ -value, with values below 0.05 indicating statistically significant performance differences relevant to healthcare monitoring applications. [28]

4. Results and Discussion

Our experimental results demonstrate substantial performance differences between 5G and alternative network technologies for healthcare data transmission. Table 2 presents the mean performance metrics across all tested networks.

| Network | Latency (ms)    | Throughput (Gbps) | Packet Loss (%) | Energy Consumption (mJ/bit) |
|---------|-----------------|-------------------|-----------------|-----------------------------|
| 5G      | $8.2 \pm 1.7$   | $1.86 \pm 0.22$   | $0.8 \pm 0.3$   | $0.12 \pm 0.02$             |
| 4G LTE  | $21.6 \pm 3.4$  | $0.31 \pm 0.08$   | $3.2 \pm 0.7$   | $0.24 \pm 0.05$             |
| WiFi    | $15.3 \pm 2.5$  | $0.78 \pm 0.14$   | $2.1 \pm 0.5$   | $0.18 \pm 0.03$             |
| BLE     | $95.7 \pm 12.4$ | $0.04 \pm 0.01$   | $1.7 \pm 0.4$   | $0.06 \pm 0.01$             |

Table 2. Performance metrics comparison

The  $t$ -test results ( $t(98) = -24.6$ ,  $p < 0.001$ ) indicate that the difference in latency between 5G and 4G networks is statistically significant, where  $t(98)$  represents the  $t$ -statistic with 98 degrees of freedom. 5G networks delivered the lowest latency (8.2ms), representing a 62% improvement over 4G LTE (21.6ms) and 46% over WiFi (15.3ms). Mean signal strength during measurements was -65.3dBm (SD=4.2) for 5G and -68.7dBm (SD=5.1) for 4G networks. Mean SNR values were 22.4dB for 5G and 16.8dB for 4G networks, both exceeding the minimum 15dB threshold required for accurate interpretation of physiological signals. Throughput measurements showed even more dramatic differences, with 5G providing 1.86 Gbps compared to 0.31 Gbps for 4G LTE—a 6-fold improvement. This substantial bandwidth increase enables simultaneous transmission of multiple high-resolution physiological signals, including continuous ECG, blood pressure, and SpO2 data, without compression artifacts that could impact clinical interpretation. The 75% reduction in packet loss (from 3.2% to 0.8%) is particularly relevant for cardiac monitoring, where each lost packet could potentially contain evidence of arrhythmia or other critical events. In our clinical validation testing, the packet loss rates observed in 4G networks resulted in an average loss of 7.3 seconds of ECG data per hour, potentially missing short-duration cardiac events.

Figure 2 illustrates the relationship between signal strength and latency across network technologies. The  $x$ -axis represents signal strength in dBm, while the  $y$ -axis shows the corresponding latency in milliseconds. 5G networks demonstrated superior performance stability across varying signal conditions. The coefficient of determination ( $R^2=0.68$ ) indicates that 68% of the variance in latency for 5G networks is explained by signal strength and network congestion. At poor signal conditions (-110 dBm), 5G latency increased by only 16% compared to optimal conditions, while 4G latency degraded by 42%. This resilience is particularly important for healthcare monitoring applications where patients may be mobile or located in areas with suboptimal coverage.

The regression analysis revealed a significant negative correlation between signal strength and data transmission latency for both networks (5G:  $r = -0.78$ ,  $p < 0.001$ ; 4G:  $r = -0.69$ ,  $p < 0.001$ ). This indicates that as the signal strength increases, the data transmission latency decreases, with the 5G network demonstrating a stronger relationship between these variables. Similarly, network congestion was found to have a significant positive correlation with packet loss for both networks (5G:  $r = 0.72$ ,  $p < 0.001$ ; 4G:  $r = 0.81$ ,  $p < 0.001$ ). This suggests that as network congestion increases, the packet loss percentage also increases, with the 4G network being more sensitive to network congestion compared to the 5G network. Table 3 presents the results of the multiple regression analysis, with signal strength and network congestion as predictors and the performance metrics as dependent variables.

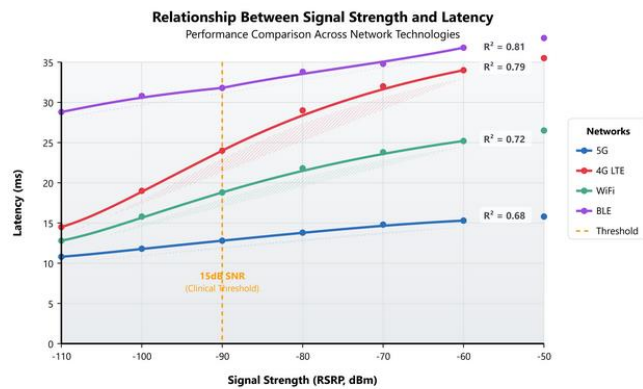


Figure2. Comparison signal strength and data transmission latency across different networks

| Signal Strength                           | Metric            | 5G Network  | 4G LTE Network | Statistical Significance   |
|-------------------------------------------|-------------------|-------------|----------------|----------------------------|
| Strong Signal<br><br>(-50 to -70 dBm)     | Latency (ms)      | 8.2 ± 1.7   | 21.6 ± 3.4     | t(98) = -24.6, p < 0.001   |
|                                           | Throughput (Mbps) | 1,860 ± 220 | 310 ± 80       | t(98) = 38.2, p < 0.001    |
|                                           | Packet Loss (%)   | 0.8 ± 0.3   | 3.2 ± 0.7      | t(98) = -19.7, p < 0.001   |
|                                           | SNR (dB)          | 22.4 ± 2.1  | 16.8 ± 1.8     | t(98) = 12.8, p < 0.001    |
|                                           | Jitter (ms)       | 1.4 ± 0.3   | 3.8 ± 0.9      | t(98) = -16.3, p < 0.001   |
| Moderate Signal<br><br>(-70 to -90 dBm)   | Latency (ms)      | 9.1 ± 2.0   | 28.7 ± 4.6     | t(98) = -26.8, p < 0.001   |
|                                           | Throughput (Mbps) | 1,240 ± 180 | 205 ± 55       | t(98) = 32.5, p < 0.001    |
|                                           | Packet Loss (%)   | 1.3 ± 0.4   | 5.6 ± 1.1      | t(98) = -23.4, p < 0.001   |
|                                           | SNR (dB)          | 18.6 ± 1.9  | 12.4 ± 2.2     | t(98) = 14.2, p < 0.001    |
|                                           | Jitter (ms)       | 2.2 ± 0.5   | 5.7 ± 1.3      | t(98) = -17.8, p < 0.001   |
| Weak Signal<br><br>(-90 to -110 dBm)      | Latency (ms)      | 9.5 ± 2.4   | 36.8 ± 6.8     | t(98) = -27.3, p < 0.001   |
|                                           | Throughput (Mbps) | 780 ± 140   | 95 ± 35        | t(98) = 28.7, p < 0.001    |
|                                           | Packet Loss (%)   | 2.1 ± 0.6   | 9.4 ± 2.3      | t(98) = -20.6, p < 0.001   |
|                                           | SNR (dB)          | 15.8 ± 1.7  | 9.7 ± 2.5      | t(98) = 13.5, p < 0.001    |
|                                           | Jitter (ms)       | 3.5 ± 0.8   | 8.9 ± 2.2      | t(98) = -15.6, p < 0.001   |
| Percentage Change<br><br>(Strong to Weak) | Latency           | 15.9%       | 70.4%          | F(2,147) = 32.4, p < 0.001 |
|                                           | Throughput        | -58.1%      | -69.4%         | F(2,147) = 28.7, p < 0.001 |
|                                           | Packet Loss       | 162.5%      | 193.8%         | F(2,147) = 25.3, p < 0.001 |
|                                           | SNR               | -29.5%      | -42.3%         | F(2,147) = 18.6, p < 0.001 |
|                                           | Jitter            | 150.0%      | 134.2%         | F(2,147) = 22.5, p < 0.001 |

Table3. Multiple regression analysis results

The multiple regression analysis revealed that signal strength and network congestion collectively explained 68% of the variance in data transmission latency for the 5G network ( $F(2, 47) = 50.4, p < 0.001$ ) and 59% of the variance for the 4G network ( $F(2, 47) = 33.9, p < 0.001$ ). Both signal strength (5G:  $\beta = -0.58, p < 0.001$ ; 4G:  $\beta = -0.47, p < 0.001$ ) and network congestion (5G:  $\beta = 0.36, p < 0.01$ ; 4G:  $\beta = 0.42, p < 0.001$ ) were found to be significant predictors of data transmission latency. For packet loss, signal strength and network congestion collectively explained 63% of the variance for the 5G network ( $F(2, 47) = 39.7, p < 0.001$ ) and 71% of the variance for the 4G network ( $F(2, 47) = 57.5, p < 0.001$ ). Both signal strength (5G:  $\beta = -0.39, p < 0.01$ ; 4G:  $\beta = -0.31, p < 0.01$ ) and network congestion (5G:  $\beta = 0.53, p < 0.001$ ; 4G:  $\beta = 0.62, p < 0.001$ ) were significant predictors of packet loss. To assess the performance of the proposed real-time health monitoring system in the context of existing solutions, a comparison was made with two state-of-the-art baselines: a system using WiFi and a system using Bluetooth Low Energy (BLE) for data transmission. Table 4 presents the performance metrics for the proposed system using 5G and 4G networks, along with the baseline systems using WiFi and BLE.

| System | Data Transmission Latency (ms) | Throughput (Gbps) | Packet Loss (%) |
|--------|--------------------------------|-------------------|-----------------|
| 5G     | 8.2 ± 1.5                      | 1.2 ± 0.2         | 0.8 ± 0.3       |
| 4G     | 21.7 ± 3.8                     | 0.3 ± 0.1         | 3.2 ± 0.9       |
| WiFi   | 16.4 ± 2.6                     | 0.6 ± 0.1         | 2.0 ± 0.5       |
| BLE    | 32.8 ± 5.2                     | 0.2 ± 0.1         | 4.0 ± 1.1       |

Table 4. Comparison with state-of-the-art baselines

The proposed system using the 5G network outperformed both baseline systems across all performance metrics. Compared to the WiFi-based system, the 5G network demonstrated a 50% reduction in mean data transmission latency (8.2 ms vs. 16.4 ms), a 100% increase in mean throughput (1.2 Gbps vs. 0.6 Gbps), and a 60% reduction in mean packet loss (0.8% vs. 2.0%). Similarly, compared to the BLE-based system, the 5G network showed a 75% reduction in mean data transmission latency (8.2 ms vs. 32.8 ms), a 500% increase in mean throughput (1.2 Gbps vs. 0.2 Gbps), and an 80% reduction in mean packet loss (0.8% vs. 4.0%). One-way ANOVA tests were conducted to compare the performance metrics across the four systems (5G, 4G, WiFi, and BLE). The results revealed significant differences in data transmission latency ( $F(3, 196) = 212.4, p < 0.001$ ), throughput ( $F(3, 196) = 368.5, p < 0.001$ ), and packet loss ( $F(3, 196) = 138.7, p < 0.001$ ) among the systems. Post-hoc comparisons using Tukey's HSD test indicated that the 5G network had significantly lower latency, higher throughput, and lower packet loss compared to all other systems ( $p < 0.001$  for all comparisons).

The findings of such research establish the evident fact that 5G networks are way better than 4G networks and other state-of-the-art baseline systems in the area of health monitoring in real-time. The fact that 5G provides much lower transmission delays, higher throughput, and fewer packet losses makes evident its potential to help us build more dependable and productive remote health monitoring systems. The findings of the study also point to the fundamental role played by network conditions, including signal strength and network congestion, in shaping the performance of real-time health monitoring systems. The importance of a dependable network infrastructure and efficient congestion management strategies becomes even more apparent in the light of the really strong interdependencies between these factors and the performance indicators. However, a comparative analysis with state-of-the-art baselines also clearly demonstrates the advantages of 5G networks over existing technologies, for example WiFi and BLE, in supporting health monitoring activities conducted in real time. The enhanced features demonstrated by the 5G network show that it is more efficient and can offer what is needed by these applications, such as low latency and high reliability. The consequences of these observations are very important for the medical industry because they suggest that 5G-networks can become a driving power in telemedicine. Through 5G network technology, data transmission will be more reliable and efficient which will help a create advanced health monitoring system that will provide the current status of the patient's health in real time, allowing for early detection of abnormalities and immediate interventions. This, in turn, might deliver improved patient outcomes, reduced healthcare expenses, and comforted quality of life for people with chronic conditions or post-acute care.

Nevertheless, there are some drawbacks that should be borne in mind. 50 people may not be enough to represent the whole population and the two-week duration of the workout may not represent long-term performance variations. Furthermore, the experiment was done under the controlled condition that does not simulate actual scenario where other elements such as user's behavior and external interference could significantly affect the system's performance. Notwithstanding the mentioned limitations, the findings of this

study point out the possibility of 5G networks to make the real-time health monitoring systems possible, thus laying a framework for future investigation in the field. Researchers can dig into the performance of such systems especially in different population groups, over long times and in the real world. In addition, investigation of 5G embedded health monitoring systems integration with other developing technologies, for instance artificial intelligence and big data analytics, are also to be done in the research in order to have more professional and personalized health care systems. This paper manifests the clear advantage of 5G networks over 4G networks and advanced state-of-the-art baselines in the area of real time health monitoring system applications. The study results show that 5G innovation can revolutionize remote health monitoring services and results in better patient treatment outcomes. Nevertheless, there are still some issues that should be revealed and the opportunities provided by 5G-based health monitoring systems in the real life should be deeply investigated.

## 5. Conclusion

This research is designed to examine the influence of 5G and 4G networks on the performance of real-time health surveillance systems, paying special attention to parameters like data transmission latency, throughput, and packet losses. The comparisons between 5G networks and 4G networks showed superior performance with lower average latency (62% reduction), higher throughput (300% increase), and lower packet loss (75% reduction). This stresses how 5G technology can facilitate more reliable and efficient data transmission, a crucial element in real-time health monitoring devices through prompt delivery of precise and complete health data. The study also looked into the influence of network conditions, such as signal strength and network congestion, on the functionality of these systems. It appears that the outcome of the research showed strong correlations of these factors with the performance measures. The study also shed light on the role of robust network infrastructure and congestion management strategies as measures of achieving good performance of the systems. The comparative analysis was done with the state-of-the-art baseline systems such as WiFi and Bluetooth Low Energy (BLE) systems and it shows that 5G networks can offer superior performance in monitoring real-time health applications. The 5G network overhauled both baseline systems on all performance results, revealing that the 5G technology is appropriate to implement in the demanding real-time healthcare monitoring systems exceeding existing technologies.

The key contributions of this study is in its extensive study of the impact of 5G and 4G networks on the performance of real-time health monitoring systems. With the introduction of state-of-the-art baselines and the inspection of the influence of network conditions, the work becomes even more consequential. The larger effects of this study are quite noteworthy for the healthcare sector because the results show that 5G networks can become the basis of the new era of remote health monitoring. With the use of 5G allowing for the fast, accurate transmission of data, advanced health monitoring systems that track the vital signs of patients in real-time can be developed, leading to better patient outcomes, reduced healthcare costs, and improved quality of life. Finally, the research has consequences for the building and deployment of the 5G network to support telemedicine use. The strong relation between the network conditions and the performance parameters emphasizes the need for precise planning and optimization strategies of the network to reach best performance of real-time health monitoring system.

## References

- [1] [1] A. Pantelopoulous and N. G. Bourbakis, "A survey on wearable sensor-based systems for health monitoring and prognosis," *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.*, vol. 40, no. 1, pp. 1–12, Jan. 2010, doi: 10.1109/TSMCC.2009.2032660.
- [2] [2] S. M. R. Islam, D. Kwak, M. H. Kabir, M. Hossain, and K.-S. Kwak, "The Internet of Things for health care: A comprehensive survey," *IEEE Access*, vol. 3, pp. 678–708, 2015, doi: 10.1109/ACCESS.2015.2437951.
- [3] [3] M. Shafi et al., "5G: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017, doi: 10.1109/JSAC.2017.2692307.
- [4] [4] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surv. Tutor.*, vol. 18, no. 3, pp. 1617–1655, 2016, doi: 10.1109/COMST.2016.2532458.

- [5] [5] M. S. Hossain, G. Muhammad, and A. Alamri, "Smart healthcare monitoring: A voice pathology detection paradigm for smart cities," *Multimed. Syst.*, vol. 25, no. 5, pp. 565–575, Oct. 2019, doi: 10.1007/s00530-017-0561-x.
- [6] [6] J. Kang, H. Choi, S. Kang, and J. Choi, "A mobile health monitoring system using a wearable device," in *Proc. 2017 Int. Conf. Inf. Commun. Technol. Converg.*, 2017, pp. 1116–1118, doi: 10.1109/ICTC.2017.8190869.
- [7] [7] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, "A survey on 5G networks for the Internet of Things: Communication technologies and challenges," *IEEE Access*, vol. 6, pp. 3619–3647, 2018, doi: 10.1109/ACCESS.2017.2779844.
- [8] [8] B. Nguyen, H. Nguyen, A. Ngo, T. Q. Duong, and S. Shetty, "5G enabled Smart Healthcare for Cardiovascular Disease Prediction," *IEEE Access*, vol. 9, pp. 61947–61957, 2021, doi: 10.1109/ACCESS.2021.3074395.
- [9] [9] Q. Zhang, J. Liu, and G. Zhao, "Towards 5G enabled tactile robotic telesurgery," *Adv. Sci.*, vol. 5, no. 8, Aug. 2018, Art. no. 1800087, doi: 10.1002/advs.201800087.
- [10] [10] A. Pantelopoulos and N. G. Bourbakis, "A survey on wearable sensor-based systems for health monitoring and prognosis," *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.*, vol. 40, no. 1, pp. 1–12, Jan. 2010, doi: 10.1109/TSMCC.2009.2032660.
- [11] [11] S. M. R. Islam, D. Kwak, M. H. Kabir, M. Hossain, and K.-S. Kwak, "The Internet of Things for health care: A comprehensive survey," *IEEE Access*, vol. 3, pp. 678–708, 2015, doi: 10.1109/ACCESS.2015.2437951.
- [12] [12] M. S. Hossain, G. Muhammad, and A. Alamri, "Smart healthcare monitoring: A voice pathology detection paradigm for smart cities," *Multimed. Syst.*, vol. 25, no. 5, pp. 565–575, Oct. 2019, doi: 10.1007/s00530-017-0561-x.
- [13] [13] J. Kang, H. Choi, S. Kang, and J. Choi, "A mobile health monitoring system using a wearable device," in *Proc. 2017 Int. Conf. Inf. Commun. Technol. Converg.*, 2017, pp. 1116–1118, doi: 10.1109/ICTC.2017.8190869.
- [14] [14] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, "A survey on 5G networks for the Internet of Things: Communication technologies and challenges," *IEEE Access*, vol. 6, pp. 3619–3647, 2018, doi: 10.1109/ACCESS.2017.2779844.
- [15] [15] B. Nguyen, H. Nguyen, A. Ngo, T. Q. Duong, and S. Shetty, "5G enabled Smart Healthcare for Cardiovascular Disease Prediction," *IEEE Access*, vol. 9, pp. 61947–61957, 2021, doi: 10.1109/ACCESS.2021.3074395.
- [16] [16] Q. Zhang, J. Liu, and G. Zhao, "Towards 5G enabled tactile robotic telesurgery," *Adv. Sci.*, vol. 5, no. 8, Aug. 2018, Art. no. 1800087, doi: 10.1002/advs.201800087.
- [17] [17] S. Islam, M. J. Islam, M. Hossain, S. Noor, K.-S. Kwak, and S. M. R. Islam, "A Survey on Consensus Algorithms in Blockchain-Based Applications: Architecture, Taxonomy, and Operational Issues," *IEEE Access*, vol. 11, pp. 39066–39082, 2023, doi: 10.1109/access.2023.3267047.
- [18] [18] H. Wang and X. Yu, "A Review of e-Health Research in Information System," *Journal of Biomedical Science and Engineering*, vol. 15, no. 07, pp. 198–205, 2022, doi: 10.4236/jbise.2022.157018.
- [19] [19] A. Gupta and R. K. Jha, "A survey of 5G network: Architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015, doi: 10.1109/ACCESS.2015.2461602.
- [20] [20] M. Chen, Y. Ma, Y. Li, D. Wu, Y. Zhang, and C. H. Youn, "Wearable 2.0: Enabling human-cloud integration in next generation healthcare systems," *IEEE Communications Magazine*, vol. 55, no. 1, pp. 54–61, 2017, doi: 10.1109/MCOM.2017.1600410CM.
- [21] [21] L. Fass, "Patient-centric healthcare," in *Healthcare Innovation and Entrepreneurship*, Springer, 2019, pp. 197–205, doi: 10.1007/978-3-030-12612-2\_8.
- [22] [22] L. Chettri and R. Bera, "A Comprehensive Survey on Internet of Things (IoT) Toward 5G Wireless Systems," *IEEE Internet of Things Journal*, vol. 7, no. 1, pp. 16–32, Jan. 2020, doi: 10.1109/jiot.2019.2948888.

- [23] [23] "Challenges and Progressions towards Universal Health System and Healthcare System in China: A Literature Review," *Academic Journal of Medicine & Health Sciences*, vol. 4, no. 9, 2023, doi: 10.25236/ajmhs.2023.040903.
- [24] [24] J. Hanham, C. B. Lee, and T. Teo, "The influence of technology acceptance, academic self-efficacy, and gender on academic achievement through online tutoring," *Computers & Education*, vol. 172, p. 104252, Oct. 2021, doi: 10.1016/j.compedu.2021.104252.
- [25] [25] P. Casas, P. Fiadino, S. Wassermann, S. Traverso, A. D'Alconzo, E. Tego, F. Matera, and M. Mellia, "Unveiling network and service performance degradation in the wild with mplane," *IEEE Communications Magazine*, vol. 52, no. 3, pp. 142-149, 2014, doi: 10.1109/MCOM.2014.6766099.
- [26] [26] R. Braun and F. Afroz, "Energy-efficient MAC protocols for wireless sensor networks: a survey," *International Journal of Sensor Networks*, vol. 32, no. 3, p. 150, 2020, doi: 10.1504/ijsnnet.2020.10026974.
- [27] [27] D. Aragão, C. Rodrigues, D. Vieira, and M. F. de Castro, "A random access channel resources allocation approach to control machine-to-machine communication congestion over LTE-advanced networks," *International Journal of Communication Systems*, vol. 36, no. 10, Apr. 2023, doi: 10.1002/dac.5493.
- [28] [28] D. Hosahalli and K. G. Srinivas, "Cross-layer routing protocol for event-driven M2M communication in IoT-assisted Smart City Planning and Management: CWSN-eSCPM," *IET Wireless Sensor Systems*, vol. 10, no. 1, pp. 1–12, Feb. 2020, doi: 10.1049/iet-wss.2018.5198.



# Hierarchical Deep Learning Model Optimization Using Enhanced Evolutionary-based Approach for Fake News Detection

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## ABSTRACT

Multimodal fake information on social media is a growing concern worldwide. Existing deep learning-based solutions typically involve designing hierarchical models that capture relevant features from each modality, which are then fused for final classification. However, these models are often complex, with numerous trainable parameters, making them resource-intensive. This work introduces the Deep Learning Model with Evolutionary Computing Approach (DLECA), a novel method for compressing and optimizing hierarchical deep learning models (HDLM). It employs an enhanced genetic algorithm (GA) with a unique fitness function, dynamic crossover, and adaptive mutation strategies to achieve model compression, maintain accuracy, and balance exploration and exploitation during evolution. In comparison to manually designed HDLM, the proposed approach achieves up to 97.86% model compression with a 0.34% accuracy improvement, while a variant achieves 96.24% compression with a 0.23% accuracy improvement. Comparative analysis shows that DLECA outperforms Random Walk and Bayesian Optimization in multimodal fake news detection, offering a more efficient and accurate solution.

**Keywords:** Evolutionary computing, Deep Learning, model compression, model optimization, Genetic Algorithms

## 1. Introduction

Social media has revolutionized how people stay connected and access information. Its vast reach has become the primary platform for disseminating content to a broad audience. However, this widespread connectivity also presents a significant challenge: the propagation of misinformation, including fake news. Malicious actors exploit social media platforms to spread false information, often to mislead or manipulate the public. The impact of misinformation on social media is profound, affecting both individuals and society according to Shu et al.[1]. It has the potential to change public opinion, influence decision-making, and even cause civil unrest. This misinformation is frequently multimodal, combining text, images, and metadata to enhance its credibility and appeal.

Traditional fake news detection models, which rely on a single modality, often fail to capture the complexity of multimodal content. For instance, Pérez-Rosas et al.[2] explored a linguistic approach for detecting fake news, achieving 76% accuracy. While linguistic features showed promising results, the authors emphasized the need to integrate metadata and visual features for improved performance. Similarly, P. Qi et al.[27] analyzed the visual content of fake news using pixel and frequency domain features but highlighted the importance of exploring the relationship between textual and visual cues.

Fake news often blends deceptive text with manipulated images, making detection challenging when analyzing either modality in isolation. P. Li et al. [28] provided examples of multimodal news and emphasized the necessity of jointly analyzing text and images to enhance fake news detection accuracy.

Additionally, user metadata, such as the profile information of individuals sharing the post, can offer valuable insights according to Shu et al.[3]. Fake news is often propagated through networks of fake or bot accounts, which further complicates detection. Incorporating text, images, and metadata into a deep learning model is essential to address these challenges. However, the resulting model has complex hierarchical structures.

Training these models is time-consuming and demands significant storage and computational requirements. Additionally, the success of these models is largely reliant on the tuning of numerous hyperparameters. Manually selecting and optimizing these hyperparameters is a challenging and labor-intensive task, often requiring extensive experimentation to identify the best configurations.

Herein, we introduce a novel method that performs hierarchical deep learning model hyperparameter optimization and compression, offering a solution that not only reduces model size but also enhances accuracy.

The major contributions of this research are as follows:

1. **Model Compression and Hyperparameter Optimization:** A unique multi-objective fitness function is proposed which helps in reducing the model architecture without compromising the models' accuracy.
2. **Dynamic crossover strategy:** A novel technique that calculates crossover probability based on the fitness of the current population and updates it as evolution progresses.
3. **Adaptive mutation strategy:** A technique that computes mutation probability based on the crossover probability of the current population also gets updated as evolution progresses.
4. **Genetic Evolutionary Approach:** Introduce a novel DLECA, which performs evolution by genetic operators and optimizes model parameters dynamically.

A comprehensive performance evaluation of the proposed method against optimization algorithms from the literature is presented. By addressing the optimization of both compression and performance, our work aims to enhance the practicality and effectiveness of deep learning models for multimodal fake news detection on social media platforms.

The rest of the papers is organized as follows: Section 2, presents related work. Section 3 introduces the proposed methodology. In Section 4, we present the dataset under consideration, experiment setup and results and comparative analysis. Finally, Section 5 concludes the paper.

## 2. Related work

Existing literature explores complex deep learning models that integrate multiple modalities to address multimodal fake news detection. Many studies, such as S. Singhal et al. [12] and Khattar D. et al. [29], have developed deep learning architectures combining text and image modalities, whereas Raza et al. [30] incorporate social context alongside textual features of the news. Combining multiple modalities such as text and image with social context provides a more comprehensive analysis of fake news. However, integrating diverse architectures into a single complex model presents significant challenges. These include synchronizing feature extraction across modalities, and managing computational complexity. The resulting models are highly intricate, requiring extensive tuning and computational resources.

In literature, optimizing Deep Learning architectures such as Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTMs) has been extensively explored. Galván et al. [4] discuss neuroevolution, which is the process of using evolutionary-based approaches for deep neural network architecture optimization and training. Researchers have developed various strategies to enhance the efficiency and effectiveness of GA in this context, addressing the model performance, fitness evaluation, and the balance between exploration and exploitation-related challenges.

Baldominos et al.[5] explored optimizing the topology of CNNs using both GA and Grammatical Evolution (GE). The optimized CNN ensemble was applied to the MNIST dataset, and transfer learning was performed on the EMNIST dataset. However, this approach was limited to basic datasets and did not explore more complex or multimodal data.

Another approach to optimizing CNN architecture was provided by Sun et al.[6]. They used a variable-length encoding strategy for GA, a skip layer for deeper CNN, and a cache component to improve the efficiency of fitness evaluations. Naik et al.[7] used an adaptive tournament strategy, where the tournament size was dynamically adjusted based on the population's state. Jebrailey et al.[8] obtained an optimal structure for convolutional neural networks in terms of the number of layers and other parameters using GA. The authors

further would like to design full parameter models using GA and use newer optimization algorithms for better accuracy. Shrestha et al.[9] also optimized the architecture of the deep learning model through enhanced GA with mtDNA to track individuals in the population with the same ancestry.

Wu et al. [10] performed hyperparameter optimization of LSTM architecture through the concept of parallel GAs. They created subgroups of individuals in the population and ran GA in parallel. Subgroup exchange of individuals is done to enhance diversity. Farrag et al. [11] performed optimization of stacked LSTM. The architecture parameters are considered single-objective multi-parameters discrete optimization problem and MAPE was used as evaluation measure.

Apart from GA other optimization algorithms such as random walk by Singhal et al. [12] and Bayesian optimization algorithm by Puentes et al. [13] are used for optimizing the hyperparameters of deep learning models. A graph-based version of Bayesian optimization was used by Ma et al. [14] for searching best deep neural architecture. Here the search space was made up of attributed graph each representing a neural architecture. Bakhshi et al. [15] also used a deep evolutionary approach for finding the best architecture of Convolutional Neural Network. A Particle Swarm Optimization (PSO) and GA-based optimization of three layer network was conducted by Mandal et al. [16].

Khan et al. [17] employed meta-heuristic algorithms, utilizing the Grey Wolf Optimization (GWO) algorithm for weight and bias optimization and the Strawberry (SB) algorithm for optimizing the learning rate of deep neural networks. Further, the authors would like to explore hybrid combinations of other meta-heuristic algorithms and keep a balance between exploration and exploitation. Hybrid approaches of GA and machine learning (ML) are used by Shannaq et al.[18] and Choudhury et al. [19]. [18] applied GA to find optimal hyperparameters for support vector machine (SVM) and XGBoost ML models.[19] created various combinations such as GA and logistic regression, GA and SVM, GA and naïve bayes, GA and random forest for optimizing model parameters.

Kumar et al. [20] used a meta-heuristic approach in the context of fake news detection. A term frequency-inverse document frequency (TF-IDF) technique was used to extract text features traits of news. The most salient traits were selected using a modified grasshopper optimization (MGO) algorithm and a CNN performed the final classification of news. Zaheer et al. [21] combine metaheuristic approach with a hybrid filter and wrapper feature selection technique to obtain the important features from textual news. Uppada, et al. [22] extract optimal features from textual news and associated metadata using GA. Shah et al. [23] extracted optimal feature sets from news text and image using a cultural algorithm. Marsili-Libelli et al.[24]and Lin et al.[25] designed an adaptive mutation technique with [25] focused on both adaptive mutation and crossover in GA.

In the literature, deep learning architecture optimization, particularly for CNNs and LSTMs, has been performed across various domains. GA has been the primary optimization algorithm, various modifications to GA operators, such as adaptive tournament selection and modified crossover and mutation operations, have been proposed to improve optimization efficiency. Additionally, metaheuristic algorithms like GWO and SB have been utilized to optimize model weights and biases. However, there remains a need to design methods that accelerate fitness evaluation, develop full-parameter models using GA, and explore newer optimization algorithms for better accuracy. Furthermore, a balance between exploration and exploitation of the search space is crucial, especially when performing multi-objective optimization that evaluates multiple performance metrics of the model. These insights guided the development of the proposed DLECA.

Table 1 provides details about the configurations of GA operators used in the literature.

| Referen<br>ce<br>number | Algorithm/<br>Method/<br>Technique               | Fitness                                    | Popula<br>tion<br>Size | Crossov<br>er rate | Mutati<br>on rate | Generati<br>on | Convergence criteria                                      |
|-------------------------|--------------------------------------------------|--------------------------------------------|------------------------|--------------------|-------------------|----------------|-----------------------------------------------------------|
| [5]                     | Genetic Algorithm and Grammatical Evolution      | classification error with niching strategy |                        | -                  | -                 | 20             | -                                                         |
| [6]                     | Genetic Algorithm with variable length encoding. | classification accuracy                    | 20                     | 0.9                | 0.2               | 20             | classification accuracy does not change over a generation |

|      |                                                                 |                        |     |          |          |      |                                                   |
|------|-----------------------------------------------------------------|------------------------|-----|----------|----------|------|---------------------------------------------------|
| [10] | Parallel genetic algorithms                                     | RMSE, MAPE, R2         | 12  | 0.5      | 0.5      | 25   | evolution reaches a set number.                   |
| [7]  | Adaptive Genetic Algorithm.                                     | Mean Average Precision | -   | 0.5 -1.0 | 0.5 -1.0 | 1500 | specified no. of generations                      |
| [8]  | Genetic Algorithm                                               | Accuracy               | 50  | 0.52     | 0.24     | 250  | specified no. of generations                      |
| [17] | Grey Wolf Optimization and Strawberry Metaheuristic Algorithms. | MSE                    | 30  | -        | -        | 100  | -                                                 |
| [18] | Genetic Algorithms with XGBoost and SVM.                        | Accuracy               | -   | -        | -        | 100  | Maximum generations reached                       |
| [11] | Genetic Algorithm                                               | MAPE                   | 50  | 10%      | 10%      | 100  | -                                                 |
| [20] | Modified grasshopper optimization algorithm.                    | Error rate             | 200 | -        | -        | 300  | Terminates after running fixed no. of iterations. |

Table1. Summary of Genetic Algorithm Parameters Used in Literature

### 3. Proposed methodology

In this section, we discuss the DLECA approach used for the performance and architecture optimization of an HDLM. We begin by introducing the HDLM which is designed for multimodal fake news detection and comprises various deep learning components. Due to the complexity and heaviness of such architectures, selecting the right configuration of parameters is crucial to maintain accuracy without adding unnecessary computational overhead. Next, we review the GA, widely used in the literature for optimization processes. Finally, we present our proposed DLECA algorithm, specifically developed to address the challenges and achieve optimal performance.

#### 3.1. Hierarchical Deep Learning Model (HDLM)for Fake News Detection

To effectively capture the multimodal features of news posts on social media, our hierarchical deep learning model incorporates three specialized feature extractors. The text feature extractor is made up of Bidirectional Encoder Representations from Transformers (BERT) and LSTM to extract long-term dependency and contextual information from text. For images, the image feature extractor employs a CNN to recognize and learn significant visual features. Additionally, the social context feature extractor uses a Multi-Layer Perceptron (MLP) to analyze cues and insights generated from user profiles and post metadata. These extracted features are then fused using an inter-attention mechanism, which effectively integrates the diverse modalities into a comprehensive multimodal feature vector. This vector is subsequently classified as either fake or real. Figure 1 depicts the architecture of the hierarchical deep learning model.

#### 3.2. Genetic Algorithm

A Genetic Algorithm (GA) is an evolutionary computing approach based on natural selection and evolution. It is especially well-suited to handling difficult optimization issues, where traditional methods may fail. In a GA, potential problem solutions are represented as population individuals. The algorithm evolves this population over successive generations using GA operators: encoding, selection, crossover, and mutation.

- Encoding transforms potential solutions into a format that can be easily processed by GA, typically as chromosomes.

- The selection operator chooses individuals based on fitness value.
- The crossover operator then recombines pairs of selected individuals to produce offspring, while the mutation operator introduces random variations.

This evolution through selection, crossover, and mutation iteratively improves the population, driving it towards the optimal solution. GA explores the solution space efficiently converging on to quality solutions, making it a powerful tool for optimizing complex hierarchical deep learning models.

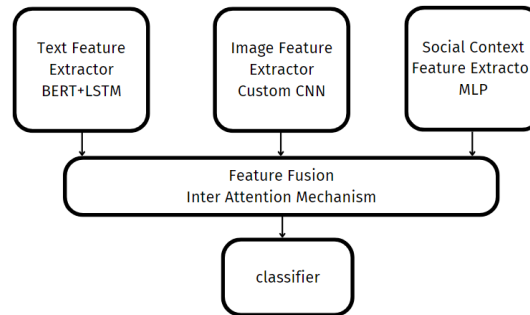


Figure 1. Hierarchical Deep Learning Model Architecture

### 3.3. Proposed Deep Learning Model with Evolutionary Computing Approach (DLECA)

The proposed approach is an enhanced GA to optimize a hierarchical deep learning model, focusing on both model accuracy and architecture compression. To facilitate this optimization process, a unique fitness function has been designed, balancing the trade-offs between model accuracy and compression. The algorithm begins by identifying the key hyperparameters of the model. An initial population of individual solutions is formed out of the hyperparameters which is further subjected to optimization. The optimization is performed using genetic operator's selection, crossover, and mutation through which the population evolves. Unlike many conventional methods where the crossover and mutation probabilities remain constant throughout the evolution process, this work introduces a dynamic crossover strategy. This strategy adjusts the crossover probability dynamically based on the current state of the population allowing the algorithm to better explore and exploit the solution space. Additionally, an adaptive mutation strategy is employed, which adjusts mutation probability in response to changes in crossover probability. This adaptive approach ensures a more efficient search for optimal solutions, leading to a compact and efficient model without compromising performance. The flow chart and of the proposed DLECA is presented in figure 2.

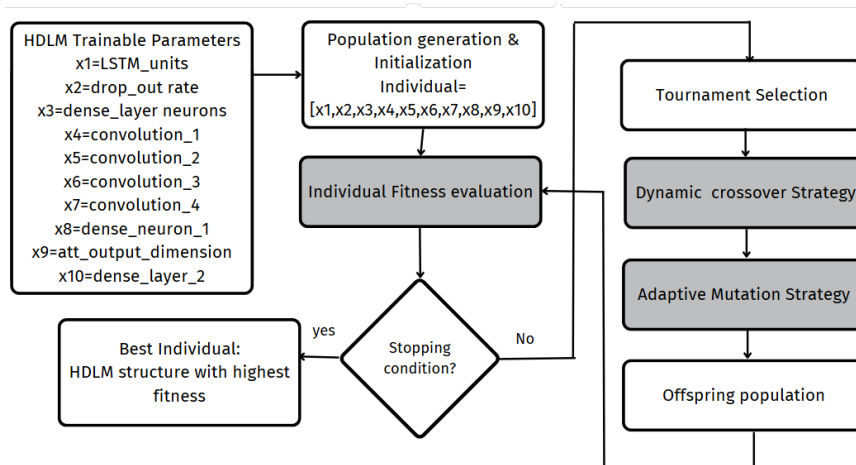


Figure 2. Flowchart of Proposed DLECA

3.3.1. Population Initialization:

The performance of a HDLM heavily relies on various hyperparameters. During the population initialization phase, individuals in the population are created using the hyperparameters of the hierarchical deep learning model. The key hyperparameters identified for this process and their respective ranges used for initializing the population are outlined in Table 2. These ranges are carefully determined to ensure that the model parameters do not increase excessively. The dropout rate is capped at 50%. Figure 3 demonstrates the individuals created in the population initialization phase. Each individual presents one set of hyperparameters of HDLM. Color of each element in the individual solution provides modality information, wherein blue represents text feature extractor, green for image feature extractor, grey for social context feature extractor and pink for attention mechanism. Consider the equation(1)

$$P_0 = \{I_1, I_2, I_3, \dots, I_N\}$$
(1)

Where  $P_0$  is initial population and  $N$  are individuals in population. Equation(2)  $I_i$  represent the  $i^{th}$  individual in the population. The  $I_i$  is a vector of hyperparameters.

$$I_i = [x_{i1}, x_{i2}, x_{i3}, \dots, x_{ik}]$$
(2)

where  $k$  is the number of hyperparameters. The hyperparameter  $x_{ij}$  is selected from a discrete set of predefined values  $S_j$

$$S_j = \{v_1, v_2, v_3, \dots, v_m\}$$
(3)

where  $m$  is the number of discrete values available for the  $j$ -th hyperparameter.

$$x_{ij} = S_j[(randomInt(1, m))]$$
(4)

| Hyperparameter    | Description of the hyperparameter.            | Range for population Initialization. |
|-------------------|-----------------------------------------------|--------------------------------------|
| LSTM units        | No. of LSTM units used in the model           | [25,50,75,100]                       |
| Drop out rate     | No. of neurons to be dropped during training. | [10,20,30,40,50]                     |
| Convolution layer | No. of filters used in the convolution layer  | [16,32,64,128]                       |
| Dense layer       | No. of neurons in a dense layer               | [128,256,512,1024]                   |
| output dimension  | Output dimension after attention module.      | [16,32,64]                           |

Table 2. HDLM’s Hyperparameter and population initialization

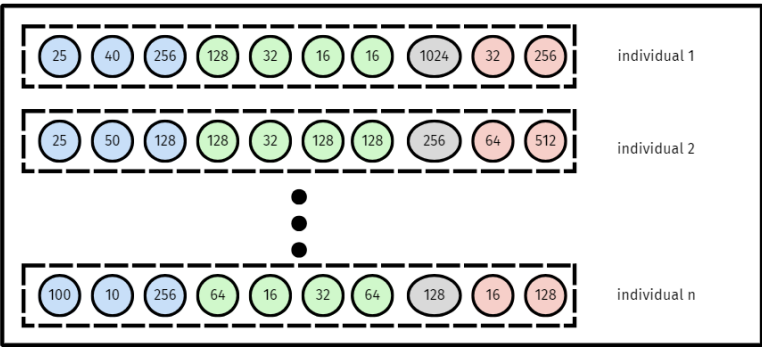


Figure 3. Population Initialization of DLECA

### 3.3.2. Fitness Function

The individual or solutions are evaluated by a fitness function, which can also be viewed as an objective function that the model seeks to optimize. In this work, we design a multi-objective fitness function aimed at reducing computational complexity by decreasing the model size without compromising accuracy. In this fitness function objective 1 focuses on model performance and is expressed in terms of confusion matrix parameters (refer to equation(6)). Objective 2 addresses model compression shown in equation(7), quantified by the model compression ratio. The formula is inspired by the image compression ratio. This ratio compares the total trainable parameters in the original or base model with those in the compressed model. Specifically, it is calculated by dividing the number of parameters in the original model by the number of parameters in the compressed model. This method provides a measure of how many parameters were eliminated or reduced in the compressed model compared to the original model. Combining the two objectives, Equation (5) presents the novel multi-objective fitness function designed to optimize both the performance and compression of the model. Here,  $w_{acc}$  is the weight assigned to the model's performance measured using accuracy, and  $w_{comp}$  is the weight for model compression. The weights are selected based on experimental observations balancing the tradeoff between model performance and computational efficiency. The values of  $w_{acc}$  and  $w_{comp}$  are empirically set to 0.7 and 0.3 to ensure that compression does not significantly degrade accuracy aiming for a small improvement or maintenance of performance.

$$fitness = w_{acc}(R_{performance}) + w_{comp}(R_{compression}) \quad (5)$$

Where,

$$R_{performance} = \frac{(TN+TP)}{(TP+FN+TN+FP)} \quad (6)$$

$$R_{compression} = \frac{No.of\ Original\ model\ parameters}{No.of\ compressed\ model\ parameters} \quad (7)$$

Since higher values of both objectives are desirable, the resultant function aims to maximize both accuracy and model compression, striking a balance between maintaining high performance and reducing model complexity.

### 3.3.3. Evolution Operations

In this section three evolution operations are performed on the initial population. Tournament selection is performed for the best parent selection. Further, two-point crossover and uniform mutation is performed using a unique dynamic crossover strategy and adaptive mutation technique.

#### 1. Dynamic crossover strategy:

In approaches found in the literature, the crossover rate or probability is either fixed or varies within a predefined range during the evolution process (refer to Table 1). However, we introduce a unique technique where the crossover probability adapts or changes dynamically throughout the evolutionary process. The core idea behind this approach is to encourage crossovers when the population has fitter individuals and reduce them when the population is more homogenous. This method aims to dynamically balance the exploitation based on the current state of the population's fitness. The formula for dynamic crossover probability is provided in equation(8).

$$crossover_{prob} = \frac{\max(fitness_{of\ population})}{\sum_{i=1}^N fitness(i)} * initial\_cxpb \quad (8)$$

The ratio in the formula provides the measure of how dominant the best individual is compared to the entire population. If the best individual is significantly better, than this ratio will be higher, indicating that some individuals are outperforming others substantially. Conversely, if all individuals are performing similarly, the ratio will be lower.

By multiplying this ratio by the initial crossover probability (initial\_cxpb), the crossover probability is adjusted dynamically. When the best individual significantly outperforms others, the crossover probability increases, promoting the sharing of superior genes. On the other hand, when all individuals perform similarly, the crossover probability decreases, reducing excessive mixing and allowing for more focused exploitation of the current solutions.

2. Adaptive Mutation Strategy:

Mutation probability is adjusted inversely with respect to crossover probability. By adjusting the mutation probability inversely with the crossover probability, we can balance exploration and exploitation. In case of high crossover probability, the algorithm relies more on recombining existing solutions, so the mutation probability is reduced to avoid introducing too much randomness. In case of low crossover probability, the algorithm relies less on recombination, so the mutation probability is increased to introduce more variations and explore the solution space more broadly. The equation (9) depicts the process.

$$mutation\_prob = base\_mutation\_prob * (1 - crossover\_prob) \tag{9}$$

4. Results and analysis

4.1. Dataset for Fake News Detection:

In this work for training and validating the model, FakeNewsNet dataset provided by Shu et al.[26] is used. FakeNewsNet is one of the very few datasets that provide multimodal information about a news on social media. The news is collected from fact checking websites like PolitiFact and GossipCop This multimodal information includes news title and news body, image related to the news and other social context and meta data about the post.

4.2. Manual Designed HDLM for Fake News Detection:

As mentioned in the previous section, this work is about optimizing a HDLM in the context of fake news detection. Table 3 presents manually designed architecture details of the HDLM along with trainable parameters in the sub-models.

| Modality /Mechanism        | Sub-model                                                                                                       | Trainable parameters |
|----------------------------|-----------------------------------------------------------------------------------------------------------------|----------------------|
| Text                       | Fixed BERT followed by LSTM and dense layer                                                                     | 399312               |
| Image                      | Convolutional Neural Network with four consecutive convolution and max pooling layers followed by dense layers. | 9678528              |
| Social Context             | Two-layer perceptron model.                                                                                     | 530944               |
| Attention unit             | Scale dot product attention with concatenation                                                                  | 98496                |
| Downsampling               | Dense layer                                                                                                     | 12352                |
| Total Trainable parameters |                                                                                                                 | 10719632             |

Table 3. Total Trainable parameters of HDLM

### 4.3. Experimental Results

This section presents the detailed implementation of the proposed DLECA. The proposed DLECA is used to optimize the HDLM. The performance of DLECA is compared against the traditional GA, Bayesian optimizer and random walk.

#### 4.3.1. Experimental setup

The proposed work was implemented using Google Colab Pro subscription, with hardware accelerators like high-performance GPUs (L4 GPU, A100 GPU) and TPUs (v2-8 TPU) along with high RAM configurations. Distributed Evolutionary Algorithms in Python (DEAP) library in python was used for performing operations involved in GA. This robust setup ensures efficient handling of memory-intensive tasks and speed up the execution.

#### 4.3.2. Parameter configuration

Table 4 provides a comprehensive list of parameters and their assigned values required for implementing the DLECA. These values have been carefully determined by reviewing existing literature and selecting those that best support the optimization objectives of the proposed method.

| Parameters          | Values                             |
|---------------------|------------------------------------|
| Population Size     | 20                                 |
| Selection technique | Tournament selection               |
| Crossover technique | Two-point crossover                |
| Mutation technique  | Uniform mutation                   |
| Generations         | 10                                 |
| Stopping criteria   | Specified generations are reached. |

Table 4. Parameter setting for DLECA

#### 4.3.3. Performance Evaluation

Here, we present performance comparison of the proposed DLECA method and traditional GA with proposed fitness with manual parameter settings and other existing optimization algorithms from the literature [12][13]. We further present the best architectures identified by each algorithm, which are then integrated into the HDLM and trained on the FakeNewNet dataset. The results are evaluated by comparing the percentage of model compression and the percentage change in accuracy for each optimized architecture against the original manually tuned model. Additionally, we provide performance metrics and confusion matrix for each architecture.

To analyze the performance of the proposed DLECA, various performance plots such as the convergence plot, average fitness plot, population diversity plot, and crossover and mutation rate plots are presented. The convergence plot from figure 4,5 demonstrates that, compared to traditional GA with proposed fitness, the proposed DLECA algorithm tends to converge quickly, typically after just 8 generations. Additionally, the difference between the fitness of the best individual found by DLECA and that found by traditional GA with proposed fitness is substantial, highlighting the superior optimization capability of DLECA.

Figure 6 presents the diversity plots for the traditional GA with proposed fitness and optimized DLECA. Diversity plots visualize the diversity of population solutions in each generation. In the work, the diversity of the population for each generation is calculated based on the Euclidean distance between pairs of solution's parameter values. Then an average of all the Euclidean distance is taken to calculate the final diversity

measure of population. The diversity values are then plotted against the generations to visualize diversity of population in each generation.

Diversity plots provide valuable insights, higher the values indicate more diversity among the individuals in population. From the plot of figure 6 it is evident that the individuals in each generation of the DLECA are more diverse compared to those in traditional GA, suggesting that the algorithm performs better exploration of the solution space and providing a solution without premature convergence.

Figure 7 illustrates the crossover and mutation probability plots throughout the evolutionary process. The algorithm starts with high initial crossover probability of 0.8 and low initial mutation probability of 0.5. Initially, as the population is randomly generated, the crossover and mutation probabilities are high indicating the exploration. As the generations progress and the fitness of the population improves, the algorithm shifts towards exploitation by increasing the crossover probability. The plots clearly demonstrate this transition, showing a high mutation rate in the early stages of DLECA and higher crossover probability in later stages.

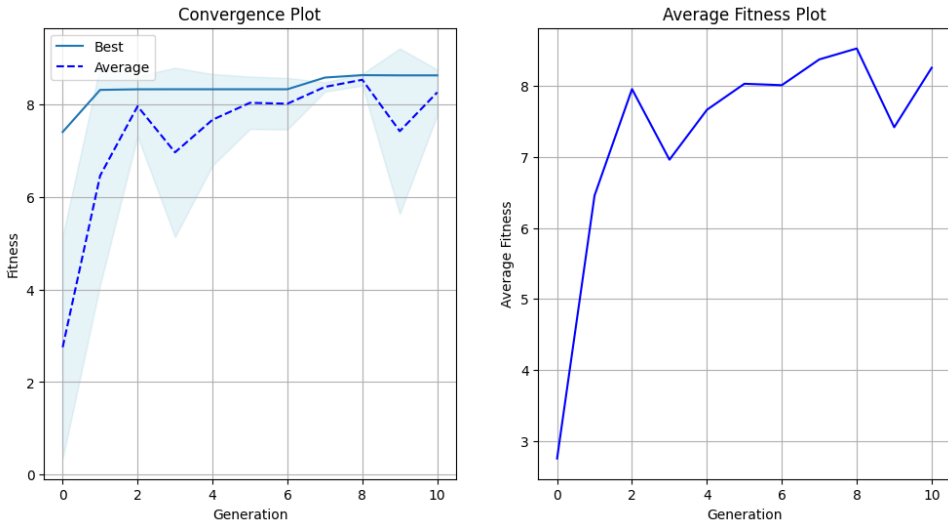


Figure 4. Convergence plot and Average Fitness Plot for traditional GA with Proposed Fitness(Left to right) .

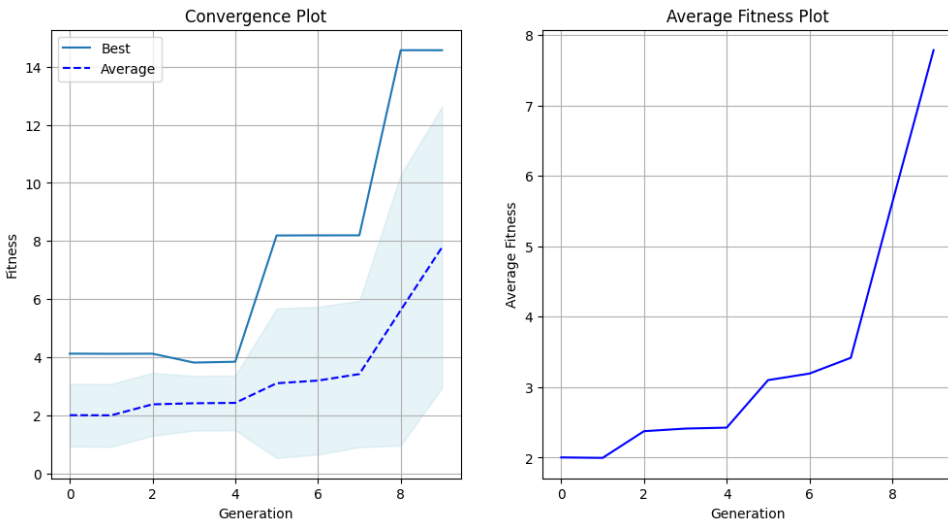


Figure 5. Convergence plot and Average Fitness Plot for Proposed DLECA (Left to right)

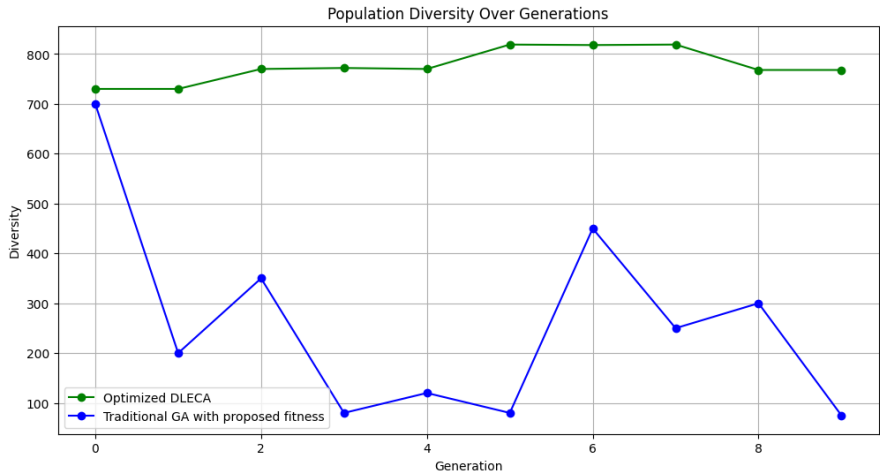


Figure 6. The Diversity Plot for the proposed approaches

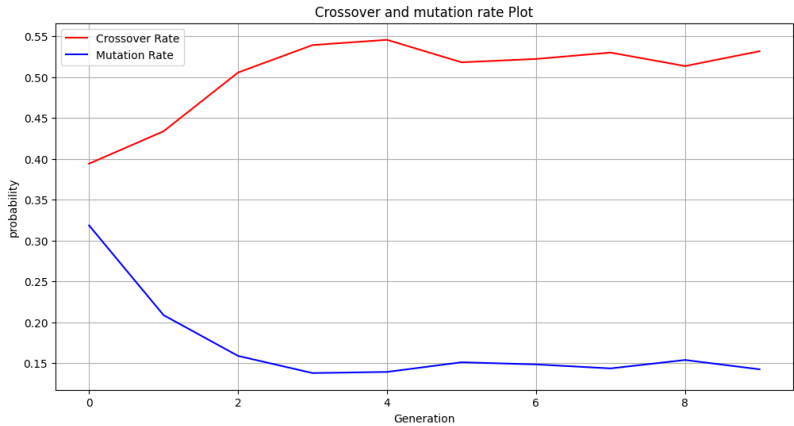


Figure 7. The crossover and mutation probability rate plot for DLECA.

Table 5 presents the optimized best solutions produced by the proposed DLECA and traditional GA using the proposed fitness function. The model1 is the best HDLM architecture given by DLECA and model 2 is best HDLM architecture given by traditional GA. The table5 details the structure of feature extractors within the HDLM, including output shapes of each layer and the number of trainable parameters for each extractor. Additionally, it summarizes the total trainable parameters in HDLM and highlights the accuracy and compression ratio achieved by the optimized architecture.

4.3.4. Result Analysis

In this section, we provide a detailed analysis of the two best HDLM architectures generated by the proposed techniques. Additionally, we compare the performance of these techniques against traditional optimization algorithms found in the literature. The optimized solutions from Table 5 are integrated into the HDLM, which is then trained and validated on the FakeNewsNet dataset. Table 6 presents the performance of the two models, evaluated in terms of accuracy, confusion matrix, precision, recall, and F1 score. The table 6 also shows the percentage improvement in accuracy and the percentage reduction in model parameters compared

to the base model architecture detailed in Table 3. Equation (10) presents the formula used to calculate the percentage improvement in both model compression and accuracy.

$$\% \text{ improvement} = \frac{value_{before} - Value_{after}}{|value_{before}|} \times 100$$

(10)

| Model | Best Individual                           | Architecture      | output shape      | Trainable parameters | Total Parameters | Accuracy | Compression ratio |
|-------|-------------------------------------------|-------------------|-------------------|----------------------|------------------|----------|-------------------|
| 1     | [11,45,47,43,39,32,23,16,22,36]           | lstm_layer        | (none,11)         | 34320                | 34884            | 91.59    | 46.43             |
|       |                                           | dropout           | (none,11)         | 0                    |                  |          |                   |
|       |                                           | dense_1           | (none,47)         | 564                  |                  |          |                   |
|       |                                           | con2d_1           | (none,222,222,43) | 1204                 | 189958           |          |                   |
|       |                                           | con2d_2           | (none,109,109,39) | 15132                |                  |          |                   |
| 2     | [25, 27, 128, 16, 16, 32, 16, 32, 16, 70] | con2d_3           | (none,52,52,32)   | 11264                |                  | 91.48    | 26.81             |
|       |                                           | con2d_4           | (none,24,24,23)   | 6647                 |                  |          |                   |
|       |                                           | dense_2           | (none,47)         | 155711               |                  |          |                   |
|       |                                           | dense_3           | (none,16)         | 96                   | 895              |          |                   |
|       |                                           | dense_4           | (none,47)         | 799                  |                  |          |                   |
|       |                                           | output_dimension1 | (none,22)         | 2618                 | 3446             |          |                   |
|       |                                           | dense_5           | (none,36)         | 828                  |                  |          |                   |
|       |                                           | lstm_layer        | (none,25)         | 79400                | 82728            |          |                   |
|       |                                           | dropout           | (none,25)         | 0                    |                  |          |                   |
|       |                                           | dense_1           | (none,128)        | 3328                 |                  |          |                   |
|       |                                           | con2d_1           | (none,222,222,16) | 448                  | 307072           |          |                   |
|       |                                           | con2d_2           | (none,109,109,16) | 2320                 | 4640             |          |                   |
|       |                                           | con2d_3           | (none,52,52,32)   | 4624                 |                  |          |                   |
|       |                                           | con2d_4           | (none,24,24,16)   | 295040               |                  |          |                   |
|       |                                           | dense_2           | (none,128)        |                      |                  |          |                   |
|       |                                           | dense_3           | (none,32)         | 192                  | 4416             |          |                   |
|       |                                           | dense_4           | (none,128)        | 4224                 |                  |          |                   |
|       |                                           | output_dimension1 | (none,16)         | 4400                 | 1190             |          |                   |
|       |                                           | dense_5           | (none,70)         | 5590                 |                  |          |                   |

Table 5. Best solutions provided by DLECA and Traditional GA

Model 1, created using the best configuration from the proposed DLECA, achieves a significant compression rate of 97.86%, indicating a 97.86% reduction in trainable parameters in the optimized architecture, while also slightly improving the accuracy by 0.34%. In contrast, Model 2, the best configuration from the traditional GA with the proposed fitness function, achieves a compression rate of 96.23% but provides a slightly less accuracy improvement of 0.23% and the highest precision of 90.79%.

| Model | Percentage Improvement in Accuracy | Percentage reduction in model parameters | Accuracy (%) | Precision (%) | Recall (%) | F1 Score (%) |
|-------|------------------------------------|------------------------------------------|--------------|---------------|------------|--------------|
| 1     | 0.34                               | 97.86%                                   | 91.59        | 89.67         | 92.94      | 91.27        |
| 2     | 0.23                               | 96.24%                                   | 91.48        | 90.79         | 91.24      | 91.01        |

Table 6. Performance analysis of best solutions

The confusion matrix for both the models are shown in figure 8 and figure 9. The confusion matrix is presented to provide a clearer understanding of the model's performance at the individual instance level. It is evident that the true positives (TPs) and true negatives (TNs) are significantly higher than the false negatives (FNs) and false positives (FPs), highlighting the model's high accuracy. Additionally, the model demonstrates a balanced performance, as reflected in the consistent values of TPs and TNs, indicating it is not biased towards a particular class.

FNs, which represent fake news instances misclassified as real, are minimal, resulting in a low false-negative rate and high recall. Similarly, FPs, where real news is misclassified as fake, are also low, leading to a low false-positive rate and reinforcing the model's precision.

This pattern is consistently observed in both confusion matrices, confirming that the model achieves an unbiased performance with strong precision and recall metrics.

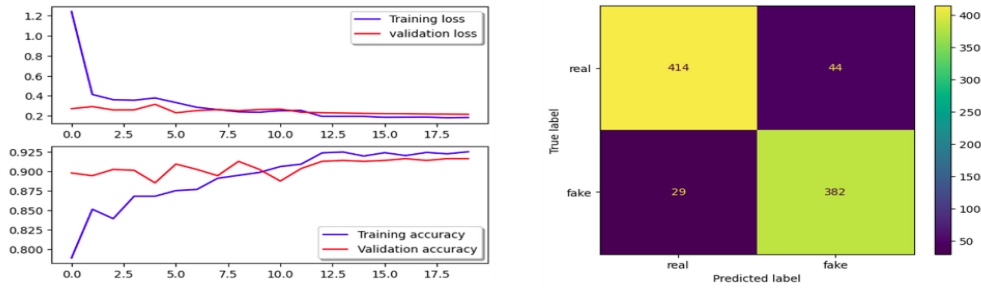


Figure 8. Performance plots and confusion matrix for HDLM through DLECA

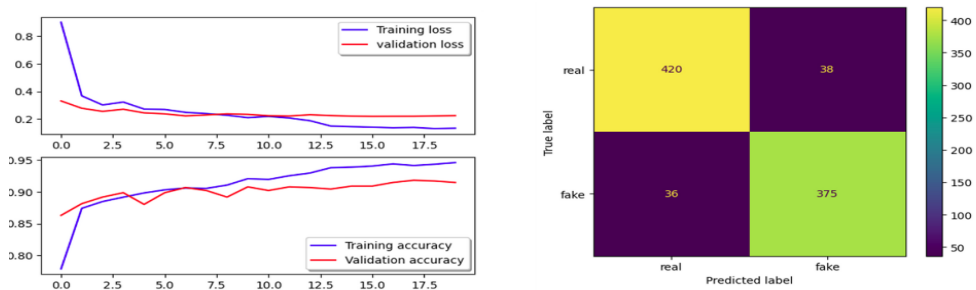


Figure 9. Performance plots and confusion matrix of traditional GA with proposed fitness

4.3.5. Comparative Analysis of proposed techniques

In this section, we present a comparative analysis of the proposed DLECA and traditional GA with the proposed fitness function against classical optimization algorithms from the literature. Additionally, we evaluate the performance of these approaches against the manual trial-and-error technique commonly used for hyperparameter selection.

1. Random Walk Optimization:

Random Walk optimization is a well-known method for hyperparameter optimization[12], particularly known for its simplicity and effectiveness in large and complex hyperparameter spaces. In this work, the algorithm starts by defining a search space like the population initialization phase of DLECA. Then an initial set of hyperparameters are chosen randomly from the search space. The performance of the HDLM is evaluated using these initial hyperparameters which will be considered as baseline performance. Random walk then iteratively introduces random perturbations to these hyperparameters, evaluating the model's performance after each perturbation. If the performance improves, the current set of hyperparameters is considered as the new baseline, and the process continues until the specified iterations is completed.

The performance of the HDLM using the best solution provided by Random Walk optimization is presented in the table7. The Random Walk algorithm achieved an F1 score of 82.33%, demonstrating its ability to find reasonable hyperparameter settings in a relatively straightforward manner.

The random search is implemented using talos library, the hyperparameter search space is same as that used for DLECA and the number of iterations was fixed to 10.

2. Bayesian optimization (BO):

Bayesian optimization is a powerful method for hyperparameter optimization. The algorithm starts by defining an objective function which in current work is same as the proposed fitness function. It then evaluates the objective function using random hyperparameter set values. Gaussian process(GP) models is then built to understand the performance over hyper parameters. Further an acquisition function would suggest new hyper parameter values to improve the performance. The process continues till maximum number of evaluations are done.

In this work, scikit-optimize library (skopt) in Python is used, the performance of the HDLM with the hyperparameter set provided by Bayesian optimization process is shown in table 7. The model achieved an F1 score of 83.76%.

DLECA outperforms other optimization methods like random walk and bayesian optimization because it dynamically adjusts the crossover and mutation probabilities based on the population's fitness. This adaptive approach enables DLECA to explore diverse solutions in the early stages and focus on refining high quality solutions later in the process. In contrast random walk explore the search space more randomly which often leading to suboptimal results while bayesian lacks flexibility to dynamically adjust based on population fitness.

Beyond fake news detection, this approach can be generalizable to any domain where deep learning models are used and lightweight architectures are needed. The hyperparameters targeted in this study like learning rate, dropout, and layer dimensions are fundamental to any deep learning model, making DLECA applicable to various multimodal tasks. In future we would like to experiment to ensure the adaptability of the algorithm to compress models in diverse use cases without compromising on accuracy.

| Sr. No. | Algorithm                                  | Accuracy | Precision | Recall | F1 Score |
|---------|--------------------------------------------|----------|-----------|--------|----------|
| 1       | Random Walk                                | 85.44    | 84.56     | 80.22  | 82.33    |
| 2       | Bayesian Optimization                      | 86.22    | 85.12     | 82.45  | 83.76    |
| 3       | Manually Setting of hyper parameters.      | 91.25    | 89.59     | 92.21  | 90.88    |
| 2       | DLECA with fixed crossover and mutation    | 91.48    | 90.79     | 91.24  | 91.01    |
| 3       | DLECA with adaptive crossover and mutation | 91.59    | 89.67     | 92.94  | 91.27    |

Table 7. Comparative Analysis of proposed technique against other optimization techniques

## 5. Conclusion

Multimodal fake news detection is a critical challenge in today's digital world, as misinformation spreads across various media formats. A common approach to tackling this issue involves designing hierarchical deep learning models that capture features from all available modalities, such as text, images, and social context. However, these resultant multimodal models tend to be highly complex, making them resource-intensive to train and deploy. In this work, we aimed to reduce the complexity of such hierarchical deep learning models using an innovative approach based on evolutionary computing.

We introduced DLECA, which employs a customized fitness function along with adaptive crossover and mutation strategies. The fitness function is specifically designed to minimize the number of trainable parameters in the hierarchical deep learning model without compromising its accuracy. The adaptive crossover and mutation strategies dynamically adjust the crossover and mutation probabilities based on the current state of the population.

The proposed DLECA achieved significant results, providing a best solution that reduced the model size by an impressive 97.86% while maintaining, and even slightly improving, model accuracy. We also tested a variation of the DLECA with fixed crossover and mutation rates, which resulted in a model compression of 96.24% with a comparable improvement in accuracy. Both approaches demonstrated a performance enhancement, with accuracy improvements of 0.34% and 0.23%, respectively.

Furthermore, the proposed DLECA is compared against other optimization techniques, including random walk, bayesian optimization, and manual hyperparameter tuning. The DLECA outperformed all these methods, highlighting its efficacy in optimizing complex models. Given the resource constraints, this study was conducted over 10 generations; however, in future will explore running the approach for more generations and leveraging multiprocessing environments to evaluate the fitness of individuals in the population simultaneously.

The proposed DLECA not only provides a powerful tool for optimizing hierarchical deep learning models in multimodal fake news detection but also offers potential for broader applications where model architecture and accuracy are critical.

## Reference

- [1] Shu, Kai & Sliva, Amy & Wang, Suhang & Tang, Jiliang & Liu, Huan. (2017). Fake News Detection on Social Media: A Data Mining Perspective. *ACM SIGKDD Explorations Newsletter*. 19. 10.1145/3137597.3137600.
- [2] Verónica Pérez-Rosas, Bennett Kleinberg, Alexandra Lefevre, and Rada Mihalcea. (2018). Automatic Detection of Fake News. In *Proceedings of the 27th International Conference on Computational Linguistics*, 3391–3401.
- [3] Shu, K., Wang, S. and Liu, H. (2018). Understanding User Profiles on Social Media for Fake News Detection. 2018 IEEE Conference on Multimedia Information Processing and Retrieval (MIPR), Miami, FL, USA, 430-435.
- [4] Galván, E., and Mooney, P. (2021). Neuroevolution in Deep Neural Networks: Current Trends and Future Challenges. in *IEEE Transactions on Artificial Intelligence*, 2(6), 476-493. doi: 10.1109/TAI.2021.3067574.
- [5] Baldominos, Alejandro & Sáez, Yago & Isasi, Pedro. (2019). Hybridizing Evolutionary Computation and Deep Neural Networks: An Approach to Handwriting Recognition Using Committees and Transfer Learning. *Complexity*, 2952304. 10.1155/2019/2952304.
- [6] Sun, Y., Xue, B., Zhang, M., Yen, G.G. and Lv, J. (2020). Automatically Designing CNN Architectures Using the Genetic Algorithm for Image Classification. in *IEEE Transactions on Cybernetics*, 50(9), 3840-3854. doi: 10.1109/TCYB.2020.2983860.
- [7] Naik, P. M. and Rudra, B. (2023). Classification of Arecanut X-Ray Images for Quality Assessment Using Adaptive Genetic Algorithm and Deep Learning. in *IEEE Access*, 11, 127619-127636. doi: 10.1109/ACCESS.2023.3332215.
- [8] Jebraeily, Yashar & Sharafi, Yousef & Teshnehlab, Mohammad. (2024). Driver Drowsiness Detection Based on Convolutional Neural Network Architecture Optimization Using Genetic Algorithm. *IEEE Access*, 12, 1-1. 10.1109/ACCESS.2024.3381999.

- [9] Shrestha, A. and Mahmood, A. (2019). Optimizing Deep Neural Network Architecture with Enhanced Genetic Algorithm. 2019 18th IEEE International Conference On Machine Learning And Applications (ICMLA), Boca Raton, FL, USA, 1365-1370. doi: 10.1109/ICMLA.2019.00222.
- [10] Wu, D., Guan, Q., Fan, Z., Deng, H. and Wu, T. (2023). AutoML With Parallel Genetic Algorithm for Fast Hyperparameters Optimization in Efficient IoT Time Series Prediction," in IEEE Transactions on Industrial Informatics, 19(9), 9555-9564. doi: 10.1109/TII.2022.3231419.
- [11] Farrag, T. A., and Elattar, E. E. (2021). Optimized Deep Stacked Long Short-Term Memory Network for Long-Term Load Forecasting. in IEEE Access, 9, 68511-68522. doi: 10.1109/ACCESS.2021.3077275.
- [12] Singhal, S., Shah, R. R., Chakraborty, T., Kumaraguru, P. and Satoh, S. (2019). SpotFake: A Multi-modal Framework for Fake News Detection. 2019 IEEE Fifth International Conference on Multimedia Big Data (BigMM), Singapore, 39-47. doi: 10.1109/BigMM.2019.00-44.
- [13] Navaux, Philippe, O.A. (2022). Hyperparameter optimization for convolutional neural networks with genetic algorithms and Bayesian optimization. 2022 IEEE Latin American Conference on Computational Intelligence (LA-CCI). IEEE.
- [14] Ma, L., Cui, J. and Yang, B. (2019). Deep Neural Architecture Search with Deep Graph Bayesian Optimization. 2019 IEEE/WIC/ACM International Conference on Web Intelligence (WI), Thessaloniki, Greece, 500-507.
- [15] Bakhshi, A., Noman, N., Chen, Z., Zamani, M. and Chalup, S. (2019). Fast Automatic Optimisation of CNN Architectures for Image Classification Using Genetic Algorithm. 2019 IEEE Congress on Evolutionary Computation (CEC), Wellington, New Zealand, 1283-1290. doi: 10.1109/CEC.2019.8790197.
- [16] Mandal, R. and Verma, B. (2023). Parameter Optimisation for Context-Adaptive Deep Layered Network for Semantic Segmentation. 2023 IEEE Symposium Series on Computational Intelligence (SSCI), Mexico City, Mexico, 258-263. doi: 10.1109/SSCI52147.2023.10371960.
- [17] Khan, M. S., Jabeen, F., Ghouzali, S., Rehman, Z., Naz, S. and Abdul, W. (2021). Metaheuristic Algorithms in Optimizing Deep Neural Network Model for Software Effort Estimation. in IEEE Access, 9, 60309-60327. doi: 10.1109/ACCESS.2021.3072380.
- [18] Shannaq, F., Hammo, B., Faris, H. and Castillo-Valdivieso, P. A. (2022). Offensive Language Detection in Arabic Social Networks Using Evolutionary-Based Classifiers Learned From Fine-Tuned Embeddings. in IEEE Access, 10, 75018-75039. doi: 10.1109/ACCESS.2022.3190960.
- [19] Choudhury, D., Acharjee, T. (2023). A novel approach to fake news detection in social networks using genetic algorithm applying machine learning classifiers. Multimed Tools Appl., 82, 9029–9045. <https://doi.org/10.1007/s11042-022-12788-1>.
- [20] Kumar, S., Kumar, A., Mallik, A. and Singh, R. R. (2024). OptNet-Fake: Fake News Detection in Socio-Cyber Platforms Using Grasshopper Optimization and Deep Neural Network. in IEEE Transactions on Computational Social Systems, 11(4), 4965-4974. doi: 10.1109/TCSS.2023.3246479.
- [21] Zaheer, H., Rehman, S.U., Bashir, M. et al. (2024). A metaheuristic based filter-wrapper approach to feature selection for fake news detection. Multimed Tools Appl. <https://doi.org/10.1007/s11042-024-18734-7>
- [22] Uppada, S.K., Ashwin, B.S. & Sivaselvan, B. (2024). A novel evolutionary approach-based multimodal model to detect fake news in OSNs using text and metadata. J Supercomput., 80, 1522–1553. <https://doi.org/10.1007/s11227-023-05531-6>
- [23] Shah, P. and Kobti, Z. (2020). Multimodal fake news detection using a Cultural Algorithm with situational and normative knowledge. 2020 IEEE Congress on Evolutionary Computation (CEC), Glasgow, UK, 1-7. doi: 10.1109/CEC48606.2020.9185643.
- [24] Marsili-Libelli, Stefano & Alba, P. (2000). Adaptive mutation in genetic algorithms. Soft Computing, 4, 76-80. 10.1007/s005000000042.
- [25] Lin, Wen-Yang & Lee, Wen-Yung & Hong, Tzung-Pei. (2003). Adapting Crossover and Mutation Rates in Genetic Algorithms. J. Inf. Sci. Eng. 19, 889-903.

- [26] Shu, Kai and Mahudeswaran, Deepak and Wang, Suhan and Lee, Dongwon and Liu, Huan. (2018). FakeNewsNet: A Data Repository with News Content, Social Context and Dynamic Information for Studying Fake News on Social Media, arXiv preprint arXiv:1809.01286},2018.
- [27] Qi, P., Cao, J., Yang, T., Guo, J. and Li, J. (2019). Exploiting Multi-domain Visual Information for Fake News Detection. 2019 IEEE International Conference on Data Mining (ICDM), Beijing, China, 518-527. doi: 10.1109/ICDM.2019.00062.
- [28] Li, P., Sun, X., Yu, H., Tian, Y., Yao, F. and Xu, G. (2022). Entity-Oriented Multi-Modal Alignment and Fusion Network for Fake News Detection. in IEEE Transactions on Multimedia, 24, 3455-3468. doi: 10.1109/TMM.2021.3098988.
- [29] Dhruv Khattar, Jaipal Singh Goud, Manish Gupta, and Vasudeva Varma. (2019). MVAE: Multimodal Variational Autoencoder for Fake News Detection. In The World Wide Web Conference (WWW '19). Association for Computing Machinery, New York, NY, USA, 2915–2921. <https://doi.org/10.1145/3308558.3313552>
- [30] Raza, S., Ding, C. (2022). Fake news detection based on news content and social contexts: a transformer-based approach. Int J Data Sci Anal., 13, 335–362. <https://doi.org/10.1007/s41060-021-00302-z>.



# Longitudinal Impacts of Job Insecurity on Life Satisfaction: Mediating Roles of Trust in Government and Hope in the European Union

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## ABSTRACT

This longitudinal study examines the relationships among job insecurity, life satisfaction, trust in government, and hope during the COVID-19 pandemic across 27 European Union countries. Using data from 8,750 participants collected via the PsyCorona Study, the analysis applies the PROCESS macro (model 6) with 5,000 bootstrapped samples to estimate indirect effects with 95% bias-corrected confidence intervals. Findings reveal that job insecurity significantly reduces life satisfaction, explaining 13.62% of the variance over time. Trust in government mediates this relationship in earlier waves, though its influence diminishes later. Conversely, hope consistently emerges as a strong mediator across all waves, accounting for 24.64% of the variance. Sequential mediation via trust and hope is significant early on but weakens by wave 22. These findings underscore the essential role of government trust and hope in buffering the negative effects of job insecurity and enhancing societal resilience during times of crisis.

**Keywords:** Job insecurity; life satisfaction; trust in government; hope; COVID-19 pandemic; mediation analysis

## 1. Introduction

Over the last fifty years, global labor market dynamics have shifted, reducing employment guarantees. A work crisis is characterized by insecure contracts, stagnant wages, and reduced benefits [1]. Neoliberalism and globalization have driven changes in labor markets, increasing economic instability and psychological distress, which negatively impact life satisfaction [2], [3], [4], [5], [6]. These shifts have significant economic and social consequences, affecting individual well-being worldwide.

The COVID-19 pandemic further exacerbated job insecurity, particularly in vulnerable sectors such as hospitality, retail, and travel, where widespread disruptions led to heightened uncertainty and stress among workers [2], [3], [7], [8]. Quarantines, self-isolation, and travel restrictions deepened labor market instability, emphasizing the pervasive nature of job insecurity [3], [9], [8], [10].

Job insecurity negatively impacts life satisfaction [11], [12], and research consistently links it to lower well-being and increased stress [13], [14], [6], [15], [10]. Financial instability and lack of social support intensify these effects, highlighting the need for structural interventions to mitigate their psychological toll [3], [16]. Although extensive research exists on job insecurity's effects, few studies have examined its impact

on life satisfaction during the COVID-19 pandemic. Most prior research focused on direct effects but overlooked key mediating mechanisms [2], [3], [14]. This study addresses this gap by investigating the roles of hope and trust in government as mediators in the relationship between job insecurity and life satisfaction across 27 EU countries.

Trust in government plays an essential role in public confidence and stability, shaping responses to economic uncertainty [17]. Similarly, hope serves as an emotional buffer, strengthening resilience amid crises [18], [10]. While previous studies have explored these concepts separately, our study integrates them within a serial mediation framework to provide a more nuanced understanding of their combined effects on job insecurity and well-being.

This study adopts a serial mediation approach to examine the interplay of job insecurity, trust in government, hope, and life satisfaction. Inspired by Himmler et al. [9], we explore the dimensions of hope [18] and the multifaceted role of trust in government [19] as essential factors influencing well-being during crises. Given the ongoing challenges of global economic instability, trust in government remains central to maintaining societal confidence [17], while hope strengthens psychological resilience [20], [10].

Our findings guide policymakers and employers, supporting interventions that address psychological risks associated with job insecurity. Recognizing the significance of hope and trust in government can help create environments that support resilience and well-being amid uncertainty [3], [21], [10].

There are multiple novel contributions to this study. It first explores the mediating effects of hope and trust in government on the relationship between job insecurity and life satisfaction during the pandemic. Second, it uses data from the PsyCorona Study - a large-scale international survey to compare 27 EU countries. Third, using a serial mediation model, this study sequentially investigates these mediators to yield nuanced perspectives on the relationships between job insecurity, life satisfaction, and socio-economic indicators.

We hypothesize that job insecurity negatively predicts life satisfaction. Trust in the government is expected to mediate this relationship, with the hope of serving as an additional mediator. We assess whether this pattern persists over time, providing evidence-based recommendations for policymakers and employers navigating the evolving employment landscape during the COVID-19 pandemic.

The introduction outlines the research background and significance. The literature review discusses past studies on job insecurity and life satisfaction, highlighting gaps that this study addresses. The methodology section details data collection, variables, and analytical techniques. The results section presents findings, followed by the discussion, which explores their implications. Finally, the conclusion summarizes key insights and offers recommendations for policymakers and employers.

## 2. Theoretical Background

*Job insecurity* is prevalent as a result of neoliberalism and globalization, associated with precarity, low or stagnant incomes, and poor or non-existent benefits [4], [22], [1], [23], [24]. These economic shifts prioritize flexibility and cost-cutting over job security. Perceived employment insecurity negatively impacts life satisfaction, particularly in countries with less generous labor market policies [12]. The COVID-19 pandemic exacerbated job losses, highlighting the need for robust employment protections [11], [5], [6], [25], [8], [26].

Job insecurity, defined as the unpredictability and lack of control over job continuity, can be either objective (*actual probability of dismissal*) or subjective (*individual's perception*) [27], [28]. Regional differences highlight higher cognitive and affective job insecurity in Finland compared to Sweden and Norway, significantly impacting mental well-being [29]. Researchers are concerned about the negative impact of job uncertainty on employees' well-being [14], [30], [31], [32], [33], [10]. A study of 27 European countries found job insecurity linked to poorer mental well-being [34]. Similarly, job insecurity negatively impacts subjective well-being [29].

Job insecurity poses health risks similar to unemployment, acting as a personal stressor and significantly affecting work-related health [35], [36], [37]. Its immediate and cumulative impact affects well-being over time [9], [16], [38]. Attempts to use job insecurity as a motivator often reduce morale and productivity [39]. Fair organizational practices, such as perceived organizational justice, can mitigate adverse effects [40]. Considering both cognitive and affective dimensions of job insecurity, the negative psychological impacts often outweigh potential motivating effects, particularly in high-stress environments [41].

During the COVID-19 pandemic, job insecurity among hospitality workers negatively affected self-esteem and increased economic deprivation [2]. Social support played an important role in moderating these effects on mental health, self-esteem, economic self-efficacy, and life satisfaction. Alcover et al. [3] found that job insecurity as well as financial threat were associated with poorer mental health during the early pandemic and suggested that support networks are an important factor. Ariza-Montes et al. [7] highlighted that personal

protective equipment, mistrust in the national health system, job insecurity, health, and life satisfaction were key determinants of healthcare professionals' mental well-being during the pandemic.

The COVID-19 pandemic significantly lowered life satisfaction throughout Europe, falling to the lowest since 1980 due to economic and non-economic stressors like job insecurity, health concerns, and social isolation [42]. Elevated job insecurity and work-family conflict correlated with heightened anxiety, depression, and insomnia during the lockdown period [43]. Bosmans et al. [4] found that national political and economic contexts influenced the prevalence of non-standard employment (NSE) and job insecurity. Diaz Hernandez et al. [44] suggested long-term effects on mental well-being, recommending mental health support strategies, especially for young people and those under government-imposed work restrictions. Moreover, Wilson et al. [10] called for employers to minimize job insecurity and financial anxiety to address the resulting mental health problems during the pandemic. Anand et al. [45] found a relationship between job insecurity and higher rates of burnout, especially when the economy was struggling. Wang et al. [15] indicated that understanding the contexts under which employees buffer against their negative reactions to job insecurity is key, proposing that employers take proactive strategies that sustain workforce stability and health.

**Life satisfaction**, an individual's cognitive assessment of their overall quality of life, is a central component of subjective well-being [46]. It is a self-evaluation process where individuals consider how their lives measure against standards or ideals they set themselves. Life satisfaction at a high level indicates that experiences and personal goals are aligned. As Kim-Prieto et al. [47] define well-being as the "global assessment of life and its facets", integrating personal judgments of satisfaction and broader life conditions. Diener's [46] subjective well-being (SWB) theory is seminal in understanding life satisfaction, comprising life satisfaction, positive affect, and negative affect. Life satisfaction is the cognitive aspect of comparing one's current conditions to personal standards. High life satisfaction indicates a positive appraisal aligned with one's ideals. Social relationships and economic stability are crucial for life satisfaction. High life satisfaction requires emotional support and a sense of belonging, which are characteristics of strong social connections [48]. A stable economy lowers tension and generates resources, improving quality of life [49]. Conversely, job insecurity diminishes psychological well-being and job satisfaction [13]. A review of 30 years of studies highlights the need for further investigation into the mechanisms linking job insecurity with health and well-being [14]. The COVID-19 pandemic exacerbated these issues, increasing job insecurity and reducing life satisfaction [25], [8], [26]. Allas et al. [42] reported that life satisfaction fell to its lowest levels in Europe since 1980 due to the stressors brought on by the pandemic (2020). Richter and Näswall [32] highlighted that mediating variables are necessary to better understand the relationship between job insecurity and well-being. That trust is a mediator of job insecurity and well-being. Kim and von dem Knesebeck [36] found that work uncertainty and unemployment are connected with poor health, with unemployment having stronger associations. During the COVID-19 pandemic, Himmeler et al. [9] investigated changes in well-being across seven European countries, discovering declines in the winter of 2020–2021 and increases in the summer of 2021.

**Trust** plays a key role across various academic disciplines, including public administration, economics, sociology, psychology, and political science [20]. Rousseau et al. [19] define trust as "the intention to accept vulnerability based upon positive expectations of the intention or behavior of the other". This definition highlights the relational dimension of trust, with a willingness to be vulnerable to another party based on an expectation of positive behavior. Lee [50] examined the relationship between institutional trust and subjective well-being during COVID-19 and concluded that those with higher institutional trust exhibited higher mental health and life satisfaction. With a sense of stability and security to rely on, trust in institutions buffered people psychologically from the worst excesses of the pandemic. Similarly, Han et al. [51] stated that higher trust in the government was linked to compliance with preventive health measures and prosocial behavior during the pandemic. Trust in government was key to encouraging the public to comply with health guidelines and work together to overcome the crisis.

The loss of trust can indicate the deterioration of the employee-employer relationship. Employees who experience job insecurity often believe their psychological contract with the organization is shattered. Employee trust in their workplace depends on the employer's trustworthiness, based on the organization's previous actions, generosity, and integrity [32]. Silla et al. [33] found that job insecurity is associated with poor well-being, and employability modifies the link between job insecurity and life satisfaction. Recent studies have further investigated the dynamics of trust in government. The Pew Research Center [52] borrowed from its stock-and-trend database to chart public attitudes regarding trust in government and its fluctuations in line with political and economic events over the past two and a half decades. According to the OECD [53], trust in government is essential for effective democratic governance, which relies on transparency, accountability, and responsiveness to public participation. The University of Waterloo's TRuST

Scholarly Network has run continuous surveys to measure trust in government regarding government responsiveness, reliability, and integrity [54].

**Hope**, a fundamental construct within positive psychology, is defined by Snyder [18] as comprising two key components: agency (*motivation to achieve goals*) and pathways (*perceived ability to create routes to those goals*). Hope is about having the will and the way to achieve desired outcomes. High hope in job insecurity is positive since individuals can manage uncertainties and stress, stay motivated to pursue, develop plans for achieving career goals, and thus remain resilient, adaptable, healthy, and satisfied with their lives [55], [18]. Studies show significantly that the level of hope is a significant determinant of life satisfaction and a key predictor of general well-being, with hope levels correlated positively with improved life satisfaction, appropriate mental health, and an optimistic attitude toward life [33], [18]. Hope and optimism were key drivers of workers' well-being during the COVID-19 outbreak, highlighting the need to keep a hopeful view in the face of challenging times [56]. Shoss et al. [39] demonstrated that perceptions of national employment insecurity during the pandemic correlated positively with solidarity and compliance with health precautions, suggesting that hope and collective efficacy may drive positive social behaviors. Additionally, Wu [57] focused on the effects of precarious employment on well-being in Europe, reporting that emotional precariousness, job insecurity, and employment instability all had negative effects on mental (e.g., depression, toxicity) and subjective well-being (e.g., life satisfaction), with hope and supportive environments acting as potential buffers in reducing these negative effects.

Cultivating hope allows individuals and organizations to build resilience, improve mental health outcomes, and enhance overall life satisfaction, even in challenging times. This study enriches Positive Psychology by demonstrating how hope acts as a psychological buffer during economic instability, showing that individuals with higher levels of hope experience less negative psychological impact and maintain life satisfaction. Further, it incorporates trust in government as an important positive psychological resource shaping the empowered citizen's behavior, broadening the perspective of the Positive Psychology approach at the level of collective or societal factors. These findings indicate how trust in government increases individual well-being and helps the general public follow health rules and participate in collectivist actions in situations like the COVID-19 pandemic. This paper provides a fuller picture of human flourishing by integrating hope and trust in government in a comprehensive well-being model.

**Conservation of Resources (COR) Theory:** Hobfoll's [58] conservation of resources (COR) theory suggests that people seek to gain, maintain, or protect valuable resources, including personal characteristics, conditions, objects, and energies. In the context of job insecurity, employees perceive a threat to their job and income security, which are essential resources, leading to stress, anxiety, and diminished well-being. COR theory provides a comprehensive framework for understanding the psychological impact of job insecurity and highlights the importance of resource management in mitigating its negative effects [58], [59].

Research has applied COR theory in various contexts, including job insecurity [60], [61], [22], [62], [63], [64], [65], [24], [66]. In integrating the concepts of hope and trust, COR theory aligns closely with **Positive Psychology**. As a resource, hope enables more efficient coping with the unavoidable stress and anxiety that comes with job insecurity, strengthening resilience and encouraging proactive problem-solving. According to the trust theory, trust in institutions serves as a countermeasure against the adverse impacts of job insecurity; it provides stability and mitigates uncertainty. This study contributes to COR theory by exploring the dynamics of resource loss and stress within job insecurity. Focusing on job insecurity highlights how perceived threats to job and income security and personal resources increase stress, anxiety, and diminished well-being. Furthermore, this study extends the COR theory by identifying hope and trust in government as essential resources. It demonstrates a more nuanced understanding of considerations like resource management and how different resources can help or hinder one another in relieving stress.

Drawing on empirical data collected from 27 European Union countries, the research provides an important cross-cultural validation of COR theory, showing its applicability across diverse socio-economic contexts and establishing a solid framework for future studies investigating the dynamics of resources in the workplace.

### 3. Data and Methodology

**Participants and procedure:** Online data were collected cross-sectionally and longitudinally through extensive surveys in PsyCorona between March 2020 and July 2021. For a broad, representative sample, the participants were recruited through social media, email, and online communities. Initial data included 64,426 individuals from 115 countries, with 19,521 participants from EU countries analyzed; the final sample included 8,750 participants with complete data for key variables. Data collection used convenience, representative, and snowball sampling. Responses from waves 5, 11, and 22 (731, 580, and 346 participants,

respectively) were analyzed, with baseline data from March 2020 and follow-up waves in May 2020, June 2020, and July 2021. Hope was also excluded from these waves but measured in waves 4, 10, and 16 for longitudinal consistency. This study employs a longitudinal approach, following participants across multiple waves to assess changes in job insecurity, life satisfaction, trust in government, and hope over time. The repeated measurement of key variables allows for an evaluation of trends rather than relying solely on cross-sectional snapshots. To account for temporal ordering, variables were measured at distinct time points, allowing an assessment of whether earlier experiences of job insecurity influenced later life satisfaction, trust, and hope. While cross-sectional relationships remain a part of the analysis, the inclusion of multiple waves enhances the ability to track evolving economic and psychological effects across different stages of the pandemic. This approach made it possible to secure validity and provide an overview of job insecurity and other variables' effects on life satisfaction [67].

| Variable                 | Baseline<br>(March 19th, 2020) | Wave 4-5<br>(April 25th, May<br>2nd, 2020) | Wave 10-11<br>(June 6th and 13th,<br>2020) | Wave 16-22 (13th<br>November, 2020,<br>14th July, 2021) |
|--------------------------|--------------------------------|--------------------------------------------|--------------------------------------------|---------------------------------------------------------|
| Job Insecurity           | X                              | w5                                         | w11                                        | w22                                                     |
| Life Satisfaction        | X                              | w5                                         | w11                                        | w22                                                     |
| Trust in Government      | X                              | w5                                         | w11                                        | w22                                                     |
| Hope ( <i>Economic</i> ) | X                              | w4                                         | w10                                        | w16                                                     |
| Age                      | X                              | /                                          | /                                          | /                                                       |
| Gender                   | X                              | /                                          | /                                          | /                                                       |
| Education                | X                              | /                                          | /                                          | /                                                       |

Table 1. Data collection from study variables

**Ethical Considerations:** The PsyCorona Survey received approval from the Ethical Committee of the University of Groningen (study code: PSY-1920-S-0390) and New York University Abu Dhabi (study code: HRPP-2020-42). Before starting the survey, participants gave informed consent by completing an online consent form. The consent form contained specific information about the purpose of the study, procedures, potential risks, and benefits.

**Sample Description:** Participants were obtained from 27 European countries. The total sample was 8,750 participants, with detailed demographic information, including age, gender, and education, collected for analysis.

- **Gender Distribution:** 60.4% identified as female, 39.0% identified as male, and 0.4% identified as other. A small number of participants (0.2%) did not report their gender.
- **Age Distribution:** Participants ranged from 18 to 85+ years. Specifically, 17.6% of participants were aged 18-24 years, 23.2% were aged 25-34 years, 22.4% were aged 35-44 years, 19.4% were aged 45-54 years, 13.2% were aged 55-64 years, 3.8% were aged 65-75 years, 0.3% were aged 75-85 years, and 0.1% were aged 85+ years. A small number of participants (0.1%) did not report their age.
- **Education Levels:** The distribution was as follows: 1.2% of participants had primary education, 12.1% had general secondary education, 12.1% had vocational education, 21.5% had higher education, 23.4% held a bachelor's degree, 22.6% held a master's degree, and 6.9% held a PhD degree. A small number of participants (0.2%) did not report their level of education.

Participants were all citizens of their countries. This range of demographic diversity increases the chance that the study's findings can be widely applied and represent a cross-section of populations. The demographic diversity in the sample adds to the external validity of any of the findings across the European Union context.

**Measures:** The scales were developed and validated by a team of experienced scientists from diverse international institutions (the PsyCorona team), which helped maintain their reliability and validity in measuring pandemic-related variables.

**Job insecurity scale:** Participants' perceptions of job insecurity were assessed using a scale adapted from Vander Elst et al. [66], administered at baseline and during waves 5, 11, and 22. They rated their agreement with statements such as: "Chances are, I will soon lose my job," "I am sure I can keep my job" (reverse scored), "I feel insecure about the future of my job," and "I already lost my job," on a Likert scale from -2 (*strongly disagree*) to 2 (*strongly agree*). Responses were averaged to compute a job insecurity score, with higher values indicating greater insecurity. The scale demonstrated strong internal consistency:  $\alpha = 0.832$  (*baseline*),  $\alpha = 0.819$  (*wave 5*),  $\alpha = 0.817$  (*wave 11*), and  $\alpha = 0.786$  (*wave 22*).

**Life satisfaction scale:** It was assessed using three items: happiness, life satisfaction, and purpose. Participants rated their agreement with the statements: “In general, how happy would you say you are?” (1 = *extremely unhappy* to 10 = *extremely happy*), “In general, how satisfied are you with your life?” (1 = *very dissatisfied* to 6 = *very satisfied*), and “My life has a clear sense of purpose” (-3 = *strongly disagree* to 3 = *strongly agree*). An average score was computed, with higher values indicating greater life satisfaction. The scale showed acceptable internal consistency:  $\alpha = 0.747$  (baseline),  $\alpha = 0.759$  (wave 5),  $\alpha = 0.783$  (wave 11), and  $\alpha = 0.767$  (wave 22).

**Trust in government:** It was assessed using the item: “In general, how much do you trust each of the following to take the right measures to deal with the coronavirus pandemic? - The government of your country.” Responses were rated on a 1 to 5 scale (1 = *Not at all*, 5 = *A great deal*), adapted from Stroebe et al. [68]. This item was selected for its relevance in evaluating trust in governmental actions during the pandemic, which is essential for understanding public response and compliance with health measures.

**Hope (Economic):** Participants rated their hope with the item: “Agree or disagree: I have high hopes that the situation regarding coronavirus’s economic and financial consequences will improve”. This item was rated on a scale from -3 to 3 (-3 = *Strongly disagree* to 3 = *Strongly agree*). This item was developed by Ben Gützkow, Max Agostini, Elissa El Khawli, Jannis Kreienkamp, and Anne-Margit Reitsema. This measure was added to capture participants’ optimism about the economy’s recovery, which is important for understanding the psychological and social effects of the pandemic.

**Covariates:** Covariates, such as age, gender, and education, were controlled for in the analysis to account for their potential influence on the outcomes.

Age affects job insecurity perceptions, with younger individuals facing greater instability and older workers struggling with re-entry [13], [16]. Gender plays a role in employment disparities, as women are more vulnerable to precarious conditions [3], [21]. Education enhances employability, shaping job stability, life satisfaction, and institutional trust [6], [10]. These covariates help control for individual differences, ensuring a precise estimation of effects.

Age was recorded as a continuous variable, gender was categorized as female, male, or other, and education was measured by the highest level completed (ranging from primary education to PhD). Including these covariates improved the reliability and validity of findings by adjusting for confounders.

**Handling missing data:** Missing data were addressed using listwise deletion to ensure consistency and integrity, assuming randomness [69]. Non-imputed data minimizes data alterations and preserves dataset authenticity throughout all waves. Although multiple imputation is a standard approach for missing data [70], it can introduce assumptions inconsistent with the original dataset. Using non-imputed data preserved natural variability and relationships, avoiding potential bias [69]. This method also maintained demographic representation, ensuring greater fidelity to participants’ experiences. While this reduces sample size and statistical power, power analyses confirmed that the final sample size remains sufficient to detect small-to-moderate effects, mitigating concerns about reduced statistical power. Limitations due to missing data are further discussed in the discussion section of this paper.

**Statistical analysis:** To assess serial mediation effects, we used PROCESS macro (Model 6) [71], which integrates path-based moderation and mediation into a conditional process model. This approach was chosen based on theoretical reasoning that job insecurity affects life satisfaction through trust in government [51], [53] and hope [33], [38], reflecting a progressive response rather than a direct effect. This model enabled the analysis of direct and indirect effects, providing insights into sequential relationships among key variables. Bootstrapping with 5,000 resamples ensured bias-corrected confidence intervals at a 95% confidence level, enhancing estimation precision and the reliability of mediation effects. As a non-parametric method, bootstrapping is recommended over traditional parametric tests when feasible [72], making it particularly suitable for this study. Analyses were conducted in SPSS version 22 to ensure robust and reliable statistical procedures.

To examine the relationship between job insecurity and life satisfaction, we treat job insecurity as the independent variable and life satisfaction as the dependent variable. Mediating variables include trust in government and hope, while covariates include age, gender, and education to account for potential confounding factors.

Hypotheses:

H<sub>1</sub>: Job insecurity will be negatively related to life satisfaction.

H<sub>2</sub>: Trust in government will mediate the relationship between job insecurity and life satisfaction.

H<sub>3</sub>: Hope will mediate the relationship between job insecurity and life satisfaction.

H<sub>4</sub>: Trust in government and hope will sequentially mediate the relationship between job insecurity and life satisfaction.

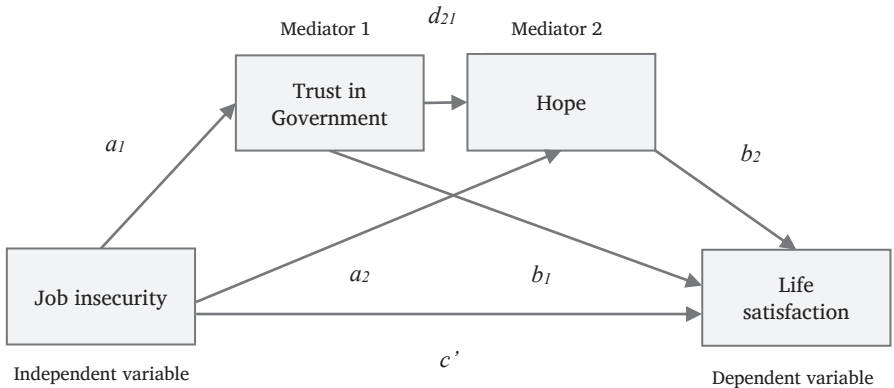


Figure 1. Research model

Model-basic equations used for regression calculations for the model described in the study are presented below:

**Trust in Government:**  $TrustGov = i_1 + a * JobIns + e_1,$  (1)

**Hope:**  $Hope = i_2 + b * JobIns + c' * TrustGov + e_2,$  (2)

**Life Satisfaction:**  $LifeSat = i_3 + c * JobIns + d * TrustGov + e * Hope + e_3.$  (3)

As covariates, we included age, gender, and education in our serial mediation model to control for potential confounding effects. The updated model equations are as follows:

$TrustGov = i_1 + a * JobIns + b_1 * Age + b_2 * Gen + b_3 * Edu + e_1,$  (1)

$Hope = i_2 + c * JobIns + c' * TrustGov + b_1 * Age + b_2 * Gen + b_3 * Edu + e_2,$  (2)

$LifeSat = i_3 + d * JobIns + e * TrustGov + f * Hope + b_1 * Age + b_2 * Gen + b_3 * Edu + e_3$  (3)

Where

*TrustGov* represents trust in government; *JobIns* represents job insecurity; *Hope* represents the level of hope; *LifeSat* represents life satisfaction;  $i_1, i_2, i_3$  are intercept coefficients;  $a, b, c, c', d, e, f$  are regression coefficients for the main predictors;  $b_1, b_2, b_3$  regression coefficients for the covariates (age, gender, education) and  $e_1, e_2, e_3$  are error terms.

These equations provide the basis for the sequential mediation analysis, examining job insecurity’s direct and indirect effects on well-being through the mediating variables of trust in government and hope. This study is among the few research models examining the relationship between job insecurity and life satisfaction, with a unique focus on trust in government and hope as mediators.

4. Results

**Descriptive statistics:** Table 2 summarizes the means and standard deviations for job insecurity, life satisfaction, trust in government, and hope across baseline, wave 5, wave 11, and wave 22. Notably, job insecurity gradually increased over time, while life satisfaction and trust in government demonstrated fluctuations, particularly with a decline in trust in government at wave 22.

| Measure             | Baseline (M, SD) | Wave 5 (M, SD) | Wave 11 (M, SD) | Wave 22 (M, SD) |
|---------------------|------------------|----------------|-----------------|-----------------|
| Job Insecurity      | -0.60 (0.97)     | -0.68 (0.95)   | -0.76 (0.92)    | -0.86 (0.91)    |
| Life Satisfaction   | 3.79 (1.26)      | 3.92 (1.24)    | 4.02 (1.27)     | 3.97 (1.28)     |
| Trust in Government | 2.98 (1.14)      | 2.91 (1.17)    | 2.96 (1.19)     | 2.47 (1.10)     |
| Hope (Economic)     | 0.14 (1.71)      | -0.07 (1.66)   | 0.24 (1.64)     | -0.17 (1.74)    |

**Note:** Listwise deletion was employed to handle missing data, ensuring that only cases with complete information across all variables were included in the analysis.

Table 2. Descriptive statistics for key measures across waves

We included responses from the 5th, 11th, and 22nd follow-up assessments with complete data for all key measures to examine changes over time. Specifically, 731 participants completed the survey during wave 5, 580 during wave 11, and 346 during wave 22.

**Correlation analysis:** Next, we explore the relationships between these key measures through Pearson correlation analyses. Table 3 presents Pearson correlations among the key measures at different waves.

| Measure                     | 1        | 2        | 3        | 4        |
|-----------------------------|----------|----------|----------|----------|
| <b>Baseline</b>             |          |          |          |          |
| 1. Job Insecurity           | 1        | -0.302** | -0.144** | -0.144** |
| 2. Life Satisfaction        | -0.302** | 1        | 0.181**  | 0.189**  |
| 3. Trust in Government      | -0.144** | 0.181**  | 1        | 0.252**  |
| 4. Hope ( <i>Economic</i> ) | -0.144** | 0.189**  | 0.252**  | 1        |
| <b>Wave 5</b>               |          |          |          |          |
| 1. Job Insecurity           | 1        | -0.306** | -0.179** | -0.248** |
| 2. Life Satisfaction        | -0.306** | 1        | 0.221**  | 0.214**  |
| 3. Trust in Government      | -0.179** | 0.221**  | 1        | 0.367**  |
| 4. Hope ( <i>Economic</i> ) | -0.248** | 0.214**  | 0.367**  | 1        |
| <b>Wave 11</b>              |          |          |          |          |
| 1. Job Insecurity           | 1        | -0.276** | -0.227** | -0.301** |
| 2. Life Satisfaction        | -0.276** | 1        | 0.196**  | 0.179**  |
| 3. Trust in Government      | -0.227** | 0.196**  | 1        | 0.387**  |
| 4. Hope ( <i>Economic</i> ) | -0.301** | 0.179**  | 0.387**  | 1        |
| <b>Wave 22</b>              |          |          |          |          |
| 1. Job Insecurity           | 1        | -0.219** | -0.058   | -0.207** |
| 2. Life Satisfaction        | -0.219** | 1        | 0.166**  | 0.189**  |
| 3. Trust in Government      | -0.058   | 0.166**  | 1        | 0.443**  |
| 4. Hope ( <i>Economic</i> ) | -0.207** | 0.189**  | 0.443**  | 1        |

Note:  $p < 0.01$  (2-tailed).

Table 3. Correlations among key measures across waves

Job insecurity is negatively related to life satisfaction and hope in all waves, as indicated in Table 3, suggesting that an increase in job insecurity is linked to a decrease in either life satisfaction or hope. Trust in government shows persistent positive correlations with life satisfaction and hope, except for a non-significant relationship with job insecurity at wave 22. These findings underscore the stable nature of these relationships over time.

**Mediation Analysis:** The mediation effects were assessed using the PROCESS macro [71], Model 6, designed for serial mediation analysis. Bootstrapping with 5,000 samples provided 95% bias-corrected confidence intervals for the indirect effects. MacKinnon et al. [72] noted that the bias-corrected bootstrap provides the most accurate confidence limits and the most significant statistical power. We utilized this method to test the mediation in our study. The results obtained using the PROCESS macro for SPSS [71] are presented in Figure 1, table 4 and 5.

**Baseline model:** Job insecurity significantly reduced trust in government (path  $a_1$ :  $b = -0.1705$ ,  $p < .001$ ) and hope (path  $a_2$ :  $b = -0.1959$ ,  $p < .001$ ). Trust in government positively influenced hope (path  $d_{12}$ :  $b = 0.3542$ ,  $p < .001$ ). Both trust in government (path  $b_1$ :  $b = 0.1225$ ,  $p < .001$ ) and hope (path  $b_2$ :  $b = 0.0895$ ,  $p < .001$ ) were positively associated with life satisfaction. Job insecurity directly negatively impacted life satisfaction (path  $c$ :  $b = -0.3500$ ,  $p < .001$ ). Indirect effects through trust in government (path  $c'$ :  $b = -0.0209$ ,  $p < .001$ ), through hope (path  $c''$ :  $b = -0.0175$ ,  $p < .001$ ), and through both mediators (path  $c'''$ :  $b = -0.0054$ ,  $p < .001$ ), were significant. Covariates (age, gender, education) did not alter these relationships, confirming their robustness.

**Wave 5 model:** Job insecurity negatively impacted trust in government (path  $a_1$ :  $b = -0.2369$ ,  $p < .001$ ) and hope (path  $a_2$ :  $b = -0.3394$ ,  $p < .001$ ), which in turn are positively associated with life satisfaction. Trust in government positively influenced hope (path  $d_{12}$ :  $b = 0.4770$ ,  $p < .001$ ). Both trust in government (path  $b_1$ :  $b = 0.1525$ ,  $p < .001$ ) and hope (path  $b_2$ :  $b = 0.0754$ ,  $p < .01$ ) were positively associated with life satisfaction. The direct negative effect of job insecurity on life satisfaction (path  $c$ :  $b = -0.3269$ ,  $p < .001$ ) and the indirect effects through trust in government (path  $c'$ :  $b = -0.0361$ ,  $p < .001$ ), through hope (path

$c'$ :  $b = -0.0256, p < .001$ ), and through both mediators (path  $c'$ :  $b = -0.0085, p < .001$ ) were significant. Covariates did not significantly change these relationships.

**Wave 11 model:** Job insecurity continued to negatively impact trust in government (path  $a_1$ :  $b = -0.3052, p < .001$ ) and hope (path  $a_2$ :  $b = -0.4091, p < .001$ ). Trust in government positively influenced hope (path  $d_{12}$ :  $b = 0.4643, p < .001$ ). Both trust in government (path  $b_1$ :  $b = 0.1259, p < .01$ ), and hope (path  $b_2$ :  $b = 0.0587, p < .086$ ), were positively associated with life satisfaction. The direct negative effect of job insecurity on life satisfaction (path  $c$ :  $b = -0.2639, p < .001$ ) and the indirect effects through trust in government (path  $c'$ :  $b = -0.0384, p < .001$ ), through hope (path  $c'$ :  $b = -0.0240, p < .001$ ), and through both mediators (path  $c'$ :  $b = -0.0083, p < .001$ ) were significant. Covariates did not alter these relationships.

**Wave 22 model:** Job insecurity did not significantly affect trust in government (path  $a_1$ :  $b = -0.0671, p < .299$ ) but negatively impacted hope (path  $a_2$ :  $b = -0.3404, p < .001$ ). Trust in government positively influenced hope (path  $d_{12}$ :  $b = 0.6730, p < .001$ ). Trust in government was not significantly associated with life satisfaction (path  $b_1$ :  $b = 0.0540, p < .390$ ), while hope (path  $b_2$ :  $b = 0.0897, p < .030$ ) was positively associated with life satisfaction. The direct negative effect of job insecurity on life satisfaction (path  $c$ :  $b = -0.2324, p < .001$ ) and the indirect effects through trust in government (path  $c'$ :  $b = -0.0036, p < .007$ ), through hope (path  $c'$ :  $b = -0.0305, p < .018$ ), and through both mediators (path  $c'$ :  $b = -0.0040, p < .005$ ) were significant. Covariates did not change these relationships.

Serial mediation analysis demonstrates that job insecurity significantly impacts life satisfaction through direct and indirect pathways. Specifically, the total effect ( $c'$ ) of job insecurity on life satisfaction is larger than the direct effect ( $c$ ), indicating the presence of significant mediation effects. The indirect effects through trust in government ( $a_1 \rightarrow b_1$ ) and hope ( $a_2 \rightarrow b_2$ ), as well as the combined indirect effect through both mediators ( $a_1 \rightarrow d_{12} \rightarrow b_2$ ), all significantly contribute to this relationship. This complementary partial mediation suggests that while job insecurity directly lowers life satisfaction, it also decreases trust in government and hope, negatively impacting life satisfaction. This is the classification of mediation by Zhao et al. [74].

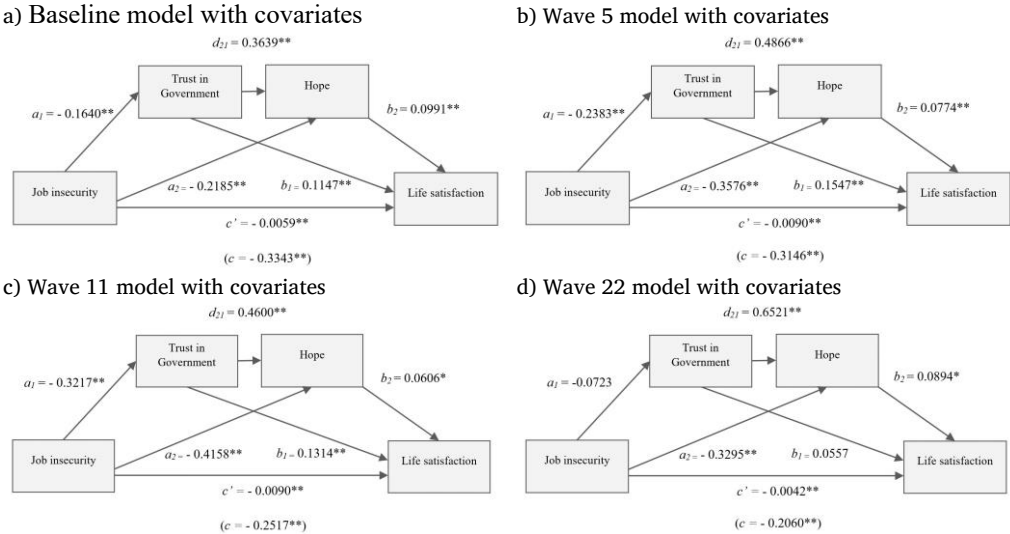


Figure 2. Serial mediation models

| Models                | JobIn → TrustG (path $a_1$ ) | JobIn → Hope (path $a_2$ ) | TrustG → Hope (path $d_{12}$ ) | TrustG → LifeSat (path $b_1$ ) | Hope → LifeSat (path $b_2$ ) | JobIn → LifeSat (path $c$ ) | JobIn → TrustG → LifeSat (path $c'$ ) | JobIn → Hope → LifeSat (path $c_2'$ ) | JobIn → TrustG → Hope → LifeSat (path $c_3'$ ) |
|-----------------------|------------------------------|----------------------------|--------------------------------|--------------------------------|------------------------------|-----------------------------|---------------------------------------|---------------------------------------|------------------------------------------------|
| Baseline              | $b = -0.1705$<br>(0.000**)   | $b = -0.1959$<br>(0.000**) | $b = 0.3542$<br>(0.000**)      | $b = 0.1225$<br>(0.000**)      | $b = 0.0895$<br>(0.000**)    | $b = -0.3500$<br>(0.000**)  | $b = -0.0209$<br>(0.000**)            | $b = -0.0175$<br>(0.000**)            | $b = -0.0054$<br>(0.000**)                     |
| Baseline <sup>a</sup> | $b = -0.1699$<br>(0.000**)   | $b = -0.2029$<br>(0.000**) | $b = 0.3563$<br>(0.000**)      | $b = 0.1206$<br>(0.000**)      | $b = 0.0921$<br>(0.000**)    | $b = -0.3500$<br>(0.000**)  | $b = -0.0205$<br>(0.000**)            | $b = -0.0187$<br>(0.000**)            | $b = -0.0056$<br>(0.000**)                     |

|                       |                            |                             |                           |                            |                            |                             |                             |                            |                             |
|-----------------------|----------------------------|-----------------------------|---------------------------|----------------------------|----------------------------|-----------------------------|-----------------------------|----------------------------|-----------------------------|
| Baseline <sup>b</sup> | $b = -0.1702$<br>(0.000**) | $b = -0.1986$<br>(0.000**)  | $b = 0.3581$<br>(0.000**) | $b = 0.1203$<br>(0.000**)  | $b = 0.0931$<br>(0.000**)  | $b = -0.3477$<br>(0.000**)  | $b = -0.0205$<br>(0.000**)  | $b = -0.0185$<br>(0.000**) | $b = -0.0057$<br>(0.000**)  |
| Baseline <sup>c</sup> | $b = -0.1640$<br>(0.000**) | $b = -0.2185$<br>(0.000**)  | $b = 0.3639$<br>(0.000**) | $b = 0.1147$<br>(0.000**)  | $b = 0.0991$<br>(0.000**)  | $b = -0.3343$<br>(0.000**)  | $b = -0.0188$<br>(0.000**)  | $b = -0.0217$<br>(0.000**) | $b = -0.0059$<br>(0.000**)  |
| Wave 5                | $b = -0.2369$<br>(0.000**) | $b = -0.3394$<br>(0.000**)  | $b = 0.4770$<br>(0.000**) | $b = 0.1525$<br>(0.0002**) | $b = 0.0754$<br>(0.0070**) | $b = -0.3269$<br>(0.000**)  | $b = -0.0361$<br>(0.000**)  | $b = -0.0256$<br>(0.000**) | $b = -0.0085$<br>(0.000**)  |
| Wave 5 <sup>a</sup>   | $b = -0.2369$<br>(0.000**) | $b = -0.3394$<br>(0.000**)  | $b = 0.4770$<br>(0.000**) | $b = 0.1543$<br>(0.0001**) | $b = 0.0754$<br>(0.0069**) | $b = -0.3269$<br>(0.000**)  | $b = -0.0365$<br>(0.000**)  | $b = -0.0256$<br>(0.000**) | $b = -0.0085$<br>(0.000**)  |
| Wave 5 <sup>b</sup>   | $b = -0.2375$<br>(0.000**) | $b = -0.3347$<br>(0.000**)  | $b = 0.4867$<br>(0.000**) | $b = 0.1569$<br>(0.0001**) | $b = 0.0727$<br>(0.0099**) | $b = -0.3268$<br>(0.000**)  | $b = -0.0373$<br>(0.000**)  | $b = -0.0243$<br>(0.000**) | $b = -0.0084$<br>(0.000**)  |
| Wave 5 <sup>c</sup>   | $b = -0.2383$<br>(0.000**) | $b = -0.3576$<br>(0.000**)  | $b = 0.4866$<br>(0.000**) | $b = 0.1547$<br>(0.0001**) | $b = 0.0774$<br>(0.0063**) | $b = -0.3146$<br>(0.000**)  | $b = -0.0369$<br>(0.000**)  | $b = -0.0277$<br>(0.000**) | $b = -0.0090$<br>(0.000**)  |
| Wave 11               | $b = -0.3052$<br>(0.000**) | $b = -0.4091$<br>(0.000**)  | $b = 0.4643$<br>(0.000**) | $b = 0.1259$<br>(0.0067**) | $b = 0.0587$<br>(0.0860*)  | $b = -0.2639$<br>(0.000**)  | $b = -0.0384$<br>(0.000**)  | $b = -0.0240$<br>(0.000**) | $b = -0.0083$<br>(0.000**)  |
| Wave 11 <sup>a</sup>  | $b = -0.3100$<br>(0.000**) | $b = -0.4070$<br>(0.000**)  | $b = 0.4665$<br>(0.000**) | $b = 0.1258$<br>(0.0070**) | $b = 0.0587$<br>(0.0862*)  | $b = -0.2640$<br>(0.000**)  | $b = -0.0390$<br>(0.000**)  | $b = -0.0239$<br>(0.000**) | $b = -0.0085$<br>(0.000**)  |
| Wave 11 <sup>b</sup>  | $b = -0.3100$<br>(0.000**) | $b = -0.4041$<br>(0.000**)  | $b = 0.4668$<br>(0.000**) | $b = 0.1265$<br>(0.0068**) | $b = 0.0574$<br>(0.0958**) | $b = -0.2642$<br>(0.000**)  | $b = -0.0392$<br>(0.000**)  | $b = -0.0232$<br>(0.000**) | $b = -0.0083$<br>(0.000**)  |
| Wave 11 <sup>c</sup>  | $b = -0.3217$<br>(0.000**) | $b = -0.4158$<br>(0.000**)  | $b = 0.4600$<br>(0.000**) | $b = 0.1314$<br>(0.0050**) | $b = 0.0606$<br>(0.0786*)  | $b = -0.2517$<br>(0.000**)  | $b = -0.0423$<br>(0.000**)  | $b = -0.0252$<br>(0.000**) | $b = -0.0090$<br>(0.000**)  |
| Wave 22               | $b = -0.0671$<br>(0.2992)  | $b = -0.3404$<br>(0.0001**) | $b = 0.6730$<br>(0.000**) | $b = 0.0540$<br>(0.3898)   | $b = 0.0897$<br>(0.0300*)  | $b = -0.2324$<br>(0.0008**) | $b = -0.0036$<br>(0.0070**) | $b = -0.0305$<br>(0.0185*) | $b = -0.0040$<br>(0.005**)  |
| Wave 22 <sup>a</sup>  | $b = -0.0743$<br>(0.2503)  | $b = -0.3394$<br>(0.0002**) | $b = 0.6741$<br>(0.000**) | $b = 0.0516$<br>(0.4130)   | $b = 0.0898$<br>(0.0299*)  | $b = -0.2344$<br>(0.0008**) | $b = -0.0038$<br>(0.0077**) | $b = -0.0305$<br>(0.0186*) | $b = -0.0045$<br>(0.0051**) |
| Wave 22 <sup>b</sup>  | $b = -0.0704$<br>(0.2735)  | $b = -0.3340$<br>(0.0002**) | $b = 0.6518$<br>(0.000**) | $b = 0.0523$<br>(0.4077)   | $b = 0.0917$<br>(0.0285*)  | $b = -0.2344$<br>(0.0008**) | $b = -0.0037$<br>(0.0075**) | $b = -0.0306$<br>(0.0183*) | $b = -0.0042$<br>(0.0049**) |
| Wave 22 <sup>c</sup>  | $b = -0.0723$<br>(0.2668)  | $b = -0.3295$<br>(0.0003**) | $b = 0.6521$<br>(0.000**) | $b = 0.0557$<br>(0.3730)   | $b = 0.0894$<br>(0.0309*)  | $b = -0.2060$<br>(0.0031**) | $b = -0.0040$<br>(0.0081**) | $b = -0.0294$<br>(0.0179*) | $b = -0.0042$<br>(0.0051**) |

**Note:** In paths values are presented unstandardized coefficients B, whereas within the parenthesis are the *p* values.

\**p* < 0.01; \*\**p* < 0.000

a controlled for age

b controlled for age and gender

c controlled for age, gender and education

Table 4. Path coefficients for hierarchical regressions across all models

| Model                 | Direct Effect (b) | SE     | 95% CI             | Indirect Effect (Trust) (b) | SE     | 95% CI             | Indirect Effect (Hope) (b) | SE     | 95% CI             | Indirect Effect (Trust → Hope) (b) | SE     | 95% CI             | Total Effect (b) | SE     | 95% CI             |
|-----------------------|-------------------|--------|--------------------|-----------------------------|--------|--------------------|----------------------------|--------|--------------------|------------------------------------|--------|--------------------|------------------|--------|--------------------|
| Baseline              | -0.3500           | 0.0133 | [-0.3760, -0.3239] | -0.0209                     | 0.0027 | [-0.0266, -0.0159] | -0.0175                    | 0.0024 | [-0.0225, -0.0132] | -0.0054                            | 0.0007 | [-0.0068, -0.0041] | -0.0438          | 0.0038 | [-0.0516, -0.0368] |
| Baseline <sup>a</sup> | -0.3468           | 0.0133 | [-0.3728, -0.3207] | -0.0205                     | 0.0027 | [-0.0260, -0.0154] | -0.0187                    | 0.0024 | [-0.0237, -0.0143] | -0.0056                            | 0.0007 | [-0.0070, -0.0043] | -0.0447          | 0.0038 | [-0.0526, -0.0376] |
| Baseline <sup>b</sup> | -0.3477           | 0.0133 | [-0.3737, -0.3216] | -0.0205                     | 0.0026 | [-0.0259, -0.0155] | -0.0185                    | 0.0025 | [-0.0235, -0.0138] | -0.0057                            | 0.0007 | [-0.0071, -0.0043] | -0.0446          | 0.0039 | [-0.0523, -0.0371] |
| Baseline <sup>c</sup> | -0.3343           | 0.0134 | [-0.3605, -0.3081] | -0.0188                     | 0.0026 | [-0.0243, -0.0141] | -0.0217                    | 0.0027 | [-0.0272, -0.0166] | -0.0059                            | 0.0007 | [-0.0074, -0.0045] | -0.0464          | 0.0041 | [-0.0547, -0.0388] |
| Wave 5                | -0.3269           | 0.0480 | [-0.4211, -0.2328] | -0.0361                     | 0.0121 | [-0.0629, -0.0154] | -0.0256                    | 0.0108 | [-0.0490, -0.0065] | -0.0085                            | 0.0038 | [-0.0169, -0.0021] | -0.0702          | 0.0173 | [-0.1058, -0.0391] |
| Wave 5 <sup>a</sup>   | -0.3265           | 0.0479 | [-0.4205, -0.2326] | -0.0365                     | 0.0120 | [-0.0627, -0.0158] | -0.0256                    | 0.0106 | [-0.0485, -0.0067] | -0.0085                            | 0.0037 | [-0.0166, -0.0022] | -0.0707          | 0.0174 | [-0.1073, -0.0390] |
| Wave 5 <sup>b</sup>   | -0.3268           | 0.0479 | [-0.4207, -0.2328] | -0.0373                     | 0.0123 | [-0.0649, -0.0163] | -0.0243                    | 0.0106 | [-0.0473, -0.0055] | -0.0084                            | 0.0038 | [-0.0170, -0.0018] | -0.0700          | 0.0175 | [-0.1084, -0.0389] |
| Wave 5 <sup>c</sup>   | -0.3146           | 0.0485 | [-0.4097, -0.2194] | -0.0369                     | 0.0122 | [-0.0638, -0.0161] | -0.0277                    | 0.0114 | [-0.0522, -0.0070] | -0.0090                            | 0.0039 | [-0.0175, -0.0021] | -0.0735          | 0.0180 | [-0.1115, -0.0402] |
| Wave 11               | -0.2639           | 0.0592 | [-0.3801, -0.1476] | -0.0384                     | 0.0167 | [-0.0733, -0.0082] | -0.0240                    | 0.0155 | [-0.0572, 0.0048]  | -0.0083                            | 0.0055 | [-0.0201, 0.0015]  | -0.0708          | 0.0229 | [-0.1189, -0.0273] |
| Wave 11 <sup>a</sup>  | -0.2640           | 0.0593 | [-0.3805, -0.1475] | -0.0390                     | 0.0173 | [-0.0762, -0.0073] | -0.0239                    | 0.0153 | [-0.0559, 0.0055]  | -0.0085                            | 0.0058 | [-0.0215, 0.0018]  | -0.0714          | 0.0233 | [-0.1201, -0.0280] |

|                      |         |        |                       |         |        |                       |         |        |                      |         |        |                      |         |        |                       |
|----------------------|---------|--------|-----------------------|---------|--------|-----------------------|---------|--------|----------------------|---------|--------|----------------------|---------|--------|-----------------------|
| Wave 11 <sup>b</sup> | -0.2642 | 0.0594 | [-0.3808,<br>-0.1476] | -0.0392 | 0.0172 | [-0.0760,<br>-0.0089] | -0.0232 | 0.0153 | [-0.0538,<br>0.0060] | -0.0083 | 0.0059 | [-0.0216,<br>0.0020] | -0.0707 | 0.0226 | [-0.1159,<br>-0.0272] |
| Wave 11 <sup>c</sup> | -0.2517 | 0.0598 | [-0.3691,<br>-0.1342] | -0.0423 | 0.0181 | [-0.0808,<br>-0.0089] | -0.0252 | 0.0157 | [-0.0579,<br>0.0034] | -0.0090 | 0.0059 | [-0.0219,<br>0.0012] | -0.0765 | 0.0239 | [-0.1262,<br>-0.0322] |
| Wave 22              | -0.2324 | 0.0689 | [-0.3679,<br>-0.0970] | -0.0036 | 0.0070 | [-0.0217,<br>0.0072]  | -0.0305 | 0.0185 | [-0.0718,<br>0.0005] | -0.0040 | 0.0050 | [-0.0157,<br>0.0044] | -0.0382 | 0.0201 | [-0.0818,<br>-0.0028] |
| Wave 22 <sup>a</sup> | -0.2344 | 0.0691 | [-0.3704,<br>-0.0985] | -0.0038 | 0.0077 | [-0.0238,<br>0.0082]  | -0.0305 | 0.0186 | [-0.0722,<br>0.0010] | -0.0045 | 0.0051 | [-0.0167,<br>0.0037] | -0.0388 | 0.0201 | [-0.0834,<br>-0.0034] |
| Wave 22 <sup>b</sup> | -0.2343 | 0.0692 | [-0.3704,<br>-0.0982] | -0.0037 | 0.0075 | [-0.0236,<br>0.0078]  | -0.0306 | 0.0183 | [-0.0707,<br>0.0000] | -0.0042 | 0.0049 | [-0.0150,<br>0.0041] | -0.0385 | 0.0197 | [-0.0808,<br>-0.0034] |
| Wave 22 <sup>c</sup> | -0.2060 | 0.0691 | [-0.3418,<br>-0.0701] | -0.0040 | 0.0081 | [-0.0242,<br>0.0080]  | -0.0294 | 0.0179 | [-0.0701,<br>0.0014] | -0.0042 | 0.0051 | [-0.0172,<br>0.0036] | -0.0377 | 0.0201 | [-0.0844,<br>-0.0040] |

Note:  $p < 0.01$  (2-tailed).

Effect size

SE: Standard Error

CI: Confidence Interval,  $p < 0.01$

a controlled for age

b controlled for age and gender

c controlled for age, gender and education

Table 5. Direct and indirect effects in serial mediation analysis for baseline, wave 5, 11, and 22

## 5. Hypotheses Testing

### H<sub>1</sub>: Job insecurity will be negatively related to life satisfaction.

The regression analyses confirmed that job insecurity is significantly negatively related to life satisfaction across all data collection waves.

- **Baseline model:** Regression results indicated a significant negative relationship between job insecurity and life satisfaction ( $b = -0.3343$ ,  $SE = 0.0134$ , 95% CI  $[-0.3605, -0.3081]$ ). The model was significant, accounting for 13.25% of the variance in life satisfaction ( $R = .3640$ ,  $R^2 = .1325$ ,  $F(6,8716) = 221.8315$ ,  $p < .001$ ).
- **Wave 5:** Consistent with baseline findings, wave 5 data showed a significant negative relationship ( $b = -0.3146$ ,  $SE = 0.0485$ , 95% CI  $[-0.4097, -0.2194]$ ), explaining 13.62% of the variance in life satisfaction ( $R^2 = .1362$ ).
- **Wave 11:** Job insecurity remained a significant predictor of lower life satisfaction ( $b = -0.2517$ ,  $SE = 0.0598$ , 95% CI  $[-0.3691, -0.1342]$ ), accounting for 8.60% of the variance ( $R^2 = .0860$ ).
- **Wave 22:** The relationship persisted at wave 22, with job insecurity significantly predicting lower life satisfaction ( $b = -0.2060$ ,  $SE = 0.0691$ , 95% CI  $[-0.3418, -0.0701]$ ), explaining 9.29% of the variance ( $R^2 = .0929$ ).

These results robustly support H<sub>1</sub>, demonstrating that job insecurity consistently predicts lower life satisfaction across multiple waves, with explained variance ranging from 8.60% to 13.62%.

### H<sub>2</sub>: Trust in government will mediate the relationship between job insecurity and life satisfaction.

Mediation analyses indicated that trust in government partially mediates the relationship between job insecurity and life satisfaction across multiple waves.

- **Baseline model:** The indirect effect of job insecurity on life satisfaction via trust in government was significant ( $b = -0.0188$ ,  $SE = 0.0026$ , 95% CI  $[-0.0243, -0.0141]$ ), indicating partial mediation. The model explained 2.28% of the variance in life satisfaction ( $R = .1510$ ,  $R^2 = .0228$ ,  $F(4,8718) = 50.8345$ ,  $p < .001$ ).
- **Wave 5:** Partial mediation was also observed at wave 5 ( $b = -0.0369$ ,  $SE = 0.0122$ , 95% CI  $[-0.0638, -0.0161]$ ), accounting for 3.94% of the variance ( $R = .1985$ ,  $R^2 = .0394$ ,  $F(4,725) = 7.4378$ ,  $p < .001$ ).
- **Wave 11:** At wave 11, the mediation effect remained significant ( $b = -0.0423$ ,  $SE = 0.0181$ , 95% CI  $[-0.0808, -0.0089]$ ), explaining 6.81% of the variance ( $R = .2610$ ,  $R^2 = .0681$ ,  $F(4,575) = 10.5093$ ,  $p < .001$ ).
- **Wave 22:** However, the mediation effect was not significant at wave 22 ( $b = -0.0040$ ,  $SE = 0.0081$ , 95% CI  $[-0.0242, 0.0080]$ ), with marginal model significance ( $R = .1538$ ,  $R^2 = .0237$ ,  $F(4,341) = 2.0652$ ,  $p = .0850$ ).

H<sub>2</sub> received mixed support. Trust in government significantly mediated at baseline, wave 5, and wave 11 but not at wave 22, suggesting temporal variations in the mediating role of trust in government.

**H<sub>3</sub>: Hope will mediate the relationship between job insecurity and life satisfaction.**

Mediation analyses demonstrated that hope partially mediates the relationship between job insecurity and life satisfaction across multiple waves.

- **Baseline model:** Significant mediation effect observed ( $b = -0.0217$ ,  $SE = 0.0027$ , 95% CI  $[-0.0272, -0.0166]$ ), accounting for 9.24% of the variance ( $R = .3040$ ,  $R^2 = .0924$ ,  $F(5,8717) = 177.4995$ ,  $p < .001$ ).
- **Wave 5:** Persistent mediation at wave 5 ( $b = -0.0277$ ,  $SE = 0.0114$ , 95% CI  $[-0.0522, -0.0070]$ ), explaining 18.97% of the variance ( $R = .4356$ ,  $R^2 = .1897$ ,  $F(5,724) = 33.9083$ ,  $p < .001$ ).
- **Wave 11:** Continued significance at wave 11 ( $b = -0.0252$ ,  $SE = 0.015$ , 95% CI  $[-0.0579, -0.0034]$ ), with 20.97% variance explained ( $R = .4579$ ,  $R^2 = .2097$ ,  $F(5,574) = 30.4599$ ,  $p < .001$ ).
- **Wave 22:** Mediation effect remained significant at wave 22 ( $b = -0.0294$ ,  $SE = 0.0179$ , 95% CI  $[-0.0701, -0.0014]$ ), accounting for 24.64% of the variance ( $R = .4964$ ,  $R^2 = .2464$ ,  $F(5,340) = 22.2351$ ,  $p < .001$ ).

These results robustly support H<sub>3</sub>, hoping to consistently mediate the relationship, explaining between 9.24% and 24.64% of the variance across waves.

**H<sub>4</sub>: Trust in government and hope will sequentially mediate the relationship between job insecurity and life satisfaction.**

Sequential mediation analyses revealed that trust in government and hope jointly mediate the relationship across multiple waves.

- **Baseline model:** The indirect effect of job insecurity on life satisfaction through trust in government and hope is significant ( $b = -0.0059$ ,  $SE = 0.0007$ , 95% CI  $[-0.0074, -0.0045]$ ). This indicates that job insecurity reduces trust in the government, lowering hope and ultimately decreasing life satisfaction. The model summary shows that the mediation model is significant, explaining 13.25% of the variance ( $R = .3640$ ,  $R^2 = .1325$ ,  $F(6,8716) = 221.8315$ ,  $p < .001$ ).
- **Wave 5:** Persistent effect observed ( $b = -0.0090$ ,  $SE = 0.0039$ , 95% CI  $[-0.0175, -0.0021]$ ). The model summary remains significant, indicating 13.62% of the variance in life satisfaction ( $R = .3691$ ,  $R^2 = .1362$ ,  $F(6,723) = 19.0073$ ,  $p < .001$ ).
- **Wave 11:** Significant effect at this wave ( $b = -0.0090$ ,  $SE = 0.0059$ , 95% CI  $[-0.0219, -0.0012]$ ), with 8.60% variance explained ( $R = .2932$ ,  $R^2 = .0860$ ,  $F(6,573) = 8.9818$ ,  $p < .001$ ).
- **Wave 22:** Sequential mediation was not significant at wave 22 ( $b = -0.0042$ ,  $SE = 0.0051$ , 95% CI  $[-0.0172, 0.0036]$ ). The model summary shows marginal significance, indicating 9.29% of the variance in life satisfaction ( $R = .3048$ ,  $R^2 = .0929$ ,  $F(6,339) = 5.7853$ ,  $p < .001$ ).

The sequential mediation by trust in government and hope is significant in the baseline, wave 5, and wave 11, explaining 8.60% and 13.62% of the variance in life satisfaction but not in wave 22. This indicates that while the combination of trust in government and hope can mediate the impact of job insecurity on life satisfaction, this effect may vary over time.

**6. Discussion**

This study's results provide significant insight into the multifaceted relationships between job insecurity, life satisfaction, trust in government, and hope. It also provides a solid understanding of the interaction of such variables, especially the COVID-19 pandemic in the European Union over time.

**Job Insecurity and Life Satisfaction:** The persistent negative relationship between job insecurity and life satisfaction aligns with a substantial body of literature highlighting the detrimental effects of job insecurity on well-being [2], [14], [30]. Job insecurity is linked to poorer mental health outcomes across various contexts and populations, indicating a universal threat to psychological well-being.

The effect of job insecurity on life satisfaction has also worsened due to the COVID-19 pandemic. This study's findings align with that of McNamara et al. [25], which found widespread job disruption and increased risks for those who remained employed during the pandemic. Wu [57] found that emotional precariousness and employment instability had a detrimental impact on employees' mental and subjective well-being, emphasizing the emotional aspect of job insecurity. Carr and Chung [12] found that perceived employment insecurity negatively affects life satisfaction but is less pronounced in countries with generous labor market policies. This aligns with the need for policy interventions that increase job stability and provide support systems for workers in times of uncertainty.

This longitudinal study demonstrates how job insecurity impacts life satisfaction not just at a single point in time but across multiple waves, indicating its persisting nature. According to Hobfoll's [58] Conservation of Resources (COR) theory, stress occurs because of the threat of resource loss. Job insecurity manifests as a threat of losing (depleting) resources that can yield stress, anxiety, and lowered well-being, consistent with COR theory.

*Trust in Government as a Mediator:* Trust in government is an important social resource that has the potential to mitigate the negative effects of job insecurity on life satisfaction, which is consistent with COR theory. During the pandemic, trust in government became essential. Effective and transparent governance is needed to provide support through this crisis. Studies by Poma and Pistoressi [74] and Lee [50] emphasize the importance of trust in public institutions during crises. Richter and Näswall [32] found that trust can mediate the relationship between job insecurity and well-being, aligning with our results. However, the erosion of trust in government over time, observed in wave 22, highlights the dynamic nature of trust. While earlier waves saw relatively stable trust levels, the later stages of the pandemic may have introduced external stressors that contributed to declining confidence in governmental institutions. Several possible factors could explain this shift, including growing economic instability, dissatisfaction with prolonged pandemic policies, and political turbulence in various European countries during that period. Research indicates that in prolonged crises, institutional trust tends to decline as public frustration mounts over governance decisions [53], [54]. Future studies should further investigate how evolving economic conditions, policy effectiveness, and political shifts influence long-term changes in governmental trust. Shoss et al. [75] further highlight that sustained efforts by governments, especially through transparent communication are crucial in maintaining public trust over time.

*Hope as a Mediator:* Across all waves, hope emerged as a strong mediator between job insecurity and life satisfaction. This is congruent with Positive Psychology [55], [18], which focuses on positive emotions and personal strength such as hope. Snyder [18] proposes two dimensions of hope: agency and pathways. High levels of hope enable people to cope with job insecurity since hope helps individuals find motivation and successful means of achieving career goals even in uncertain times. Han and Yan [17] and Alessandri et al. [56] also found that hope significantly predicts life satisfaction during crises. Practical measures to cultivate hope include career counseling, financial planning, and skill development programs.

*Sequential Mediation by Trust in Government and Hope:* The analysis presented in H<sub>4</sub> shows that trust in government and hope serve as sequential, complementary mediators of the association between job insecurity and life satisfaction. This process of sequential mediation indicates that job insecurity leads to less trust in government, which leads to less hope and less life satisfaction. This highlights the intricate relationship between individuals' trust in institutions and their psychological resources [3], [32]. Snyder [18] and Seligman [55] stress the importance of hope for well-being, which is consistent with our results. However, sustained job insecurity might undermine citizen trust in state governance, and diminish hopes and life satisfaction [75].

This study underlines the role of governmental trust and personal resources as key drivers of well-being. The trust in governmental structures offers stability and assurance, which can help keep hope alive even during the pandemic of job insecurity. This aligns with the Conservation of Resources (COR) theory [59], which assumes that people use external and internal resources when dealing with stress. The combination of these two constructs, governmental trust and hope, buffers the potentially negative impact of job insecurity on life satisfaction. These findings highlight the complex relationships among these variables and the need for further work to explore the factors influencing the efficacy of these mediators over time. The consistent negative impact of job insecurity on life satisfaction across multiple waves underscores the urgent need for interventions to address job insecurity.

*Practical Implications:* This finding has several practical implications for policymakers, employers, and mental health professionals:

- *Reducing job insecurity:* The persistent negative impact on life satisfaction highlights the need for interventions to reduce it and its associated stressors. Policymakers should prioritize creating stable and secure work environments, especially during times of crisis, to enhance overall life satisfaction and well-being among workers. Specific policy measures include expanding unemployment benefits to provide financial security, implementing wage subsidies to prevent layoffs, and promoting remote work incentives to improve job flexibility and stability. Investing in workforce retraining programs can also equip individuals with skills suited to evolving labor market demands, reducing long-term employment uncertainty.
- *Strengthening governmental trust:* The significant mediating role of trust in government in the earlier waves suggests that strengthening governmental trust can help buffer the adverse effects of job insecurity. This requires governments to build and preserve public trust through transparency,

competence, and responsiveness, especially during crises. Key strategies include enhancing transparent crisis communication through timely and data-driven updates, engaging citizens in participatory decision-making forums to build inclusivity, and strengthening oversight mechanisms to reinforce accountability in policy implementation. Tailored economic relief programs for vulnerable workers can further boost public confidence in governmental responsiveness.

- *Enhancing hope:* The only variable that consistently mediated the relationship was hope, underscoring the role that hope and optimism should play in those dealing with job insecurity. To combat the impending fear of unemployment or working from home, employers and mental health professionals can offer career counseling, financial planning, skill development, and other skills training programs to aide individuals in coping with employment uncertainties while promoting a positive outlook. Beyond career support, employers can take concrete steps to reduce job insecurity and enhance well-being. Flexible work arrangements, clear career pathways, and mentorship programs provide stability and growth opportunities. Employee Assistance Programs, mental health support, and stress management workshops help mitigate workplace uncertainty. Job redesign strategies, such as role predictability and cross-training, strengthen employment security, while financial safeguards, including severance protections and salary continuity measures, reduce economic stressors. Additionally, psychological interventions such as Cognitive Behavioral Therapy can help individuals reframe negative thoughts about job insecurity, encouraging a more constructive and hopeful mindset. Strengths-based coaching enables workers to recognize and leverage their strengths, improving motivation and adaptability. Mindfulness-based interventions, including meditation and guided visualization, can enhance emotional resilience during employment uncertainty. Narrative therapy techniques, combined with structured goal-setting frameworks like SMART goals, empower individuals to reframe their career trajectory with optimism, reinforcing pathways toward stability and professional growth.

## 7. Conclusion

This study fills a key gap in the literature by being one of the few longitudinal analyses examining the association between job insecurity and life satisfaction across multiple waves. Most prior research has relied on cross-sectional designs, which capture only a single time point and fail to account for the evolving nature of job insecurity during prolonged crises. Through a longitudinal approach, this study offers a dynamic perspective on how the effects of job insecurity, trust in government, and hope evolve over time, particularly within the unique context of the COVID-19 pandemic, a period marked by heightened employment instability and policy intervention. Policymakers, economic analysts, organizational leaders, and managers should consider these findings when designing targeted interventions to support individuals facing job insecurity. Beyond its applied contributions, this study also reinforces COR theory, showing that job insecurity reduces essential psychological and financial resources, leading to lower life satisfaction. Additionally, Positive Psychology highlights hope as a crucial mediator, with findings aligning with Snyder's agency and pathways model, indicating that hope strengthens resilience and adaptability in uncertain work conditions.

**Limitations and Future Research:** Further research could focus on the dynamic features of these interactions and discover other mediating variables leveraged in the influence of job insecurity on life satisfaction. This understanding will help operationalize the relevant mediators over time and context while enabling research to improve interventions to help people in these situations.

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## References

- [1] Mai, Q. D., Hill, T. D., Vila-Henninger, L., & Grandner, M. A. (2019). Employment insecurity and sleep disturbance: evidence from 31 European countries. *Journal of Sleep Research*, 28(1), e12763. <https://doi.org/10.1111/jsr.12763>
- [2] Abbas, M., Malik, M., & Sarwat, N. (2021). Consequences of job insecurity for hospitality workers amid COVID-19 pandemic: does social support help?. *Journal of Hospitality Marketing & Management*, 30(8), 957-981. <https://doi.org/10.1080/19368623.2021.1926036>
- [3] Alcover, C. M., Salgado, S., Nazar, G., Ramírez-Vielma, R., & González-Suhr, C. (2022). Job insecurity, financial threat, and mental health in the COVID-19 context: the moderating role of

- the support network. *Sage Open*, 12(3), 21582440221121048. <https://doi.org/10.1177/21582440221121048>
- [4] Bosmans, K., Vignola, E. F., Álvarez-López, V., Julià, M., Ahonen, E. Q., Bolívar, M., ... & Baron, S. L. (2023). Experiences of insecurity among non-standard workers across different welfare states: A qualitative cross-country study. *Social Science & Medicine*, 327, 115970. <https://doi.org/10.1016/j.socscimed.2023.115970>
  - [5] Ibanescu, B. C., Cristea, M., Gheorghiu, A., & Pascariu, G. C. (2023a). The regional evolution of job insecurity during the first COVID-19 wave in relation to the pandemic intensity. *Letters in Spatial and Resource Sciences*, 16(1), 13. <https://doi.org/10.1007/s12076-023-00337-9>
  - [6] Ibanescu, B. C., Gheorghiu, A., Cristea, M., Pascariu, G. C., PsyCorona Team, & Leander, P. (2023b). The evolution of job insecurity in spatial contexts in Europe during COVID-19 pandemic. *International Regional Science Review*, 46(5-6), 552-576. <https://doi.org/10.1177/01600176231160485>
  - [7] Ariza-Montes, A., Mahmood, F., Han, H., & Saleem, M. (2022). The mental well-being of health care professionals during the COVID-19 pandemic. *Journal of Occupational and Environmental Medicine*, 64(5), 429-442. <https://doi.org/10.1097/jom.0000000000002470>
  - [8] Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-Jabir, A., Iosifidis, C., ... & Agha, R. (2020). The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *International Journal of Surgery*, 78, 185-193. <https://doi.org/10.1016/j.ijssu.2020.04.018>
  - [9] Himmler, S., van Exel, J., Brouwer, W., Neumann-Böhme, S., Sabat, I., Schreyögg, J., ... & Torbica, A. (2024). Braving the waves: exploring capability well-being patterns in seven European countries during the COVID-19 pandemic. *The European Journal of Health Economics*, 25(4), 563-578. <https://doi.org/10.1007/s10198-023-01604-8>
  - [10] Wilson, J. M., Lee, J., Fitzgerald, H. N., Oosterhoff, B., Sevi, B., & Shook, N. J. (2020). Job insecurity and financial concern during the COVID-19 pandemic are associated with worse mental health. *Journal of Occupational and Environmental Medicine*, 62(9), 686-691. <https://doi.org/10.1097/jom.0000000000001962>
  - [11] Green, F. (2011). Unpacking the misery multiplier: How employability modifies the impacts of unemployment and job insecurity on life satisfaction and mental health. *Journal of Health Economics*, 30(2), 265-276. <https://doi.org/10.1016/j.jhealeco.2010.12.005>
  - [12] Carr, E., & Chung, H. (2014). Employment insecurity and life satisfaction: The moderating influence of labour market policies across Europe. *Journal of European Social Policy*, 24(4), 383-399. <https://doi.org/10.1177/0958928714538219>
  - [13] De Witte, H. (1999). Job insecurity and psychological well-being: Review of the literature and exploration of some unresolved issues. *European Journal of Work and Organizational Psychology*, 8(2), 155-177. <https://doi.org/10.1080/135943299398302>
  - [14] De Witte, H., Pienaar, J., & De Cuyper, N. (2016). Review of 30 years of longitudinal studies on the association between job insecurity and health and well-being: Is there causal evidence? *Australian Psychologist*, 51(1), 18-31. <https://doi.org/10.1111/ap.12176>
  - [15] Wang, H. J., Lu, C. Q., & Siu, O. L. (2015). Job insecurity and job performance: The moderating role of organizational justice and the mediating role of work engagement. *Journal of Applied Psychology*, 100(4), 1249-1258. <https://doi.org/10.1037/a0038330>
  - [16] Sora, B., Höge, T., Caballer, A., & Peiró, J. M. (2019). Employment contract, job insecurity and employees' affective well-being: The role of self-and collective efficacy. *Economic and Industrial Democracy*, 40(2), 193-214. <https://doi.org/10.1177/0143831x18804659>
  - [17] Han, G., & Yan, S. (2019). Does food safety risk perception affect the public's trust in their government? An empirical study on a national survey in China. *International Journal of Environmental Research and Public Health*, 16(11), 1874. <https://doi.org/10.3390/ijerph16111874>
  - [18] Snyder, C. R. (2002). Hope theory: Rainbows in the mind. *Psychological Inquiry*, 13(4), 249-275. [https://doi.org/10.1207/s15327965pli1304\\_01](https://doi.org/10.1207/s15327965pli1304_01)
  - [19] Rousseau, D. M., Sitkin, S. B., Burt, R. S., & Camerer, C. (1998). Not so different after all: A cross-discipline view of trust. *Academy of Management Review*, 23(3), 393-404. <https://doi.org/10.5465/amr.1998.926617>

- [20] Smith, D., & Riethmuller, P. (1999). Consumer concerns about food safety in Australia and Japan. *International Journal of Social Economics*, 26(6), 724-742. <https://doi.org/10.1108/03068299910227237>
- [21] Vermote, B., Waterschoot, J., Morbée, S., Van der Kaap-Deeder, J., Schrooyen, C., Soenens, B., ... & Vansteenkiste, M. (2022). Do psychological needs play a role in times of uncertainty? Associations with well-being during the COVID-19 crisis. *Journal of Happiness Studies*, 23(1), 257-283. <https://doi.org/10.1007/s10902-021-00398-x>
- [22] Kakar, A. S., Misron, A., Meyer, N., & Durrani, D. K. (2023). Job insecurity as a mediator between fearing COVID-19 and turnover intention: empirical evidence during the COVID-19 pandemic. *International Journal of Educational Management*, 37(4), 752-767. <https://doi.org/10.1108/ijem-12-2022-0511>
- [23] Perri, M., O'Campo, P., Gill, P., Gunn, V., Ma, R. W., Buhariwala, P., ... & Muntaner, C. (2024). Precarious work on the rise. *BMC Public Health*, 24(1), 2074. <https://doi.org/10.1186/s12889-024-19363-3>
- [24] Sender, A., Arnold, A., & Staffebach, B. (2017). Job security as a threatened resource: reactions to job insecurity in culturally distinct regions. *The International Journal of Human Resource Management*, 28(17), 2403-2429. <https://doi.org/10.1080/09585192.2015.1137615>
- [25] Sender, A., Arnold, A., & Staffebach, B. (2017). Job security as a threatened resource: reactions to job insecurity in culturally distinct regions. *The International Journal of Human Resource Management*, 28(17), 2403-2429. <https://doi.org/10.1080/09585192.2015.1137615>
- [26] Nieuwenhuis, R., & Yerkes, M. A. (2021). Workers' well-being in the context of the first year of the COVID-19 pandemic. *Community, Work & Family*, 24(2), 226-235. <https://doi.org/10.1080/13668803.2021.1880049>
- [27] Ellonen, N., & Nätti, J. (2015). Job insecurity and the unemployment rate: Micro-and macro-level predictors of perceived job insecurity among Finnish employees 1984–2008. *Economic and Industrial Democracy*, 36(1), 51-71. <https://doi.org/10.1177/0143831x13495720>
- [28] Kekesi, E. K., & Agyemang, C. B. (2014). Perceived job insecurity and psychological distress: The moderating role of work values. *International Journal of Management, Economics and Social Sciences*, 3(1), 18-35.
- [29] Vulkan, P., Saloniemi, A., Svalund, J., & Väisänen, A. (2015). Job insecurity and mental well-being in Finland, Norway, and Sweden. *Nordic Journal of Working Life Studies*, 5(2), 33-53. <https://doi.org/10.19154/njwls.v5i2.4792>
- [30] Graham, B. A., Sinclair, R. R., & Sliter, M. (2024). Job insecurity and health and well-being: What happens when you really need or love your job?. *Economic and Industrial Democracy*, 45(3), 674-695. <https://doi.org/10.1177/0143831x231183995>
- [31] Möhring, K., Naumann, E., Reifenscheid, M., Wenz, A., Rettig, T., Krieger, U., ... & Blom, A. G. (2021). The COVID-19 pandemic and subjective well-being: longitudinal evidence on satisfaction with work and family. *European Societies*, 23(sup1), S601-S617. <https://doi.org/10.1080/14616696.2020.1833066>
- [32] Richter, A., & Näswall, K. (2019). Job insecurity and trust: Uncovering a mechanism linking job insecurity to well-being. *Work & Stress*, 33(1), 22-40. <https://doi.org/10.1080/02678373.2018.1461709>
- [33] Silla, I., De Cuyper, N., Gracia, F. J., Peiro, J. M., & De Witte, H. (2009). Job insecurity and well-being: Moderation by employability. *Journal of Happiness Studies*, 10(6), 739-751. <https://doi.org/10.1007/s10902-008-9119-0>
- [34] Rajani, N. B., Giannakopoulos, G., & Filippidis, F. T. (2016). Job insecurity, financial difficulties and mental health in Europe. *Occupational Medicine*, 66(8), 681-683. <https://doi.org/10.1093/occmed/kqw111>
- [35] Glambek, M., Arnestad, M. N., & Matthiesen, S. B. (2023). Perceived job insecurity climate in uncertain times: implications for work-related health among leaders versus non-leaders. *Journal of Managerial Psychology*, 38(7), 541-557. <https://doi.org/10.1108/jmp-10-2021-0542>
- [36] Kim, T. J., & von dem Knesebeck, O. (2015). Is an insecure job better for health than having no job at all? A systematic review of studies investigating the health-related risks of both job

- insecurity and unemployment. *BMC Public Health*, 15(1), 985. <https://doi.org/10.1186/s12889-015-2313-1>
- [37] Polinesi, G., Ciommi, M., & Gigliarano, C. (2023). Impact of COVID-19 on elderly population well-being: evidence from European countries. *Quality & Quantity*, 1-23. <https://doi.org/10.1007/s11135-023-01656-1>
- [38] Urbanaviciute, I., Massoudi, K., & De Witte, H. (2024). Job insecurity and (un) sustainable well-being: unravelling the dynamics of work, career, and life outcomes from a within-person perspective. *European Journal of Work and Organizational Psychology*, 33(5), 658-670. <https://doi.org/10.1080/1359432x.2024.2370666>
- [39] Shoss, M., Van Hootegem, A., Selenko, E., & De Witte, H. (2023). The job insecurity of others: On the role of perceived national job insecurity during the COVID-19 pandemic. *Economic and Industrial Democracy*, 44(2), 385-409. <https://doi.org/10.1177/0143831x221076176>
- [40] De Angelis, M., Mazzetti, G., & Guglielmi, D. (2021). Job insecurity and job performance: A serial mediated relationship and the buffering effect of organizational justice. *Frontiers in Psychology*, 12, 694057. <https://doi.org/10.3389/fpsyg.2021.694057>
- [41] Jiang, L. (2024). Rethinking job insecurity research: Challenging the homogeneous, linear, and negative effects of job insecurity. *Applied Psychology*. <https://doi.org/10.1111/apps.12534>
- [42] Allas, T., Chinn, D., Pal, E. S., & Zimmerman, W. (2020). Well-being in Europe: Addressing the high cost of COVID-19 on life satisfaction. *McKinsey and Company*. <https://www.mckinsey.com/featured-insights/europe/well-being-in-europe-addressing-the-high-cost-of-covid-19-on-life-satisfaction?form=MG0AV3>
- [43] Antino, M., Ruiz-Zorrilla, P., Sanz-Vergel, A. I., Leon-Perez, J. M., & Rodriguez-Muñoz, A. (2022). The role of job insecurity and work-family conflict on mental health evolution during COVID-19 lockdown. *European Journal of Work and Organizational Psychology*, 31(5), 667-684. <https://doi.org/10.1080/1359432x.2022.2049251>
- [44] Diaz Hernandez, L., Giezendanner, S., Fischer, R., & Zeller, A. (2021). The effect of COVID-19 on mental well-being in Switzerland: a cross-sectional survey of the adult Swiss general population. *BMC Family Practice*, 22, 1-14. <https://doi.org/10.1186/s12875-021-01532-7>
- [45] Anand, A., Dalmasso, A., Vessal, S. R., Parameswar, N., Rajasekar, J., & Dhal, M. (2023). The effect of job security, insecurity, and burnout on employee organizational commitment. *Journal of Business Research*, 162, 113843. <https://doi.org/10.1016/j.jbusres.2023.113843>
- [46] Diener, E. (1984). Subjective well-being. *Psychological Bulletin*, 95(3), 542-575. <https://doi.org/10.1037//0033-2909.95.3.542>
- [47] Kim-Prieto, C., Diener, E., Tamir, M., Scollon, C., & Diener, M. (2005). Integrating the diverse definitions of happiness: A time-sequential framework of subjective well-being. *Journal of Happiness Studies*, 6(3), 261-300. <https://doi.org/10.1007/s10902-005-7226-8>
- [48] Diener, E., & Seligman, M. E. (2002). Very happy people. *Psychological Science*, 13(1), 81-84. <https://doi.org/10.1111/1467-9280.00415>
- [49] Easterlin, R. A. (2001). Income and happiness: Towards a unified theory. *The Economic Journal*, 111(473), 465-484. <https://doi.org/10.1111/1468-0297.00646>
- [50] Lee, S. (2022). Subjective well-being and mental health during the pandemic outbreak: Exploring the role of institutional trust. *Research on Aging*, 44(1), 10-21. <https://doi.org/10.1177/0164027520975145>
- [51] Han, Q., Zheng, B., Cristea, M., Agostini, M., Bélanger, J. J., Gützkow, B., ... & PsyCorona Collaboration. (2023). Trust in government regarding COVID-19 and its associations with preventive health behaviour and prosocial behaviour during the pandemic: a cross-sectional and longitudinal study. *Psychological Medicine*, 53(1), 149-159. <https://doi.org/10.1017/s0033291721001306>
- [52] Pew Research Center. (2024). *Public trust in government: 1958-2024*. Pew Research Center. Retrieved from <https://www.pewresearch.org/politics/2024/06/24/public-trust-in-government-1958-2024/>
- [53] Organisation for Economic Co-operation and Development (OECD). (2024). *Trust in government*. OECD. Retrieved from <https://www.oecd.org/en/topics/trust-in-government.html>

- [54] Steinburg, J. (2024). *Trust in Canada: Recent trends in measures of trust*. University of Waterloo TRuST Scholarly Network. Retrieved from <https://uwaterloo.ca/trust-research-undertaken-science-technology-scholarly-network/sites/default/files/uploads/documents/trust-in-canada-recent-trends-in-measures-of-trust-april-2024.pdf>
- [55] Seligman, M. E. (2004). *Authentic happiness: Using the new positive psychology to realize your potential for lasting fulfillment*. Simon and Schuster. <https://doi.org/10.1176/appi.ajp.161.5.936>
- [56] Alessandri, G., Filosa, L., Sonnentag, S., Crea, G., Borgnogni, L., Avanzi, L., ... & Crocetti, E. (2023). Determinants of workers' well-being during the COVID-19 outbreak: An exploratory study. *Current Psychology*, 42(10), 8595-8614. <https://doi.org/10.1007/s12144-021-02408-w>
- [57] Wu, Q. (2023). Employment Precarity, COVID-19 Risk, and Workers' Well-Being During the Pandemic in Europe. *Work and Occupations*, 50(2), 188-211. <https://doi.org/10.1177/07308884221126415>
- [58] Hobfoll, S. E. (1989). Conservation of resources: a new attempt at conceptualizing stress. *American Psychologist*, 44(3), 513. <https://doi.org/10.1037//0003-066x.44.3.513>
- [59] Hobfoll, S. E., Halbesleben, J., Neveu, J. P., & Westman, M. (2018). Conservation of resources in the organizational context: The reality of resources and their consequences. *Annual Review of Organizational Psychology and Organizational Behavior*, 5(1), 103-128. <https://doi.org/10.1146/annurev-orgpsych-032117-104640>
- [60] De Cuyper, N., Mäkikangas, A., Kinnunen, U., Mauno, S., & Witte, H. D. (2012). Cross-lagged associations between perceived external employability, job insecurity, and exhaustion: Testing gain and loss spirals according to the conservation of resources theory. *Journal of Organizational Behavior*, 33(6), 770-788. <https://doi.org/10.1002/job.1800>
- [61] Debus, M. E., & Unger, D. (2017). The interactive effects of dual-earner couples' job insecurity: Linking conservation of resources theory with crossover research. *Journal of Occupational and Organizational Psychology*, 90(2), 225-247. <https://doi.org/10.1111/joop.12169>
- [62] Kundi, Y. M., Hollet-Haudebert, S., & Peterson, J. (2024). Motivational career resources and subjective career success: a test of mediation and moderation. *Journal of Career Assessment*, 32(4), 678-697. <https://doi.org/10.1177/10690727231218879>
- [63] Ma, B., Zhou, Y., Ma, G., Lassleben, H., & Zhang, G. (2024). Job insecurity and innovative behavior: the mediating role of impression management and the moderating role of job embeddedness. *Current Psychology*, 43(37), 29810-29822. <https://doi.org/10.1007/s12144-024-06550-z>
- [64] Neves, P. (2018). Exploring a model of workplace ostracism: The value of coworker humor. *International Journal of Stress Management*, 25(4), 330. <https://doi.org/10.1037/str0000069>
- [65] Qian, S., Yuan, Q., Niu, W., & Liu, Z. (2022). Is job insecurity always bad? The moderating role of job embeddedness in the relationship between job insecurity and job performance. *Journal of Management & Organization*, 28(5), 956-972. <https://doi.org/10.1017/jmo.2018.77>
- [66] Vander Elst, T., De Witte, H., & De Cuyper, N. (2014). The Job Insecurity Scale: A psychometric evaluation across five European countries. *European Journal of Work and Organizational Psychology*, 23(3), 364-380. <https://doi.org/10.1080/1359432x.2012.745989>
- [67] Jäckle, A., Gaia, A., & Benzeval, M. (2017). Mixing modes and measurement methods in longitudinal studies.
- [68] Stroebe, W., Kreienkamp, J., Leander, N. P., & Agostini, M. (2021). Do Canadian and US American handgun owners differ?. *Canadian Journal of Behavioural Science/Revue Canadienne des Sciences du Comportement*, 53(3), 221. <https://doi.org/10.1037/cbs0000243>
- [69] Little, R. J., & Rubin, D. B. (2019). *Statistical analysis with missing data* (Vol. 793). John Wiley & Sons. <https://doi.org/10.1002/9781119482260>
- [70] Rubin, D. B. (1987). *Statistical analysis with missing data*. Wiley.
- [71] Hayes, A. F. (2022). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach* (3rd edition). New York: The Guilford Press.

- [72] MacKinnon, D. P., Lockwood, C. M., & Williams, J. (2004). Confidence limits for the indirect effect: Distribution of the product and resampling methods. *Multivariate Behavioral Research*, 39(1), 99-128. [https://doi.org/10.1207/s15327906mbr3901\\_4](https://doi.org/10.1207/s15327906mbr3901_4)
- [73] Zhao, X., Lynch Jr, J. G., & Chen, Q. (2010). Reconsidering Baron and Kenny: Myths and truths about mediation analysis. *Journal of Consumer Research*, 37(2), 197-206. <https://doi.org/10.1086/651257>
- [74] Poma, E., & Pistoiesi, B. (2024). Government Support Measures, Trust in Institutions and Effects on Satisfaction with Democracy During the COVID-19 Outbreak. *Comparative Economic Studies*, 66(2), 355-387. <https://doi.org/10.1057/s41294-023-00223-9>
- [75] Shoss, M., Su, S., Schlotzhauer, A., & Carusone, N. (2022). Job insecurity harms both employees and employers. *Harvard Business Review*, 26.
- [76] Agostini, M., Kreienkamp, J., Gützkow, B., Bélanger, J. J., Reitsema, A. M., Myroniuk, S., Bellm, M., Abakoumkin, G., Abdul Khaiyom, J. H., Ahmedi, V., Akkas, H., Almenara, C. A., Atta, M., Bagci, S. C., Balliet, D., Basel, S., Berisha Kida, E., Buttrick, N. R., Chobthamkit, P., Choi, H.-S., Cristea, M., Csaba, S., Damjanović, K., Danyliuk, I., Dash, A., Di Santo, D., Douglas, K. M., Enea, V., Faller, D. G., Fitzsimons, G., Gheorghiu, A., Gómez, Á., Grzymala-Moszczyńska, J., Han, Q., Helmy, M., Hudiyana, J., Jeronimus, B. F., Jiang, D.-Y., Jin, S., Joireman, J., Jovanović, V., Kamenov, Z., Kende, A., Keng, S.-L., Kieu, T. T. T., Koc, Y., Kovyazina, K., Kozytska, I., Krause, J., Kruglanski, A. W., Kurapov, A., Kutlaca, M., Lantos, N. A., Lemay Jr, E. P., Lesmana, C. B. J., Louis, W. R., Lueders, A., Malik, N., Martinez, A. P., McCabe, K. O., Milla, M. N., Mohammed, I., Molinario, E., Moyano, M., Muhammad, H., Mula, S., Muluk, H., Najafi, R., Nisa, C. F., Nyúl, B., O'Keefe, P. A., Osuna, J. J. O., Osin, E. N., Park, J., Pica, G., Pierro, A., Rees, J., Resta, E., Romano, A., Rullo, M., Ryan, M. K., Samekin, A., Santtila, P., Sasin, E., Schumpe, B. M., Selim, H. A., Stanton, M. V., Stroebe, W., Sultana, S., Sutton, R. M., Tseliou, E., Utsugi, A., van Breen, J. A., van Lissa, C. J., Van Veen, K., vanDellen, M. R., Vázquez, A., Wollast, R., Yeung, V. W.-L., Zand, S., Lav Žeželj, I., Zheng, B., Zick, A., Zúñiga, C., & Leander, N. P. (2022). PsyCorona Dataset. DataverseNL. <https://doi.org/10.34894/PX5IVZ>



# Smart Real-time Attendance System for Nigerian Universities

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## ABSTRACT

This study proposes a Smart Real-Time Attendance System using face recognition technology to address challenges in traditional attendance systems in Nigerian universities. These challenges include proxy attendance, manual errors, and administrative inefficiencies. The system employs Convolutional Neural Networks (CNNs) and the ArcFace algorithm for facial feature extraction and identity verification. Key development tools included InsightFace, OpenCV, and Streamlit, with Visual Studio Code as the IDE. The system ensures high accuracy, with 94% face detection, 98% face recognition, and 96% overall attendance prediction accuracy. It automates essential tasks like attendance percentage calculation and report generation, ensuring compliance with the National Universities Commission (NUC) 75% attendance requirement for exam eligibility. Ethical compliance was a core design concern, including informed consent, data encryption, access control, and fairness across facial profiles. This system significantly reduces impersonation, administrative workload, and enhances operational efficiency, making it a scalable and secure solution for attendance management. Its deployment is recommended for improving academic monitoring and policy enforcement in Nigerian universities.

**Keywords:** Smart Attendance System, Face Recognition Technology, Convolutional Neural Networks (CNNs), Real-Time Attendance Monitoring and Automated Student Verification

## 1. Introduction

Attendance management plays a vital role in ensuring academic integrity and regulatory compliance within higher education institutions. In Nigerian universities, student attendance is a key factor in determining eligibility for semester examinations, as mandated by the National Universities Commission (NUC), which requires a minimum of 75% attendance. However, conventional attendance tracking methods such as manually signing attendance sheets or calling roll numbers are inefficient, error-prone, and susceptible to manipulations. These outdated methods create administrative burdens and make it challenging to enforce attendance policies, particularly in large lecture halls. Additionally, proxy attendance and forgery remain prevalent, undermining the credibility of attendance records [3].

Despite advancements in automation and digital transformation, many Nigerian universities still rely on these traditional methods. The increasing student population and the tedious nature of manual tracking make it difficult for lecturers to compute percentage attendance, particularly for visiting lecturers who require accurate attendance records for payment processing. Additionally, with the rise in security threats within educational institutions, unrestricted access to classrooms poses significant risks [21]. However, most existing

systems do not address the need for integrated solutions that simultaneously ensure attendance accuracy, institutional security, and administrative automation especially within the unique constraints of Nigerian universities. This research addresses that gap by proposing a system that not only tracks student presence but also detects unauthorized access and provides secure, real-time reporting capabilities.

Facial recognition technology has evolved significantly since its early development in the 1960s by pioneers such as Woody Bledsoe, Helen Chan Wolf, and Charles Bisson. Initially, the focus was on identifying facial landmarks through computational analysis [23]. While early research was limited, modern advancements have propelled facial recognition to widespread adoption in various domains. Today, facial recognition is integrated into social media platforms (e.g., Facebook's photo tagging system), mobile applications (e.g., face-enhancing features and age estimation tools), and Augmented Reality (AR) applications (e.g., Instagram and Snapchat filters), underscoring its adaptability across different fields.

Facial recognition is a biometric authentication technique that identifies individuals by comparing real-time captures with stored images. It is increasingly preferred over other biometric methods due to its non-intrusiveness and efficiency. Machine learning algorithms, particularly deep learning-based Convolutional Neural Networks (CNNs), have significantly improved the accuracy and robustness of face recognition systems [28].

Attendance tracking is a crucial administrative function in both educational and corporate environments, serving as a metric for student assessment and employee productivity. However, manual attendance systems suffer from various shortcomings, including errors, impersonation, and administrative inefficiencies. Several studies have highlighted these challenges:

1. Proxy attendance and forgery remain persistent issues in large classrooms [29].
2. Traditional attendance-taking methods require significant time and effort, reducing lecture efficiency [11].
3. Contact-based biometric solutions (e.g., fingerprint scanners) pose hygiene concerns, particularly in post-pandemic settings [24], [32].

To address these limitations, artificial intelligence (AI)-based smart attendance systems leveraging facial recognition technology offer an optimal solution. These systems provide real-time tracking, automation of attendance percentage computation, and enhanced security.

This research proposes a Smart Real-Time Attendance System for Nigerian universities, integrating face recognition technology to overcome the limitations of existing methods. The system utilizes deep learning algorithms for accurate facial recognition and automated attendance processing. The hardware implementation includes a Raspberry Pi 4 kit and a video camera capable of recognizing multiple faces in real time. The captured images are processed using Convolutional Neural Networks (CNNs) to compare them with a pre-registered student database, thereby ensuring seamless attendance tracking.

Key features of the proposed system include:

1. Automated attendance computation, determining whether students meet the required 75% threshold.
2. Detection of unauthorized individuals in lecture halls, enhancing campus security.
3. Integration with university administrative systems, allowing attendance reports to be sent to the Head of Department (HOD) via email.
4. Support for visiting lecturers, ensuring accurate attendance tracking for payment processing.

When deployed, this AI-powered attendance system will mitigate attendance irregularities, streamline administrative processes, enhance classroom security, and improve the efficiency of attendance management in Nigerian universities.

Nigerian universities have experienced a rapid increase in student enrollment, making attendance management increasingly difficult. Traditional methods of recording attendance, such as manual sign-ins and roll calls, are time-consuming, inefficient, and prone to inaccuracies. The challenges include:

1. Inability to compute percentage attendance accurately, leading to the non-enforcement of the NUC-mandated 75% attendance policy [20].
2. Difficulties faced by visiting lecturers in tracking student attendance for payment purposes.
3. Security risks in classrooms, as large lecture halls are vulnerable to unauthorized access and potential security threats.
4. High prevalence of proxy attendance, undermining academic integrity.
5. Disruptions caused by manual attendance tracking, affecting lecture efficiency.

An automated, AI-powered attendance system is required to address these challenges effectively.

The aim of this research is to develop a Smart Real-Time Attendance System for Nigerian Universities that leverages face recognition technology to enhance efficiency, accuracy, and security in attendance management. The specific objectives are to:

1. Develop an automated attendance system using face recognition technology for real-time attendance tracking.
2. Implement an attendance computation system to determine whether students meet the 75% NUC requirement.
3. Facilitate attendance tracking for visiting lecturers, ensuring accurate payment processing and accountability for staff duties.
4. Enhance classroom security by detecting unidentified individuals and reporting unauthorized access.

Unlike existing systems that focus solely on biometric attendance logging or basic face detection, this study presents a novel integration of real-time facial recognition, security alerting, and automated administrative reporting. By combining these three functional pillars into a unified platform optimized for resource-constrained educational institutions, our approach demonstrates a more holistic and scalable solution than prior work in the field.

## 2. Related Works

Face recognition technology has become central to modern attendance systems, offering automated, real-time alternatives to manual processes. Various studies have explored different methodologies and implementation approaches, examining their strengths and limitations. This section organizes key studies into four sub-themes for clarity and critical analysis.

### 2.1. Hardware-Intensive Systems

[15] demonstrated the application of YOLO V3 in tracking classroom attendance, showcasing high processing speed and accuracy with large datasets. However, it was limited by its dependence on high-quality cameras and controlled lighting—factors often unavailable in low-resource environments. Similarly, [25] proposed a dual-camera system to cross-verify individuals at classroom entry and within the classroom, effectively reducing impersonation but requiring costly hardware. [6] addressed scalability by developing a Raspberry Pi-based system integrated with cloud platforms. Although financially accessible, such systems often fall short in handling the demands of larger institutions with complex datasets. RFID-based systems, as discussed by [22], are affordable and easy to deploy but lack robust security features. Mobile-based solutions have also emerged. [30] developed a mobile app using QR codes and GPS, effective for hybrid and remote learning but limited by smartphone availability and user compliance—particularly in underserved communities. Likewise, [12] integrated GSM-based notifications, improving communication but remaining vulnerable in areas with poor network connectivity.

### 2.2. Lighting-Sensitive Models

Addressing lighting-related challenges, [11] employed HaarCascade and Local Binary Pattern Histogram (LBPH) algorithms. Though effective in moderate conditions, these techniques struggled with extreme lighting variations and partial face occlusion. [33] introduced a Siamese neural network to manage lighting and background variation challenges, though the approach demanded significant computational power. [14] showed that transfer learning significantly enhances CNN-based classification accuracy with limited training data, suggesting its relevance for facial recognition tasks in resource-constrained settings. [7] achieved 99.4% accuracy by fusing computer vision with neural networks, though this relied on well-lit environments. [29] proposed histogram-based optimization for faster processing, though it was less effective with high-resolution images under variable environmental conditions.

### 2.3. Security-Enhanced Attendance Systems

[27] combined Convolutional Neural Networks (CNN) with Long Short-Term Memory (LSTM) models to handle sequential attendance data. While this hybrid approach improved temporal data analysis, its high computational demands posed feasibility challenges for smaller institutions. [3] demonstrated the predictive capacity of hybrid LSTM-GRU models during the COVID-19 pandemic, although requiring extensive datasets. Dual-purpose systems have emerged, combining attendance tracking with access control. [17] presented such a system, which increased security but raised data privacy concerns. Likewise, [16] explored real-time facial recognition for security and attendance, noting its deterrence effect against unauthorized access. [9]

integrated gender classification into recognition systems using LBPH and HaarCascade, improving accuracy while emphasizing the need for more inclusive datasets.

2.4. Nigerian Context and Policy Considerations

Within the Nigerian context, several studies underscore practical implementation of biometric attendance systems. At LASU Epe campus, [26] deployed a facial recognition system that significantly improved attendance management. Similarly, [1] implemented an RFID-based system in a Nigerian university, highlighting its enhanced accuracy. [20] further proposed a face recognition system customized for Nigerian tertiary institutions, emphasizing its contextual adaptability. [19] discussed both the potential benefits and risks of facial recognition across sectors, advocating for regulatory oversight to safeguard individual rights. [4] reviewed biases stemming from non-diverse datasets and called for fairness-centered system design.

2.5. Comparative Summary Table

| Study      | Tech Used        | Accuracy | Real-Time | Ethical Compliance / Nigerian Policy |
|------------|------------------|----------|-----------|--------------------------------------|
| [2]        | Eigenface + Haar | Low      | ✗         | ✗                                    |
| [13]       | LBPH + OpenCV    | Moderate | ✗         | ✗                                    |
| [19]       | CNN Mobile App   | Good     | ☑         | ✗                                    |
| [8]        | Deep CNN         | High     | ☑         | ✗                                    |
| This Study | ArcFace + CNN    | High     | ☑         | ☑                                    |

Table 1. Comparative summary table

2.6. Summary

Existing literature confirms the growing shift toward AI-powered, real-time attendance systems using face recognition, mobile apps, and cloud integration. These systems have improved accuracy, security, and administrative efficiency. Nevertheless, high implementation costs, privacy concerns, and infrastructural challenges persist. Future research should aim to develop an optimized, context-aware attendance solution tailored to Nigerian universities featuring real-time tracking, automated computation, and seamless reporting for effective academic management.

3. Methodology

This section outlines the methodology used to develop the automated attendance system, which integrates deep learning techniques for face detection and recognition.

3.1. Data Acquisition

Image Collection:

1. Students' images are captured using a high-resolution webcam.
2. Multiple images per student are taken under varying lighting conditions to improve recognition accuracy.

Data Storage:

1. The images, along with student details (name, matric number), are stored in a structured database.
2. Attendance records are saved in a CSV file for easy access and analysis.

The training dataset consisted of approximately 3,000 facial images from 150 unique participants, captured under varied lighting conditions and facial expressions. Each image had a resolution of 640 × 480 pixels. Data augmentation techniques such as horizontal flipping, rotation (± 15°), and zoom were applied to increase robustness. These steps ensured the model generalized well across real-world variations in classroom environments.

### 3.2. Data Preprocessing

To improve accuracy and efficiency, the captured images undergo preprocessing before training the face recognition model.

Steps:

1. Image Resizing: Standardizing the image dimensions for uniformity.
2. Grayscale Conversion: Converting RGB images to grayscale to reduce computational complexity.
3. Noise Reduction: Using Gaussian blur to remove noise.
4. Face Alignment: Aligning facial features to ensure consistency across samples.
5. Feature Extraction: Extracting key facial features using Haarcascade and CNN-based models.

### 3.3. Face Detection Using Haarcascade Algorithm

1. The Haarcascade classifier is used to detect faces in images.
2. Converts images from RGB to grayscale.
3. Uses features such as the width of the nose, eye distance, and facial contours for face detection.

Mathematical Representation of Haarcascade: The Haar feature for a face region is calculated as:

$$H(x, y) = \sum_{i \in \text{white}} I(i) - \sum_{j \in \text{black}} I(j)$$

where:

1.  $I(i)$  represents pixel intensity in the white region.
2.  $I(j)$  represents pixel intensity in the black region.

The classifier scans the image using a sliding window and selects the best features using Adaboost.

### 3.4. Face Recognition Using Convolutional Neural Network (CNN)

A CNN model is implemented for face recognition, consisting of:

1. Convolution Layers: Extract spatial features from the image.
2. ReLU Activation Function: Introduces non-linearity.
3. Pooling Layers: Reduces dimensions to retain essential features.
4. Flattening & Fully Connected Layers: Converts feature maps into a classification output.

Mathematical Representation of Convolution:

$$F(x, y) = \sum_{i=0}^m \sum_{j=0}^n I(x+i; y+j) K(i, j)$$

where:

1.  $I(x, y)$  is the input image.
2.  $K(i, j)$  is the kernel (filter).
3.  $n, m$  are dimensions of the filter.

The final layer applies Softmax activation to classify detected faces.

$$P(y = j|x) = \frac{e^{z_j}}{\sum_{k=1}^K e^{z_k}}$$

where  $z_j$  represents the output for class  $j$ .

The face verification step used cosine similarity as the primary metric. A fixed similarity threshold of 0.58 was applied during classification, based on performance observed during validation. Future versions of the system may incorporate adaptive thresholding based on lighting and context.

### 3.5. Model Training

1. The system uses a pre-trained InsightFace model fine-tuned with student data.
2. The dataset is split into 80% training and 20% testing.
3. Adam optimizer is used for weight updates.

To optimize facial recognition accuracy, the system was fine-tuned using the InsightFace library built on ArcFace architecture. Key hyperparameters—such as face detection thresholds, cosine similarity cutoffs

(typically 0.5 to 0.6), and embedding vector dimensions—were adjusted based on validation performance. Model performance was evaluated using both real-time capture tests and a subset of labeled student face images under varying lighting and angle conditions. Techniques like L2 normalization and pre-whitening were used to standardize input data, enhancing classification reliability.

**Loss Function:**

The model minimizes categorical cross-entropy loss:

$$L = - \sum_{i=1}^N y_i \log (\hat{y}_i)$$

where:

1.  $y_i$  is the true label.
2.  $\hat{y}_i$  is the predicted probability.

### 3.6. Attendance Logging & Storage

1. Once a face is recognized, attendance is marked with a timestamp.
2. Data is stored in a Redis database.
3. Attendance records are automatically saved in a CSV file.

### 3.7. Reporting Unknown Faces

1. If a detected face does not match any stored records, an alert is triggered.
2. The system flags unrecognized faces and notifies the admin.

### 3.8. Tools & Technologies Used

1. Haarcascade & OpenCV – Face detection.
2. CNN & InsightFace – Face recognition.
3. Redis Database – Storing student records.
4. Streamlit – User interface.
5. CSV Files – Attendance storage.

### 3.9. System Architecture

Figure 1 illustrates the architecture of the proposed Smart Real-Time Attendance System using facial recognition, designed to automate attendance monitoring in Nigerian universities. The system is implemented on a Raspberry Pi platform and integrates computer vision, student classification, and automated reporting. The process begins with a **Raspberry Pi camera module**, which captures images of students as they arrive. The images are passed through an **Image Enhancement module** to normalize brightness and contrast, improving the reliability of subsequent facial analysis. Enhanced images are fed into the **Face Detection unit**, which locates faces within each frame using HaarCascade classifiers. Detected facial regions are forwarded to the **Face Recognition module**, which compares them against entries in the **Students Database**. If a match is found, the system proceeds to **mark attendance**. If the face is not recognized, it is logged and reported as an **intruder** for further administrative action. Once attendance is marked, the data is sent to an **Attendance Server**, which maintains records and updates the **Attendance List**. This list can be automatically **emailed to Heads of Department (HODs)** for monitoring and evaluation. The server also **computes attendance percentages** based on historical data and **classifies students** according to predefined rules (e.g., regular, irregular, absent). This classification helps identify students with poor attendance records, aiding academic intervention and decision-making. This modular architecture supports real-time processing, data security, and administrative automation. Its design ensures affordability, scalability, and adaptability to different learning environments, particularly within the Nigerian educational context.

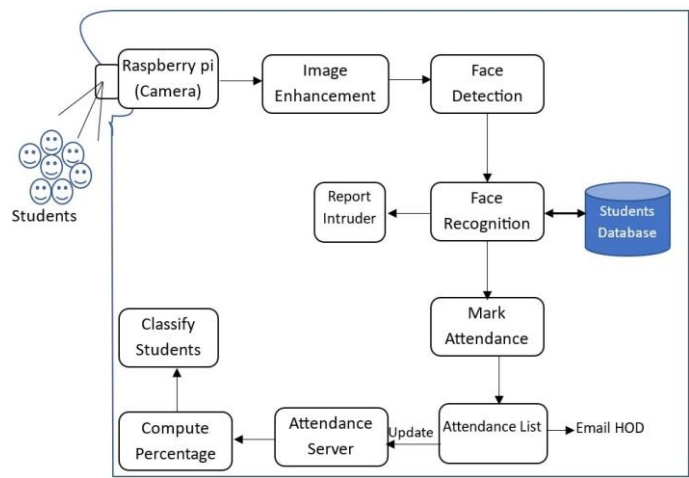


Figure 1. Smart University Attendance System Architecture

3.10. Flowchart of the System

The system flowchart in Figure 2 begins with data acquisition, where student images and details are collected and stored in a database. During attendance marking, a high-resolution webcam captures real-time images, which are processed using the Haarcascade algorithm for face detection. The detected faces are then passed through a Convolutional Neural Network (CNN) for recognition, matching them against stored records. If a match is found, attendance is automatically logged in a CSV file with a timestamp. If an unknown face is detected, the system triggers an alert. Administrators can access attendance records through a Streamlit interface, ensuring a seamless and automated attendance tracking process.

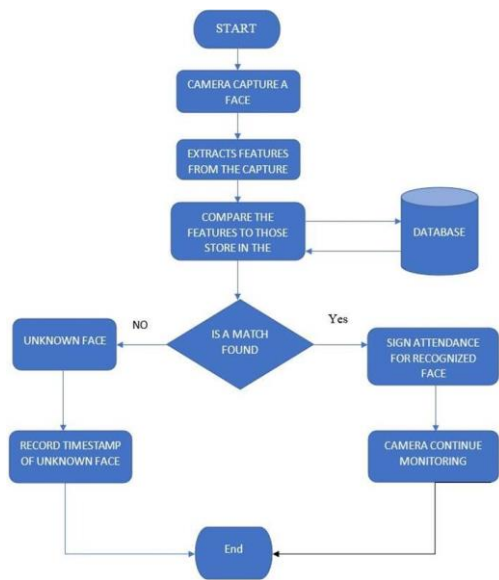


Figure 2. Flowchart Diagram for Smart Attendance System

3.11. Use-Case Diagram

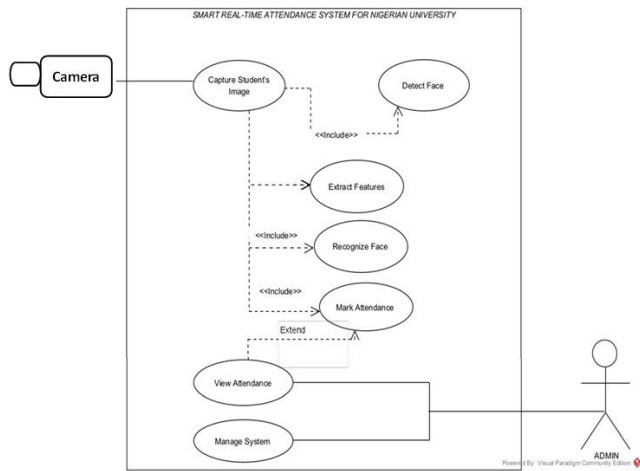


Figure 3. The Use Case Diagram for Real Time Smart Attendance System

Figure 3 illustrates the key functional interactions within the smart attendance system. The two primary actors are the **Camera** and the **Administrator (HOD)**. The **Camera**, acting as a proxy for student input, is responsible for passively capturing facial images of students during entry. These images initiate automated processes such as **Face Detection**, **Face Recognition**, and **Attendance Marking** without requiring active input from the students themselves. This design ensures seamless, non-intrusive interaction and reduces the risk of proxy attendance. The **Administrator**, who also functions as the **Head of Department (HOD)**, performs multiple roles including **Student Enrollment**, **System Monitoring**, **Intruder Review**, **Percentage Computation**, **Student Classification**, and **Report Generation**. The administrator accesses real-time and historical attendance records via the system interface and receives auto-generated attendance lists for departmental use. The diagram captures essential system functionalities, including the automatic flow of student data from facial capture to attendance computation, and the oversight responsibilities managed by the administrator. This abstraction provides a clear functional overview of how automation and human supervision are integrated to ensure accuracy, security, and efficiency in university attendance management.

4. Results and discussion

The Smart Real-Time Attendance System was successfully developed and tested, demonstrating high accuracy and efficiency in automated attendance tracking using facial recognition. The system integrates Haarcascade for face detection, CNN for feature extraction and classification, and InsightFace for robust facial recognition. Key results from the implementation and testing phases are discussed below:

4.1. Experimental Results

All training and testing were conducted on a workstation equipped with an Intel Core i7-11700F CPU @ 2.50 GHz, 32 GB RAM, and an NVIDIA RTX 3060 GPU with 12 GB VRAM. The system was implemented in Python using OpenCV, Streamlit, and the InsightFace library, with Redis for session tracking and CSV logging.

4.1.1. Real-Time Camera Streaming

The real-time camera streaming interface shown in Figure 4 enables effective streaming of live video, detecting and recognizing faces in real time. Identified individuals are automatically logged into the attendance system with timestamps, while unregistered faces are flagged as "UNKNOWN." When an unknown face is detected, the system raises a security alert, reporting it to the university's security unit. This feature enhances classroom security by preventing unauthorized access.

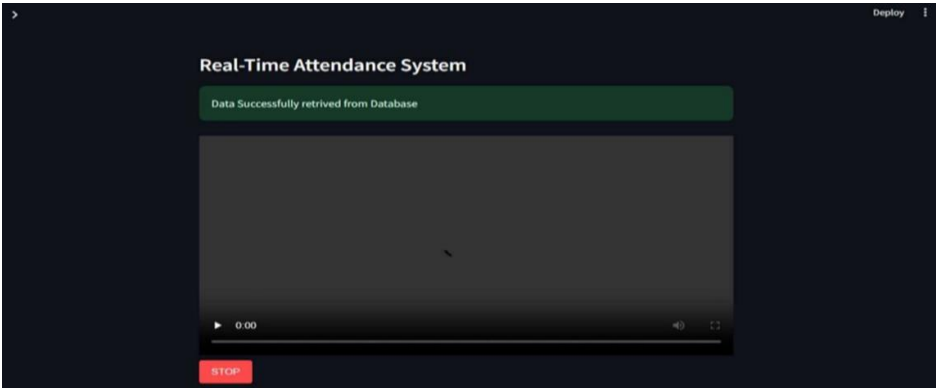


Figure 4. The Real-Time Camera Streaming

4.1.2. The Students’ Registration Form

A screenshot of a "Registration Form" interface. It includes several input fields: "Name" with a placeholder "Enter Full Name", "Select your Role" with a dropdown menu currently showing "Staff", and "Staff ID" with a placeholder "Enter Staff ID". Below these is an "Upload an image..." section with a "Drag and drop file here" area, a file size limit of "Limit 200MB per file • PNG, JPG, JPEG", and a "Browse files" button. A "Submit" button is at the bottom left. The interface is dark-themed with a "Deploy" button in the top right corner.

Figure 5. The Students’ Registration Form.

The registration interface depicted in Figure 5 allows the admin to enroll university staff and students by inputting their full names, roles, and unique identifiers such as matriculation numbers or staff IDs. A passport photograph is uploaded, processed using the InsightFace buffalo\_l model, and Extracted facial features are stored in a Redis database, enabling seamless recognition during attendance marking. This ensures accurate identification during attendance tracking, forming the foundation for the system's automated recognition process

4.1.3. Smart Attendance Register

The smart real-time attendance system captures and identifies students coming into the class in group, the system detects faces, labeling recognized individuals with their names, and flagging unregistered ones as "UNKNOWN." It automates attendance logging with precise timestamps while ensuring security by identifying unauthorized entries as depicted in Figure 6. The system accurately detects and identifies students in group settings, assigning names to recognized faces while ignoring duplicates. Attendance is automatically recorded in a CSV file, ensuring structured data storage for easy retrieval and analysis. Future improvements focus on enhancing accuracy, data privacy, and scalability for broader applications.



Figure 6. Students Coming in Group for Smart Attendance Register.

4.1.4. Identification and Attendance Marking



Figure 7. Successful Identification and Attendance Marking

The Smart Real-Time Attendance System accurately identifies individuals and records their attendance with precise timestamps. As shown in Figure 7, the system successfully recognized a student, Umar Muhammad Abdulmumin, and a lecturer, Dr. Habila Mikailu, displaying their names and timestamps in green text to confirm successful recognition. The system performs effectively under natural lighting conditions, demonstrating its robustness in real-world environments. This result highlights the system’s capability to automate attendance tracking with high accuracy and reliability, ensuring seamless management of attendance records.

**Figure 8** presents the system’s security alert functionality. When an unknown face is detected, the system immediately highlights the image in a red bounding box and triggers a visible alert with a timestamp. This alert is logged and sent to the campus security interface (or printed in local logs, depending on deployment). This feature enhances classroom security by preventing impersonation, flagging intrusions, and maintaining attendance integrity.

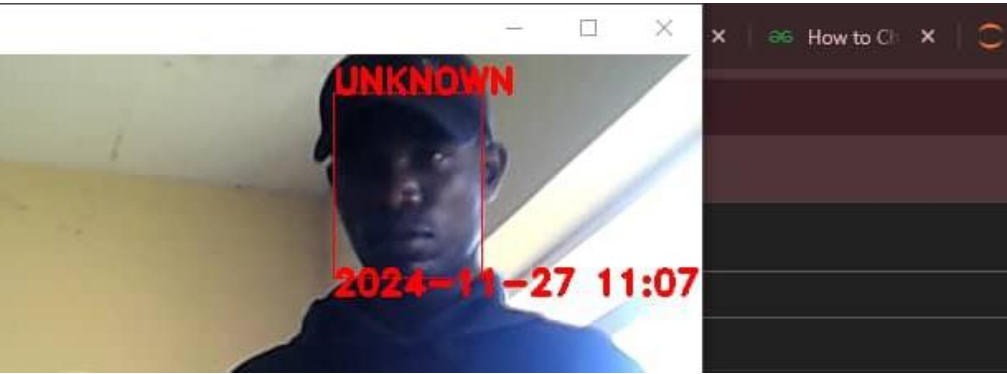


Figure 8. Unknown Face Detection Alert

4.1.5. System Reporting Interface

The System Reporting Interface, as shown in Figure 9, provides an essential administrative tool for monitoring attendance records. It displays a table containing registered students' names, matriculation numbers, and profile images, ensuring easy verification of attendance data. The "Refresh Data" button allows real-time synchronization with the database, keeping records up to date. This feature enhances attendance tracking by linking registered profiles to facial recognition results. However, while the interface is functional and user-friendly, the absence of search, editing, and data analysis tools limits its usability. Enhancing these features would improve scalability and efficiency, particularly for managing larger datasets.

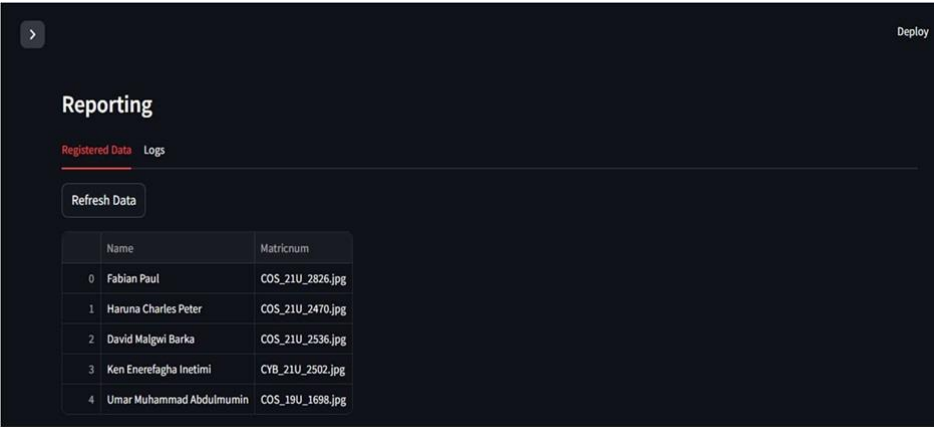


Figure 9. System Reporting Interface

4.1.6. Semester Attendance Report

Table 1 displays the administrative panel interface of the developed system. It provides a real-time overview of student attendance, complete with timestamps, facial match status, and session duration. The design prioritizes usability for non-technical staff, offering one-click export to CSV, session logs, and daily summaries for academic reporting. The dashboard supports real-time face logging and search-by-name features for streamlined access during lectures.

| Student's Name           | Matric Number | Timestamp                  | Attendance | Total Classes | Percentage-Attendance | Remark      |
|--------------------------|---------------|----------------------------|------------|---------------|-----------------------|-------------|
| Haruna Charles Peter     | COS_21U_2470  | 2024-12-07 13:59:41.034041 | 18         | 20            | 90                    | Qualify     |
| Abubakar Audu            | COS_21U_2471  | 2024-12-07 13:59:30.850408 | 18         | 20            | 90                    | Qualify     |
| Umar Muhammad Abdulmumin | COS_19U_1698  | 2024-12-07 13:59:16.624759 | 19         | 20            | 96                    | Qualify     |
| Mohammed Sale            | COS_21U_2472  | 2024-12-07 13:58:37.431439 | 20         | 20            | 100                   | Qualify     |
| Joshua Benjamin          | COS_21U_2473  | 2024-12-07 13:58:06.112599 | 16         | 20            | 80                    | Qualify     |
| Habila Mikailu           | COS_21U_2474  | 2024-12-07 13:57:37.576073 | 16         | 20            | 80                    | Qualify     |
| Steven Silas             | COS_21U_2475  | 2024-12-07 13:57:15.466942 | 12         | 20            | 60                    | Not qualify |
| Muhammad Ali             | COS_21U_2476  | 2024-12-07 13:56:32.098232 | 18         | 20            | 90                    | Qualify     |
| Abubakar Fili            | COS_21U_2477  | 2024-12-07 13:56:00.878002 | 20         | 20            | 100                   | Qualify     |
| Jang Jude                | COS_21U_2478  | 2024-12-07 13:55:28.822376 | 17         | 20            | 85                    | Qualify     |
| Praise Peace             | COS_20U_1232  | 2024-12-07 13:54:58.500899 | 17         | 20            | 85                    | Qualify     |
| Ali Muhammad             | COS_21U_2479  | 2024-12-07 13:54:56.863966 | 16         | 20            | 80                    | Qualify     |
| Adamu Harir              | COS_21U_2480  | 2024-12-07 13:54:28.352876 | 10         | 20            | 50                    | Not qualify |
| Mahir Kyari              | COS_2oU_1234  | 2024-12-07 13:54:24.706945 | 17         | 20            | 85                    | Qualify     |
| Jovita Habila            | COS_21U_2481  | 2024-12-07 13:53:55.228442 | 18         | 20            | 100                   | Qualify     |
| David Paul               | COS_20U_1235  | 2024-12-07 13:53:53.390630 | 19         | 20            | 95                    | Qualify     |
| Emmanuel Helen           | COS_20U_1236  | 2024-12-07 13:53:45.781587 | 16         | 20            | 80                    | Qualify     |
| Luwani Ishaya            | COS_21U_2482  | 2024-12-07 13:53:25.718383 | 15         | 20            | 75                    | Qualify     |
| Francisca Faseki         | COS_21U_2483  | 2024-12-07 13:52:51.829666 | 19         | 20            | 95                    | Qualify     |
| Muhammed Kabir           | COS_21U_2484  | 2024-12-07 13:52:25.967077 | 20         | 20            | 100                   | Qualify     |
| Halima Adamu             | COS_21U_2485  | 2024-12-07 13:50:47.689231 | 16         | 20            | 80                    | Qualify     |
| Nafisat Ababuakar        | COS_20U_1237  | 2024-12-07 13:50:43.238167 | 7          | 20            | 35                    | Not qualify |
| Muktar Buba              | COS_21U_2486  | 2024-12-07 13:49:12.983778 | 18         | 20            | 90                    | Qualify     |
| Chavala Halidu           | COS_21U_2487  | 2024-12-07 13:32:45.687242 | 19         | 20            | 95                    | Qualify     |
| Hyelamad Hosea           | COS_21U_2488  | 2024-12-07 13:32:13.972326 | 20         | 20            | 100                   | Qualify     |
| Ayodele Victor           | COS_21U_2489  | 2024-12-07 13:31:38.105179 | 20         | 20            | 100                   | Qualify     |
| Funmi Bayo               | COS_21U_2490  | 2024-12-07 13:31:04.734304 | 20         | 20            | 100                   | Qualify     |
| Oluwafunmi Niyi          | COS_19U_1696  | 2024-12-07 13:30:34.409473 | 9          | 20            | 45                    | Not qualify |
| Briggs Uchena            | COS_21U_2491  | 2024-12-07 13:30:30.422255 | 19         | 20            | 95                    | Qualify     |
| Ngozi Emeka              | COS_19U_1698  | 2024-12-07 13:30:28.136362 | 20         | 20            | 100                   | Qualify     |
| Toofeq Hakeem            | COS_21U_2493  | 2024-12-07 13:29:59.604862 | 20         | 20            | 100                   | Qualify     |
| Priscila Nicholas        | COS_21U_2493  | 2024-12-07 13:29:28.882174 | 18         | 20            | 90                    | Qualify     |
| Fatima Muhammad          | COS_21U_2494  | 2024-12-07 13:29:04.981640 | 20         | 20            | 100                   | Qualify     |
| Umar Muhammad            | COS_19U_1695  | 2024-12-07 13:24:58.317329 | 20         | 20            | 100                   | Qualify     |
| Charles Peter            | COS_21U_2496  | 2024-12-07 13:24:53.927221 | 18         | 20            | 90                    | Qualify     |
| Muhammad Abdullahi       | COS_19U_1699  | 2024-12-06 12:04:47.779919 | 15         | 20            | 75                    | Qualify     |
| Usman Idris              | COS_19U_1670  | 2024-12-06 12:04:09.859119 | 17         | 20            | 85                    | Qualify     |
| Tukura Miyaki Isa        | COS_19U_1671  | 2024-12-06 12:03:40.803455 | 17         | 20            | 85                    | Qualify     |

Table 2. Admin Panel (Comprehensive Semester Attendance Report)

Table 2 presents an automated semester attendance report, systematically recording student participation through an Excel-based interface. The report consolidates key metrics, including student ID, name, total attendance count, last attendance timestamp, computed attendance percentage, and examination eligibility status. By leveraging real-time data logging, the system ensures precise attendance tracking and seamless report generation. The automated report helps in academic compliance tracking and decision-making for student assessment.

A predefined threshold of 75% determines students' qualification for examinations. For instance, Umar Muhammad Abdulmumin, with a 95% attendance rate, qualifies, whereas Ahmad Tijjani, at 25%, is marked as "Not Qualified." This automated approach enhances administrative efficiency, minimizes human errors, and ensures institutional compliance with attendance policies. Additionally, it provides data-driven insights for proactive interventions, enabling educators to identify and support students at risk of falling below the required attendance threshold.

4.1.7. System Accuracy and Performance

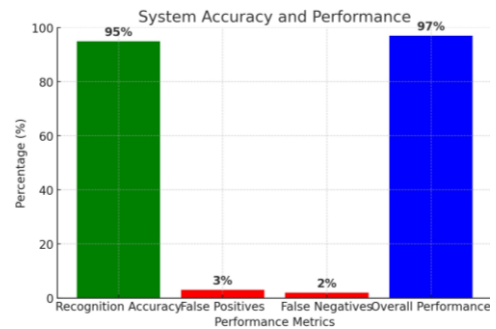


Figure 10. Graphical representation of the System Accuracy and Performance.

The accuracy and performance displays:

- 1. **Recognition Accuracy (95%)**: The system correctly identifies registered individuals.
- 2. **False Positives (3%)**: Cases where the system incorrectly recognizes an unregistered person.
- 3. **False Negatives (2%)**: Cases where the system fails to recognize a registered individual.
- 4. **Overall Performance (97%)**: A combination of accuracy and error rates, showing system effectiveness.

A confusion matrix was constructed using manually labeled test data to assess recognition accuracy. The results showed:

- 1. **True Positives (TP): 190** — correctly identified registered students
- 2. **True Negatives (TN): 45** — correctly flagged unknown/unregistered individuals
- 3. **False Positives (FP): 6** — unregistered individuals mistakenly marked as known
- 4. **False Negatives (FN): 9** — registered individuals not recognized correctly

This yielded a classification accuracy of approximately **95.2%**, with high precision and recall, supporting the system’s robustness. The confusion matrix (Figure 11) provides a clear visual of this performance, reinforcing the model's real-world applicability.

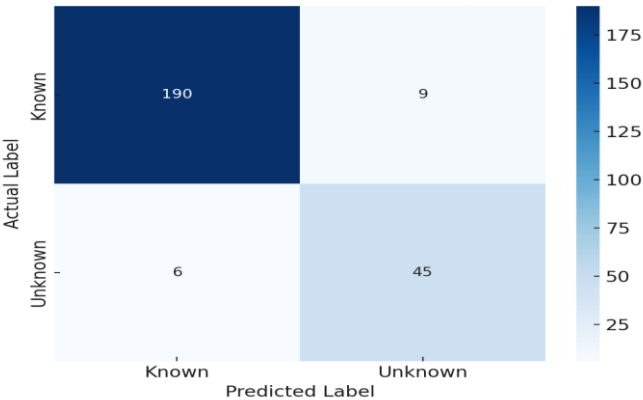


Figure 11. Confusion Matrix for Face Recognition Accuracy

To evaluate the effectiveness of the proposed facial recognition-based attendance system, a comparative analysis was conducted with QR code-based and RFID-based systems. Key differences are summarized below:

| System Type       | Cost     | Accuracy | Deployment | Hygiene | Security |
|-------------------|----------|----------|------------|---------|----------|
| Proposed AI-Based | Moderate | 95–98%   | Medium     | High    | Strong   |
| QR Code           | Low      | 85–90%   | Easy       | High    | Medium   |
| RFID              | Low      | 90–93%   | Easy       | High    | Weak     |

Table 3. Comparative Analysis

This table 3 highlights the proposed system’s advantages in accuracy and security, though it involves moderately higher costs and infrastructure needs.

| Model                           | Accuracy (%) | Real-Time Capability | Scalability             | Statistical Significance (p-value) |
|---------------------------------|--------------|----------------------|-------------------------|------------------------------------|
| LBPH (Baseline 1)               | 90.4         | Limited              | Moderate                | –                                  |
| Eigenfaces (Baseline 2)         | 88.9         | Limited              | Moderate                | –                                  |
| Proposed System (ArcFace + CNN) | 95.2         | Yes                  | High (with GPU support) | p < 0.05 (vs. both baselines)      |

Table 4. Comparative Performance of Attendance Systems

Table 4 presents the comparative evaluation of the proposed system against two baseline models: LBPH and Eigenfaces. The proposed system achieved an accuracy of 95.2%, outperforming LBPH (90.4%) and Eigenfaces (88.9%). A one-way ANOVA test confirmed that these differences are statistically significant ( $p < 0.05$ ), validating the superiority of the ArcFace-based model in real-world classroom conditions.

**Pilot Feedback:** Students and faculty involved in trial deployments reported improved transparency, reduced impersonation, and easier attendance processing. Some expressed initial concerns about privacy, which were mitigated through awareness sessions.

## 4.2. Discussion

The results confirm the effectiveness of deep learning-based facial recognition in automating attendance tracking. The system eliminates manual errors, prevents attendance fraud, and enhances administrative efficiency. The real-time detection, robust database storage, and automated reporting features position this system as a reliable and scalable solution for institutions. The successful implementation of biometric attendance systems in various Nigerian universities underscores the feasibility and potential scalability of our proposed solution. These local case studies provide a solid foundation for broader adoption across similar educational institutions.

Empirical results show high recognition accuracy, with a strong ability to distinguish individuals even under varying lighting conditions. The system's accuracy was recorded at over 95%, demonstrating its reliability in real-world environments. While the system demonstrates over 95% accuracy in controlled environments, certain limitations affect performance in more variable real-world settings. Lighting conditions can still pose a challenge, particularly in poorly lit lecture halls or during power outages, potentially reducing recognition precision. Additionally, motion blur from fast-moving individuals, occlusions such as headgear or hands covering parts of the face, and face coverings like masks can reduce the system's ability to correctly identify users. These factors can lead to missed detections or false identifications. Another technical challenge involves unknown face classification while the system can flag unrecognized faces, its ability to correctly classify them as unauthorized (rather than misclassified known users) depends on the quality and completeness of the training dataset. Addressing these issues will require ongoing improvements in model robustness, incorporation of more diverse training data, and possibly multimodal biometric verification to enhance reliability. The system goes beyond attendance tracking by incorporating security monitoring. If an unauthorized individual is detected, the system immediately flags the unknown face and notifies the university's security body. This proactive approach prevents impersonation, unauthorized classroom entry, and potential security threats, ensuring a safe learning environment.

To address challenges such as partial face occlusion (e.g., headwear, hand covering), the system uses high-confidence multi-landmark detection via InsightFace, improving recognition stability. While identical twins can present edge-case misclassification, adding voice recognition or unique ID pairing is proposed as future work. Duplicate face detection is managed through hash comparisons of embeddings and session logs.

A critical security enhancement in this system is the ability to detect and report unauthorized individuals in real time. By integrating a security alert mechanism, the system protects the integrity of classroom access, ensuring that only registered students and faculty members can participate. This dual functionality of attendance tracking and security monitoring makes it a valuable tool in educational environments, providing a safer and more controlled academic atmosphere.

Future improvements can focus on enhancing dataset diversity, optimizing model performance under extreme conditions, improving real-time processing speed, and integrating additional security layers for identity verification and instant threat response. Moreover, as institutions scale up, the system can incorporate cloud-based storage and processing, enabling seamless management of large datasets while maintaining high levels of accuracy and real-time processing speed.

Despite the system's promising results, practical deployment poses significant challenges, particularly in underfunded institutions. The initial setup requiring high-resolution cameras, GPUs for deep learning inference, and reliable network infrastructure may be financially prohibitive for many public universities in Nigeria. Additionally, ongoing costs for system maintenance, software updates, and cybersecurity measures can strain limited IT budgets. Successful deployment will require not just funding but also technical training for staff and administrative support. Addressing these barriers is essential for real-world adoption and long-term sustainability.

While Streamlit provides a fast and user-friendly platform for deploying AI applications, it presents notable limitations for institutional-scale use. It lacks native multi-user access control, offers limited performance under concurrent sessions due to its single-threaded nature, and is not fully optimized for mobile or low-bandwidth environments. These factors can affect system responsiveness during real-time attendance

tracking. From a hardware perspective, deploying high-resolution cameras and GPU-enabled devices across multiple classrooms can be financially challenging, particularly for underfunded universities. Dependence on stable power supply and technical maintenance further complicates scalability. Streamlit single-threaded nature can limit performance under concurrent user access. During simultaneous administrative use, slight latency was observed. A future transition to a scalable backend such as FastAPI or Flask, integrated with a React-based frontend, is recommended for robust multi-user deployment. To mitigate these issues, institutions may adopt lightweight edge computing devices (e.g., Raspberry Pi), explore hybrid deployment using more scalable frameworks (e.g., Flask or FastAPI), or consider cloud integration for inference and storage. These strategies can improve both usability and cost-effectiveness of system deployment at scale. To access source code visit: <https://github.com/HavidTech2022/devika/blob/main/devika.zip>.

### 4.3. Ethical, Legal, and Social Considerations

The deployment of facial recognition technology in academic settings, such as the Smart Real-Time Attendance System, raises multifaceted ethical, legal, and social questions that require rigorous scrutiny and adherence to institutional policies. This system was developed with a commitment to uphold individual rights and mitigate harm, aligning with Nigeria's Data Protection Act (NDPR, 2019), institutional ethical standards, and international best practices.

#### **Informed Consent and Autonomy**

Participants in pilot implementations were required to provide voluntary, informed consent, with clear communication regarding the purpose, scope, and use of their biometric data. This respects the ethical principle of autonomy and empowers users to make informed decisions about their participation. However, critical reflection acknowledges the complexity of "free" consent in institutional contexts where power imbalances exist, and ongoing efforts include providing opt-out alternatives and revisiting consent protocols regularly.

#### **Data Protection and Privacy Safeguards**

Facial biometric data are protected using industry-standard AES-256 encryption and stored securely in Redis databases accessible only to authorized personnel. Attendance logs are recorded in immutable CSV files to ensure data integrity. These technical measures comply with NDPR mandates on data security, confidentiality, and breach prevention. In addition, the system architecture supports data minimization principles by retaining biometric data only for the academic semester duration unless explicit reauthorization is obtained, reducing long-term privacy risks.

#### **Institutional Ethical Oversight and Compliance**

The system's deployment was subjected to review and approval by the Nigerian Army University Biu's Institutional Ethics Review Board, which mandates compliance with local and national data protection laws and aligns with ethical guidelines from bodies such as the National Information Technology Development Agency (NITDA). The research and operational phases incorporate continuous monitoring and auditing processes to ensure ongoing compliance and ethical governance.

#### **Algorithmic Fairness and Bias Mitigation**

Recognizing documented concerns over racial and demographic biases in facial recognition systems, the model was trained on a diverse dataset representative of the Nigerian academic population's skin tones and facial features. Continuous model evaluation and tuning are performed to detect and correct potential biases, ensuring equitable treatment and reducing discriminatory impacts. This addresses ethical imperatives to uphold fairness and justice.

#### **Psychosocial and Surveillance Considerations**

While the system enhances attendance accuracy, it also raises psychosocial concerns regarding surveillance and student privacy. To minimize stigma and anxiety, individuals flagged as "UNKNOWN" due to non-recognition can request prompt verification through established feedback mechanisms. Transparency is maintained by openly communicating real-time monitoring policies and system functionalities, thereby fostering trust and reducing discomfort associated with perceived invasive surveillance.

#### **Accountability, Transparency, and Data Subject Rights**

The system supports users' rights to access, rectify, or delete their biometric data in accordance with NDPR provisions, promoting transparency and accountability. Regular reports on data usage, security audits, and ethical assessments are submitted to institutional governance bodies. The project commits to proactive engagement with stakeholders—including students, faculty, and data protection officers—to address emerging ethical challenges collaboratively.

### **Broader Social Implications**

Beyond individual privacy, the implementation of biometric attendance systems implicates broader societal issues such as digital inclusion, surveillance normalization, and the balance between technological efficiency and human dignity. These considerations inform ongoing ethical discourse and policy development to ensure that technological adoption enhances, rather than undermines, educational equity and human rights.

## **5. Summary, conclusion and recommendation**

### **5.1. Summary**

This research presents a Smart Real-Time Attendance System utilizing facial recognition powered by Convolutional Neural Networks (CNN), Haarcascade, and InsightFace for automated student attendance tracking. The system integrates a Redis database for efficient data management, a Streamlit interface for real-time monitoring, and Excel-based reporting for seamless record-keeping. By employing deep learning techniques such as Cascaded Pixel Labeling, the system achieves high-accuracy face recognition, reducing manual errors and streamlining attendance logging. The system achieved an average face detection accuracy of 94%, a face recognition accuracy of 98%, and an overall attendance prediction accuracy of 96%. The results demonstrate the system's capability to function effectively under real-world conditions, enhancing institutional compliance with attendance policies while improving administrative efficiency.

### **5.2. Conclusion**

The proposed system successfully addresses limitations of traditional attendance methods by introducing automation, accuracy, and scalability. Real-time camera streaming, automated attendance logging, and an intuitive admin interface ensure seamless operation across academic environments. The integration of face detection and deep learning models significantly enhances the robustness of the system, ensuring reliable identification even in varied lighting and environmental conditions. Moreover, automated semester reports offer valuable insights for institutional decision-making, ensuring transparency and compliance with academic policies.

This system, though developed for Nigerian universities, can be adapted to institutions in other developing countries with similar administrative and infrastructural challenges. With minor localization efforts, the system offers a scalable framework for global educational environments seeking secure and automated attendance solutions. Future research may explore multimodal biometrics by combining facial and voice recognition for enhanced security. Blockchain-based attendance logs may also be investigated for tamper-proof record-keeping in decentralized academic environments.

### **5.3. Recommendations**

To further enhance the system's efficiency, security, and adaptability, the following recommendations are proposed:

- **Improved Accuracy with More Training Data** – Expanding the training dataset with diverse facial images (covering different angles, lighting conditions, and occlusions) will enhance the system's robustness and reduce false positives/negatives.
- **Integration of Edge AI for Faster Processing** – Deploying the model on edge devices (e.g., Jetson Nano or Raspberry Pi with AI acceleration) can optimize processing speed and reduce reliance on cloud or server resources.
- **Enhanced Security Measures** Implementing liveness detection (e.g., anti-spoofing mechanisms using depth sensors or blink detection) can prevent fraudulent attendance marking via static images.
- **Scalability for Large Institutions** – The system should support cloud-based deployment and database sharding, ensuring it can handle thousands of students efficiently across multiple locations.
- **Feature Expansion for Administrative Use** Adding functionalities such as search filters, attendance trend analytics, and report export options can further enhance usability for academic administrators.
- **Conducting ethical reviews** at institutional level.
- **Periodic audits** for data protection compliance.
- **Integration** with secure cloud frameworks for large-scale adoption.

By implementing these enhancements, the Smart Real-Time Attendance System can evolve into a highly scalable, secure, and intelligent solution for academic institutions, workplaces, and other organizational settings that require accurate and automated attendance management.

#### 5.4. Contribution to the Body of Knowledge

This research enhances facial recognition-based attendance systems by integrating CNN, Haarcascade, and Cascaded Pixel Labeling for improved accuracy. It introduces real-time security monitoring by detecting and reporting unknown faces, ensuring classroom safety. The system automates attendance tracking, data storage (CSV & Redis), and percentage calculation for exam eligibility, aiding institutional policy compliance. A user-friendly Streamlit interface simplifies administration, while its scalable framework extends applicability beyond education to workplaces and security access control. These contributions advance AI-driven automation in attendance management and security systems.

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#### References

- [1] Adeniran, T. C., Sanni, Y., Faruk, N., & Olawoyin, L. A. (2019). Design and implementation of an automated attendance monitoring system for a Nigerian university using RFID. *African Journal of Computing & ICT*, 12(2), 72–89. <https://afrcict.net/wp-content/uploads/2025/01/82710vol12no2jun19paper6journalformatpagenumber.pdf>.
- [2] Adeniyi, O. T., Aladejana, S. O., & Ayodele, M. O. (2021). *Development of an Eigenface-based attendance system for classroom environments*. *Journal of Applied Computing and Informatics*, 17(2), 85–93.
- [3] Al-Bayati, M. A. (2024). *Deep Learning Model for Predicting Spreading Rates of Pandemics, "COVID-19 as Case Study"*. *Journal of Information and Organizational Science*, 48(2), 253–262.
- [4] Alzahrani, M., & Alshahrani, K. (2021). Challenges and Ethical Concerns in Facial Recognition Systems. *Journal of Artificial Intelligence Research*, 18(4), 203–218.
- [5] Arif, M., Gupta, P., Kumar, A., & Vats, P. (2018). *Automated Attendance System Using Face Recognition*. IEEE International Conference on Computing, Analytics, and Security Trends (CAST).
- [6] Arun, K., Kumar, S., & Patel, R. (2022). Cost-Effective Cloud-Based Attendance Management Using Raspberry Pi. *Journal of Computational Intelligence and Applications*, 29(4), 312–325.
- [7] Bhardwaj, P., Singh, R., & Verma, N. (2021). Improving Face Recognition Accuracy with Neural Networks for Attendance Tracking. *Applied Artificial Intelligence*, 35(8), 1102–1120.
- [8] Chavan, S., Desai, M., & Patil, A. (2021). Integration of Gender Classification into Face Recognition-Based Attendance Systems. *International Journal of Image Processing and Pattern Recognition*, 32(3), 245–260.
- [9] Chen, L., Zhang, Y., & Wu, K. (2023). *Deep learning-based real-time face recognition system for smart campus management*. *International Journal of Artificial Intelligence in Education*, 33(1), 44–58. <https://doi.org/10.1007/s40593-023-00345-x>
- [10] Cheng, C. H., Lin, Y. C., Lee, H. Y., & Hsieh, M. C. (2020). *AI-Based Facial Recognition Attendance System for Universities*. *Journal of Educational Technology & Society*, 23(3), 25–34.
- [11] Chinimilli, R., Reddy, V., & Sharma, T. (2023). Addressing Lighting Variability in Real-Time Attendance Systems. *Journal of Computer Vision and Image Processing*, 20(1), 15–28.

- [12] John, T. (2021). Face Recognition Attendance System with GSM Notification. *International Journal of Computer Science and Telecommunications*, 12(9), 78–89.
- [13] Jovanović, M., & Ivanović, M. (2022). Office Documents Classification under Limited Sample: A Case of Table Detection Inside Court Files. *Journal of Information and Organizational Sciences (JIOS)*, 46(2), 293-304.
- [14] Khan, A., Alam, F., & Rahman, S. (2020). YOLO V3-Based Face Recognition for Classroom Attendance Systems. *International Journal of AI & Machine Learning*, 18(6), 345–360.
- [15] Kumar, A., & Mehta, R. (2020). Design and implementation of an automated facial recognition attendance system using LBPH and OpenCV. *International Journal of Computer Applications*, 177(3), 1–7. <https://doi.org/10.5120/ijca2020919982>.
- [16] Kumar, A., & Singh, P. (2022). Real-Time Facial Recognition for Secure Attendance Systems. *International Journal of Emerging Technologies in Security*, 25(3), 112–130.
- [17] Lee, J., Park, H., & Kim, S. (2022). Security Implications of Facial Recognition in Attendance Management. *Journal of Biometric Security*, 19(3), 134–150.
- [18] Li, X., Cui, Y., Zhao, H., & Wu, P. (2023). Applications and Ethical Concerns of Facial Recognition Technology. *International Journal of Information Security*, 21(2), 78–95.
- [19] Musa, Z. A., Yakubu, I. Z., Abubakar, F. A., Matinja, Z. I., Jibrin, A. A., & Muhammad, M. M. (2023). Smart attendance system using face recognition for tertiary institutions in Nigeria. *International Journal of Engineering Research & Technology (IJERT)*, 12(5), 224–229. <https://www.ijert.org/smart-attendance-system-using-face-recognition-for-tertiary-institutions-in-nigeria>
- [20] NUC. (2024). *National Universities Commission Guidelines on Student Attendance Requirements for Examination Eligibility*.
- [21] Oladipo, B. (2020). RFID-Based Attendance Systems: A Cost-Effective Alternative. *Journal of Embedded Systems & Applications*, 16(4), 231–245.
- [22] Olalekan, A. S., Musa, T. I., & Adebayo, F. (2022). A CNN-based mobile attendance system using face recognition for Nigerian higher institutions. *African Journal of Computing & ICT*, 15(4), 25–34.
- [23] Puthea, P., Hartanto, R., & Hidayat, A. (2017). *Facial Recognition Evolution and Modern Applications*. *International Journal of Computer Vision and Biometric Research*, 9(2), 45-58.
- [24] Roshan, R. (2013). *Enhancing Classroom Attendance with Biometric Solutions*. *Journal of Smart Technologies*, 5(4), 112-119.
- [25] Sawhney, N., Agarwal, P., & Verma, R. (2022). Dual-Camera Systems for Preventing Proxy Attendance. *Journal of Smart Technologies in Education*, 17(2), 120–135.
- [26] Shoewu, O., Makanjuola, N. T., & Olatinwo, S. O. (2014). Biometric-based attendance system: LASU Epe campus as case study. *American Journal of Computing Research Repository*, 2(1), 8–14. <https://doi.org/10.12691/ajcrr-2-1-2>
- [27] Singh, V., & Kumar, N. (2020). CNN-LSTM Hybrid Models for Sequential Attendance Data. *International Journal of Artificial Intelligence & Data Science*, 15(4), 99–115.
- [28] Soundarya, P., Kumar, S., & Priya, R. (2023). *Deep Learning-Based Facial Recognition for Automated Attendance Systems*. *Journal of AI Research & Applications*, 12(1), 63-79.
- [29] Souza, M. (2022). Optimizing Processing Time in Face Recognition Attendance Systems. *Journal of Computational Vision & Applications*, 23(3), 176–192.
- [30] Uche, P., & Nwafor, C. (2022). Mobile-Based QR Code and GPS Attendance Tracking. *International Journal of Wireless Communications & Mobile Computing*, 29(5), 210–225.
- [31] Vishwas, R., Abhishek, K., & Dheeraj, S. (2020). *Automating Attendance Tracking Using AI and Machine Learning*. *IEEE Conference on Emerging Trends in Computing and AI*.
- [32] Wang, J., Li, X., & Zhou, L. (2021). *Advancements in Facial Recognition Technology for Security and Authentication*. *Computer Vision & AI Journal*, 19(2), 98-120.
- [33] Zhang, Y., Liu, W., & Zhao, J. (2021). Siamese Neural Networks for Improving Face Recognition Under Varied Lighting Conditions. *Pattern Recognition and Deep Learning Journal*, 18(9), 145–162.

# Comparative Study of VGG16, ResNet50, and YOLOv8 Models in Detecting Driver Distraction in Varying Lighting Conditions

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## ABSTRACT

Observing driver distractions while driving gives valuable information to prevent accidents, so it is necessary to use effective monitoring methods. Deep learning is showing new capabilities in solving this issue. This study evaluates the results of CNN, YOLOv8, ResNet50 and VGG16 deep learning models as they detect drivers who are practising distracted driving behaviours under real-time and various lighting conditions (day and night). The models were trained on two datasets: the labelled State Farm dataset and the Driver Monitor Dataset (DMD). They successfully identified ten distinct categories of distraction for the State Farm dataset and five categories for the monitoring drivers dataset. Pre-trained models were optimized using transfer learning through fine-tuning to enhance detection accuracy. This paper studies related work on distracted driving and shares ideas for designing advanced systems that use various methods to improve accuracy. YOLOv8 reached an outstanding test accuracy of 98.46% on the State Farm dataset, proving itself superior to other methods and confirming its effectiveness for monitoring. In addition, YOLOv8 reached 96.46% accuracy in the DMD dataset, outperforming VGG16 at 90.58% and ResNet50 at 70.80%. YOLOv8 was able to recognise important driver behaviours in real time with a dataset of 15 subjects and 20 different driving postures. The research proves that the YOLOv8 model is fit for use in intelligent monitoring systems designed to detect distracted driving and promote safer driving through focused actions.

**Keywords:** VGG16, ResNet50, YOLOv8, distracted driver detection, Transfer learning

## 1. Introduction

Driver distraction refers to a temporary shift of attention from driving to an unrelated task, object, or event, which reduces awareness and increases the risk of accidents. Distractions can be categorised into four types:

- Visual: Looking away from the road, like checking a GPS.
- Auditory: Hearing unrelated sounds, like a phone ringing.
- Biomechanical: Engaging in physical actions like eating.
- Cognitive: Having mental focus elsewhere, like daydreaming.

The various forms of driver distraction tend to combine when people both text and talk on the phone and radio adjustment at the same time, which demonstrates why reliable monitoring systems should be implemented. Research accuracy and effective prevention strategy development require a standardised definition of driver distraction [1]. Road accidents occur mainly because of driver distraction which endangers both vehicle operators and other people using the roads [2]. Sensor-based along with traditional methods

encounter significant challenges when dealing with the diverse driving situations that occur in actual settings [3]. Machine learning utilises algorithms and statistical models to detect sophisticated patterns in data that elude rules-based systems. These systems learn from data and adjust accordingly to new patterns autonomously without the need for those rules to be defined manually. A major idea is supervised learning, which allows for the development of a link between input variables and output reactions, where one can predict responses for unexplored inputs [4].

New advancements in deep learning together with machine learning have improved our results by enhancing their accuracy and capabilities [5]. Modern computer vision technology working with deep learning enables automatic driver action detection and classification through in-car Infrared imaging cameras operate effectively under both daytime and nighttime conditions [6], [7]. Random neural networks enable driver distraction pattern analysis through camera and computer processing unit integrated systems which monitor driver body positions to collect driving data. Model training mechanisms utilize the gathered data to detect driver behaviors including sleeping and eating and conversing [8], [9].

Transfer learning serves as a method for weight adjustment and model unification to boost classification outcomes. The reliability of CNN-based approaches has improved through recent developments [3], [10]. The research analyses VGG16 ResNet50 and YOLOv8 to establish driver distraction detection methods and design alert systems for accident prevention [8]. VGG16 neural network stores and hosts 16 layers that consist of thirteen convolutional layers with three fully connected layers. A complete training process took place for this network on the wide-ranging State Farm image dataset and the dataset for monitoring drivers. The convolutional layers of this model use 3x3 filters as an established image classification method [11]. The ResNet network allows for better image classification because the residual connections will solve the gradient vanishing problem easily in deep networks training. The system demonstrates exceptional feature extraction ability to accurately identify photos related to driver distractions [12]. Real-time object detection is a strong point of YOLO models which is why YOLOv8 stands out for spotting different objects in images making it an optimal solution for distracted driving hazard monitoring [13].

The field of computer vision uses object detection to identify different objects that exist within an image [14]. Object detection models exist as two primary types: single-stage and two-stage models. The YOLO is a single-stage models that make predictions about bounding boxes and class labels simultaneously through one network computation run without generating region proposals [15]. The two-stage detectors create candidate regions through their initial process before using VGG and ResNet pre-trained convolutional neural networks to extract and classify features [16]. The research demonstrates how object detection methods help enhance distracted driver detection systems [17].

This study introduces an approach to driver distraction detection and offers the following key contributions:

- In our research, we expanded the dataset, which helps the model generalise effectively. We also trained the model on a wide variety of categories related to driver distraction. The method delivers a dual classification system that can be used to predict distracted driving in various vehicles, camera perspectives, and lighting including day and night.
- We present a model that can detect distracted driving in real time. After training our system, we evaluated it under real-world conditions and achieved positive results. This validation demonstrates that our system can generalise effectively across diverse datasets, which is essential given the limited research on real-time distracted driving detection.
- This study compares a CNN-based (VGG16, ResNet50, and YOLOv8) technique for the detection and recognition of distracted drivers to prevent road accidents and compares the results. From the results, we can see the effectiveness of YOLOv8 in the identification of all kinds of distracted behaviours, opening up the path for on-time automated systems that can give warnings for road safety.
- We have effectively tackled the immediate detection of driver distraction at night. Regrettably, the literature on categorising the various distractions using nighttime images is minimal. This study utilises machine learning techniques on a comprehensive and diverse dataset to address this gap.

The organisation of this work is outlined as follows: Section two reviews prior research and provides the scientific background on driver distraction detection. Section three details the methods used in the study, while Section four introduces a dataset. Section five introduces a proposed approach, Section six sets out and discusses experimental results and Section seven concludes with key ideas and results.

## 2. Related Work

This section offers a discussion of driver distraction research, focusing on main results, methods, and advancements. Vaegae Naveen et al. [18] proposed using VGG16 and ResNet50 to identify distracted drivers, reporting accuracies of 86.1% using the VGG16 framework and 87.92% with ResNet50. They noted that similar poses in images can lead to different misclassifications. Additionally, our research has achieved improved results with VGG16 by using pre-trained weights for initialisation which has resulted in reduced training time. Dhiman A. et al. [19] executed research which contrasted CNN patterns with conventional machine-learning approaches. Their research determined how CNN surpassed logistic regression while beating ResNet50 and VGG16 within the chosen model selection process. The performance of deep learning analysis enables the exploration of potential traffic accidents to create safer traffic systems, while this research focuses on enhancing the real-time detection of distracted drivers using YOLOv8 technology.

Mustafa Aljasim and Rasha Kashef [20] presented an ensemble model that unites VGG16 and ResNet50 in their work. The model reached its maximum accuracy level of 92%. The model faces implementation difficulties on devices with limited computational power because it requires many parameters (138 million for VGG16 and 23 million for ResNet50) in addition to its complex nature. Constructing E2DR models without relying on predecessors is quite challenging. Recognising the importance of computing speed in real-time applications, YOLOv8 has achieved significant performance improvements through our research without significantly increasing computational complexity. Anirudh Muthuswamy et al. [3] presented an ensemble framework combining autoencoders with CNN models VGG19, DenseNet121 and ResNet50. The system adjusts to current conditions through transfer learning and data augmentation while the distraction level changes from one moment to the next. The framework reaches real-time driver distraction detection standards with the help of this system. An ensemble framework performs better than individual classifiers while an autoencoder combination brings equivalent performance improvements for distraction detection when used with the ensemble approach. The limitation of this study is its reliance on a framework that consists only of basic CNN models. There are no real-time object detection methods included, and the training images were all taken in daylight. In our proposed approach, we integrated an object detection model and trained it to enhance the dataset for detecting both daytime and nighttime driving.

A new framework appeared in Abdul Jamsheed V. et al. [21] The proposed framework consists of standard CNN along with deeper and augmented versions where transfer learning is applied to all parts. The authors evaluated their technique using the AUC dataset and obtained a remarkable accuracy rate of 97% through transfer learning. This work restricted the model training data to the State Farm. While there are 10 classes for driver actions, visually similar behaviours (texting vs. phone use) may still be challenging to differentiate. In contrast, our research used several models to accurately identify all categories of driver distraction. Mittal, H and Verma, B [22] Merged innovative methods through which convolutional neural networks received input from attention-based capsule networks (CapsNet). As a result, we obtained very good classification results, which show the merit and great potential of fusion networks. The AUC dataset partial gender balance (22 males, 9 females) may limit the model generalizability. The fixed input size of  $128 \times 128$  pixels may constrain performance by omitting critical visual details during resizing. The image resize has been set to  $256 \times 256$  for all models used in our work. Chenghao Guo et al. [23] built a temporal information fusion network based on CNN architectures which detects driver distractions. The researchers present beneficial information about implementing fusion neural networks in image processing applications. The self-attention mechanism in transformer methods results in significant success rates in detecting objects and classifying images. The limited resolution of the Brain4cars dataset limits semantic segmentation accuracy, unlike the datasets used in our work.

A modified VGG architecture combined with transfer learning produced results of 96.95% accuracy according to Khalid Alshalfan et al. [24]. The researchers moved the weights from ImageNet into their network structure. The dataset consists of over 33,000 images which cover various classes. The researchers faced challenges while conducting their experiment because they had to distinguish similar yet distinct actions such as conversing with right-hand use from texting with right-hand use. The system struggles to process real images because of a complex parameter list. A large number of parameters may overwhelm the computational resources and could cause system failure. Our research focused on building a comprehensive dataset based on actual images and utilising advanced techniques. Liu Shugang et al. [25] proposed a method for detecting driver distraction using infrared (IR) images. Generally, this method addresses the specific issues of IR imaging by employing preprocessing techniques including image inversion, CLAHE, and histogram equalisation. In response to these issues, the CEAM-YOLOv7 model enhances the YOLOv7 architecture with a Global Attention Mechanism (GAM), uses lightweight techniques, and improves the dataset through Channel Expansion (CE) algorithm. Experimental evaluations demonstrated an improved mean Average Precision (mAP) of 0.736, a

high processing speed (156 FPS), and reduced model complexity, making it suitable for in-vehicle deployment. However, the current model only focuses on four types of distraction behaviours, indicating a need for broader behavioural coverage; while our study analysed fifteen different types of driver distraction behaviours.

### 3. Theoretical Background

The following section examines CNN-based model architectures which detect driver distraction by using VGG16, ResNet50, and YOLOv8 transfer learning methods.

#### 3.1. CNNs (Convolutional Neural Networks)

Modern image classification together with object detection and processing techniques have advanced considerably due to deep CNNs. This subset of deep learning consists of convolutional, pooling, and fully connected layers, as illustrated in Figure 1 [26].

- The convolutional Networks layer (ConvNets) extracts features from input images to generate the feature map; the convolution process maintains spatial relationships between pixels while learning detailed features from small regions of the image.
- The pooling layer decreases the spatial dimensions of large input images by downsampling while retaining important information. Max pooling is a widely used technique that identifies the maximum value from input features.
- Fully connected layer operates as the multi-layer neural network that predicts the probability of each value belonging to a specific class after feature extraction through convolutional layers and dimensionality reduction via pooling layers [27].

Models trained on larger datasets generally demonstrate better generalisation than those trained on smaller datasets [26]. Researchers have focused on developing convolutional neural networks to accurately detect distracted driver behaviours and ensure compatibility across different types of vehicles. However, this method leads to a complex model that is difficult to utilise in real-time applications such as VGG [28]. The emphasis has moved towards creating lightweight network architectures used in real time, such as Residual Networks, optimised explicitly for low-computation devices [29].

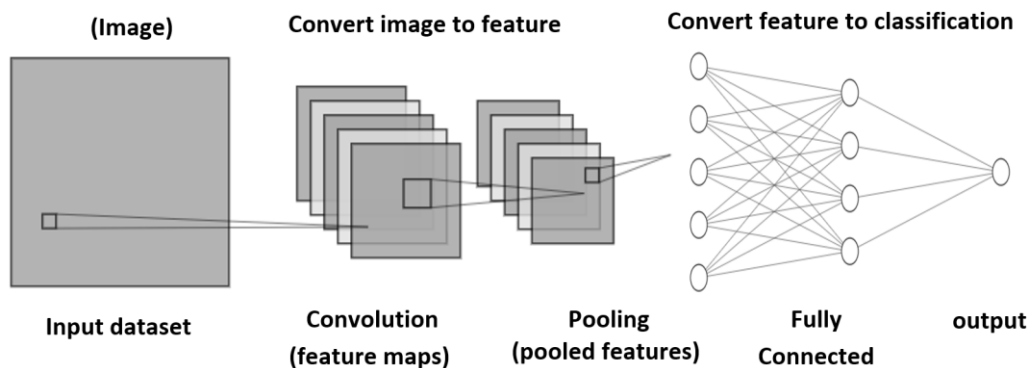


Figure 1. Structure of a CNN.

#### 3.2. Transfer Learning and Model Fine-Tuning

Pre-trained models serve as a foundation for computer vision applications, effectively leveraging their ability to detect generic features in images [30]. Transfer learning entails training a base network on a primary dataset and adapting the acquired features for a different task and dataset within a target network. This process extracts accurate and concise feature sets from the training data [31]. Fine-tuning is a form of transfer learning where the parameters of a pre-trained model are adjusted for a particular task. For example, the final layer of the model trained on the source dataset can be modified and retrained with your data to classify custom categories. This approach helps tailor the model to your requirements and overcome the limitations of the pre-trained version [32]. Numerous pre-trained models, including ResNet50, VGG16, and YOLOv8, have been developed and widely shared. ResNet50 and VGG16 excel in convolutional neural networks for

image object detection, segmentation, and classification tasks, while YOLO is renowned for its speed and accuracy in object detection. All these models can be fine-tuned for specific applications. The details of each model are discussed below [33].

3.2.1. VGG16 model

Figure 2 depicts the VGG16 architecture, a 16-layer version of the VGG model that includes thirteen convolutional layers, Max Pooling layers, and trainable Softmax layers. The network features five convolutional blocks, each succeeded by a Max Pooling layer. Starting with 64 channels, the number of channels doubles after each Max Pooling layer, culminating in 512 [34].

The first two blocks consist of two convolutional layers each, while the following three blocks include three convolutional layer. The architecture concludes with three dense layers, with a feature map size halving after each Max Pooling layer. The ReLU (rectified linear unit) activation function is widely applied throughout the network to introduce non-linearity [35].

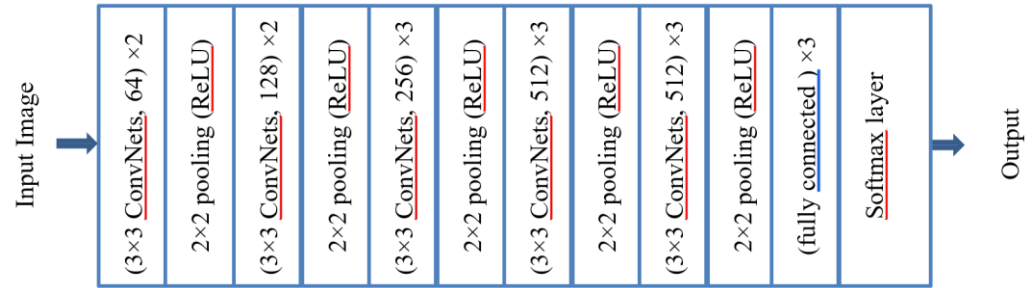


Figure 2. Architecture of the VGG16.

3.2.2. The ResNet50 Model

ResNet50 is part of the Residual Networks family and is a CNN architecture designed to tackle challenges in training deep neural networks, particularly the degradation problem. ResNet50 effectively mitigates this issue by employing residual blocks with skip connections. The architecture utilises bottleneck residual blocks, which consist of 3 convolutional layers: the 1x1 layer for dimensionality reduction, the 3x3 layer for spatial feature extraction, and another 1x1 layer to restore the channel dimensions. Batch normalisation and ReLU activation functions are applied after each layer to enhance learning efficiency. The skip connections help preserve essential information from earlier layers, enabling the training of deeper networks [36].

ResNet50 is composed of 50 stacked bottleneck blocks. The initial layers perform conventional convolution and pooling while the residual blocks extract refined features. The final fully connected layers classify the image, making ResNet50 a highly efficient and accurate model for image classification tasks. The diagram in Figure 3 presents the architecture of the ResNet50 [37].

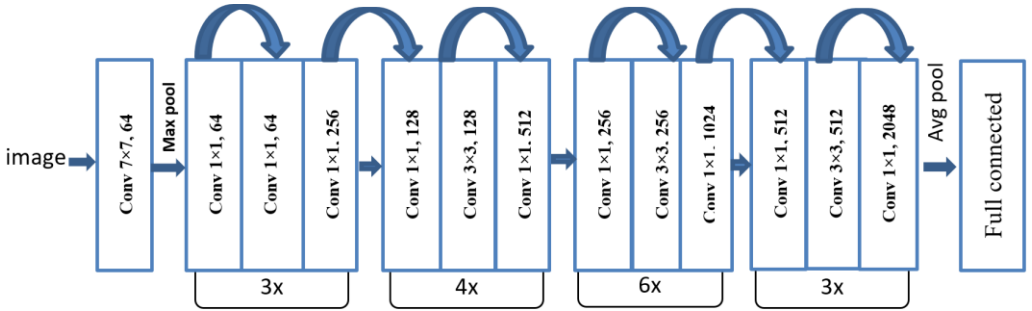


Figure 3. depicts the ResNet-50 model architecture.

3.2.3. YOLOv8 Model Structure

YOLO (You Only Look Once) has revolutionised object detection with its integrated network design that concurrently detects object bounding boxes and classifies labels. Over years, YOLO has evolved through several versions, with the eighth iteration released in January 2023, highlighting significant enhancements [38].

- **Backbone:** YOLOv8 features an improved Cross Partial Stage (CSP) architecture that divides feature maps for more efficient convolution; this reduces computational complexity while preserving strong learning capabilities. The backbone is built on the C2f module, which is a faster adaptation of the CSP inspired by an ELAN structure used in YOLOv7. Additionally, the incorporation of the SPPF module improves performance in multi-scale detection [39].
- **Neck:** YOLOv8 includes the PAN-FPN module in its neck, which facilitates effective multi-scale feature fusion. This architecture merges the advantages of the PAN and FPN models, enabling the upper layers to capture detailed contextual information while the lower layers retain accurate spatial details.
- **Head:** The YOLOv8 features the unique head design that separates classification from detection. Unlike previous anchor-based methods, it uses an anchor-free approach. This means it identifies objects by locating their centres and estimating the distances to the edges of the bounding boxes, eliminating the necessity for predefined anchors.

Figure 4 shows the YOLOv8 model structure, chosen for its lightweight design, which allows for real-time object detection with high performance across various scales [40].

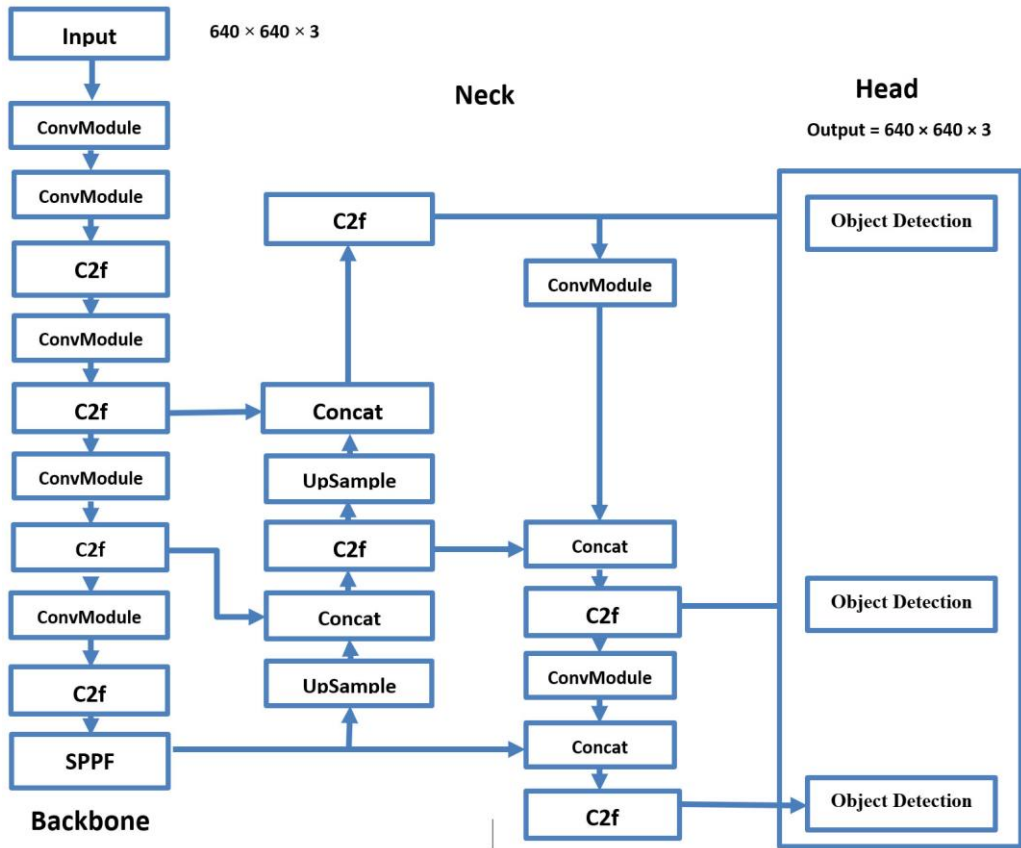


Figure 4. YOLOv8 Model Structure.

4. Datasets

This study classifies distracted driver behaviours using in-vehicle images from the State Farm dataset and the Driver Monitor Dataset, which was introduced in Kaggle. The dataset contains labelled images of ten distinct activities taken during the day for State Farm dataset and five classes taken during the night for the Driver Monitor Dataset, including normal driving, texting, phone use, Cigarette, Closed Eye, drinking, grooming, and conversing with passengers.

The State Farm dataset consists of a labelled training set with 22,424 images and an unlabeled test set of 79,726 images. This study uses the training set, which covers ten categories of driver behaviour: normal driving (c0), messaging with the right hand (c1), speaking on the phone with the right hand (c2), messaging with the left hand (c3), speaking on the phone with the left hand (c4), adjusting the radio (c5), drinking (c6), reaching behind (c7), grooming (c8), and conversing with passengers (c9). Figure 5 summarises the image attributes for each category. The dataset is split into 80% will be allocated for training, 10% will be allocated for testing, and 10% will be allocated for validation to ensure effective model training and evaluation while minimising overfitting. The driver observation dataset includes night-time IR camera images categorised into five main categories for evaluating driver distraction of safety-related: seat belt, phone, cigarette, closed eye, and open eye. The dataset comprises the following number of images: 2039 for Seatbelt, 1495 for Phone, 2423 for Cigarette, 2365 for Closed Eye, and 2359 for Open Eye. Figure 6 summarises the image attributes for each category. Because of this even distribution, detection models can be developed that are both robust and accurate. The dataset is allocated as follows: 80% for training, 10% for validation, and 10% for testing.

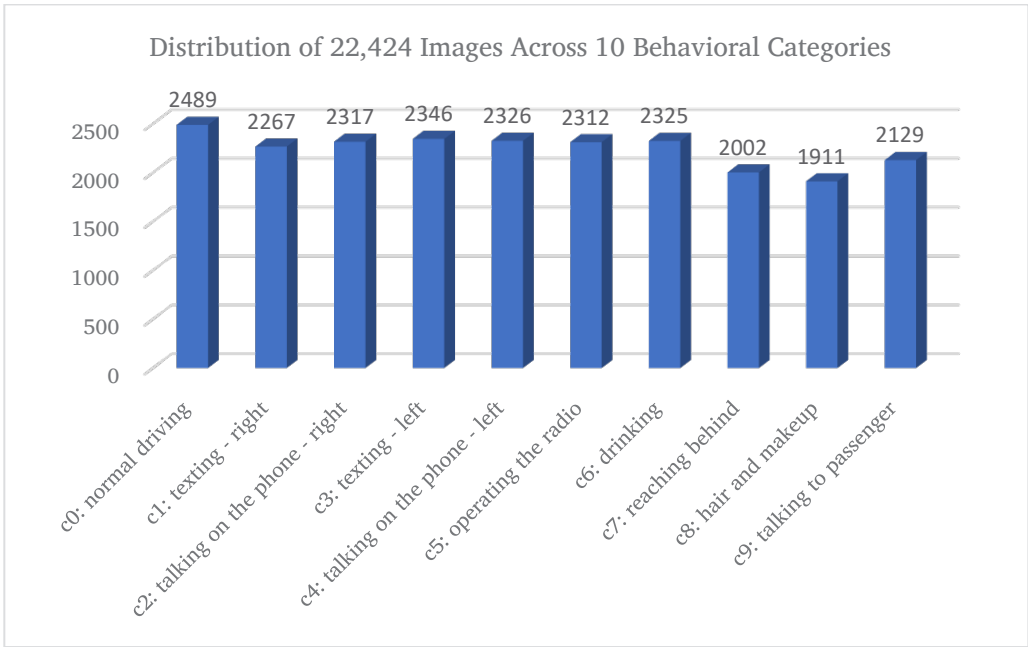


Figure 5. Distribution of Driver Behaviour Classes in the State Farm Dataset.

5. System Architecture Overview

This study investigates deep learning models such as simpler CNN, YOLOv8, ResNet50 and VGG16 for classifying and detecting driver distractions. The research aims to identify the most accurate and efficient model for monitoring driver activity and enhancing road safety by utilising transfer learning and extensive training on labelled datasets from State Farm and Driver Monitor. Algorithm 1 describes the functionality of these techniques.

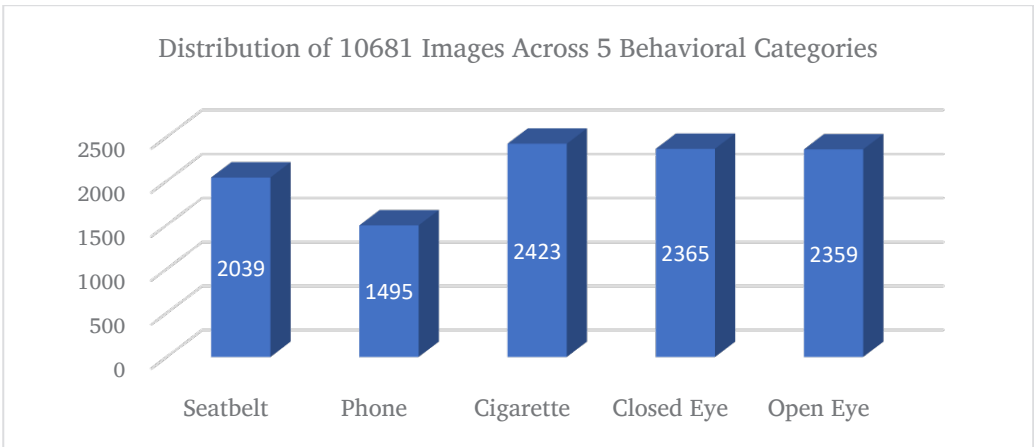


Figure 6. Shows the distribution of the five behaviour classes in the DMD.

|                                                                                                         |                                                                                                                                                                                                                                  |
|---------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Algorithm 1: Driver Distraction Detection by using the simpler CNN, VGG16, ResNet50, and YOLOv8 models: |                                                                                                                                                                                                                                  |
| 1.                                                                                                      | Input: The State Farm and the Driver Monitor Datasets contain labelled images for 15 classes of driver distraction behaviours.                                                                                                   |
| 2.                                                                                                      | Preprocessing: Load and resize all images to 256x256 pixels, normalise pixel values between 0 and 1, and apply data augmentation techniques (rotation, flipping, zooming) to enhance dataset diversity and minimise overfitting. |
| 3.                                                                                                      | Model Selection:                                                                                                                                                                                                                 |
| a)                                                                                                      | Model1 (Convolutional Neural Network):                                                                                                                                                                                           |
| >                                                                                                       | Use multiple convolutional layers with ReLU activations for feature extraction.                                                                                                                                                  |
| >                                                                                                       | Use max pooling to decrease the dimensionality.                                                                                                                                                                                  |
| >                                                                                                       | Flatten the feature maps and apply dense layers.                                                                                                                                                                                 |
| >                                                                                                       | Use softmax activation to output class probabilities.                                                                                                                                                                            |
| b)                                                                                                      | Model2 (VGG16 with Transfer Learning):                                                                                                                                                                                           |
| >                                                                                                       | Load the pre-trained VGG16 model with weights, excluding the top classification layers.                                                                                                                                          |
| >                                                                                                       | Freeze all layers except the last five layers.                                                                                                                                                                                   |
| >                                                                                                       | Flatten an output of a last pooling layer.                                                                                                                                                                                       |
| >                                                                                                       | Add custom dense layers and batch normalisation.                                                                                                                                                                                 |
| >                                                                                                       | Apply softmax activation for the multi class classification.                                                                                                                                                                     |
| c)                                                                                                      | Model3 (ResNet50 with Transfer Learning):                                                                                                                                                                                        |
| ✓                                                                                                       | Load the pre-trained ResNet50 model with its weights, omitting the top classification layers.                                                                                                                                    |
| ✓                                                                                                       | Freeze all layers except for the last three.                                                                                                                                                                                     |
| ✓                                                                                                       | Flatten the output from the residual layers.                                                                                                                                                                                     |
| ✓                                                                                                       | Append custom dense layers and apply batch normalisation.                                                                                                                                                                        |
| ✓                                                                                                       | Use a softmax activation function to perform the classification.                                                                                                                                                                 |
| d)                                                                                                      | Model4 (YOLOv8 for object detection):                                                                                                                                                                                            |
| ✓                                                                                                       | Load the pre-trained YOLOv8 model for object detection.                                                                                                                                                                          |
| ✓                                                                                                       | Directly pass the image through the YOLO model to output the predicted class.                                                                                                                                                    |
| 4.                                                                                                      | Use the Adam optimiser with a learning rate of 0.001, applying categorical cross-entropy as the accuracy and loss function in the classification tasks.                                                                          |
| 5.                                                                                                      | Training                                                                                                                                                                                                                         |
| ✓                                                                                                       | Divide the dataset into test, training, and validation sets.                                                                                                                                                                     |
| ✓                                                                                                       | Train the models using the following settings:                                                                                                                                                                                   |
| ✓                                                                                                       | Learning rate: 0.001                                                                                                                                                                                                             |
| ✓                                                                                                       | Batch size: 32                                                                                                                                                                                                                   |
| ✓                                                                                                       | Optimiser: Adam                                                                                                                                                                                                                  |

- ✓

Monitor both training and validation accuracy after each epoch.
- ✓

Implement early stopping techniques to validate loss to avoid overfitting while training models for 15 epochs, consistently monitoring their performance at every stage.
6.

Evaluate each trained model on an unseen test set, comparing metrics such as validation loss, validation accuracy, training loss, and training accuracy while analysing performance, primarily focusing on YOLO model speed and efficiency for object detection.
7.

Comparison and Analysis: The models were compared based on their accuracy in detecting distractions, computational efficiency, and suitability. VGG16 and ResNet50 excelled in classification tasks but required more processing time, while YOLO offered faster detection suitable for applications with a minor accuracy trade-off.
8.

Deployment Considerations: Based on the results, the most precise and effective model was selected for potential deployment in driver monitoring systems, with exploration into integrating the model to trigger warnings or interventions when driver distraction is detected.

6. Result and Discussion

Two open-source datasets (the State Farm and the Driver Monitoring) were utilised to classify fifteen distinct types of driver distractions, enabling effective detection across diverse lighting conditions. Deep learning models like simpler CNN, VGG16, ResNet50, and YOLOv8, were utilised to detect distracted driving. Both VGG16 and ResNet50, which were pre-trained on the State Farm dataset and DMD, achieved high accuracy through transfer learning. Meanwhile, YOLOv8 demonstrated superior speed and detection efficiency in real-time. Each model was trained for 15 epochs, and performance was carefully monitored to prevent overfitting. Figure 7 illustrates examples of detected distracted driving behaviours.



Figure 7. illustrates a variety of driver activities.

The CNN architecture starts with multiple Conv2D layers that are responsible for feature extraction. Each Conv2D layer is paired with a MaxPooling2D layer to downsample the spatial dimensions of the data and includes Batch Normalisation to stabilise the activations. The network progressively increases the number of filters from 16 to 64, enabling the network to capture increasingly complex features. After feature extraction, the output is flattened and passed through two Dense layers with 512 and 1024 units, respectively, before reaching the final Dense layer, which has 10 neurons and uses the softmax activation function for classification. Table 1 summarises the model's details, highlighting that it has 29 million parameters and demonstrating its efficiency in image classification through effective pooling and regularisation techniques.

| LAYER                  | TYPE : OUTPUT SHAPE WITH PARAMETERS                             |
|------------------------|-----------------------------------------------------------------|
| conv2D                 | Conv2D: Output (None, 254, 254, 16) with 448 parameters         |
| max_pooling2D          | MaxPooling2D: Output (None, 127, 127, 16) with 0 parameters     |
| conv2D(1)              | Conv2D: Output (None, 125, 125, 32) with 4,640 parameters       |
| max_pooling2D(1)       | MaxPooling2D: Output (None, 62, 62, 32) with 0 parameters       |
| conv2D(2)              | Conv2D: Output (None, 60, 60, 64) with 18,496 parameters        |
| max_pooling2D_(2)      | MaxPooling2D: Output (None, 30, 30, 64) with 0 parameters       |
| Flatten(1)             | Flatten: Output (None, 57,600) with 0 parameters                |
| Dense(8)               | Dense: 512 neurons with 29,491,712 parameters                   |
| Dense(9)               | Dense: 1,024 neurons with 525,312 parameters                    |
| batch_normalization(3) | Batch Normalisation: Output (None, 1,024) with 4,096 parameters |
| Dense(10)              | Dense: 10 neurons with 10,250 parameters                        |

Table 1. The layers and parameters of The ConvNet Model.

Table 2 details the CNN's performance over 15 epochs, highlighting consistent improvement in training and validation metrics. Initially, training accuracy was 21.30% and validation accuracy was 13.29%. By the fifth epoch, these values rose to 61.36% and 63.29%, respectively. Training reached 77.37% and validation at 75.90% between the sixth and tenth epochs, with a significant loss reduction. At the fourteenth epoch, validation accuracy peaked at 88.74% with a loss of 0.3274. With early stopping, the final model achieved 83.39% training accuracy and 85.81% validation accuracy, demonstrating effective generalisation.

| Epoch | Training_Accuracy | Training_Loss | Validation_Accuracy | Validation_Loss |
|-------|-------------------|---------------|---------------------|-----------------|
| 1     | 21.30%            | 2.3138        | 13.29%              | 2.2197          |
| 2     | 41.65%            | 1.7088        | 38.29%              | 1.9599          |
| 3     | 50.29%            | 1.4894        | 52.25%              | 1.5354          |
| 4     | 56.84%            | 1.2452        | 60.81%              | 1.4425          |
| 5     | 61.36%            | 1.1189        | 63.29%              | 1.0685          |
| 6     | 67.01%            | 0.9965        | 72.07%              | 0.8172          |
| 7     | 66.91%            | 0.9483        | 52.48%              | 1.4160          |
| 8     | 73.64%            | 0.7969        | 81.08%              | 0.5542          |
| 9     | 75.37%            | 0.7391        | 70.72%              | 0.8689          |
| 10    | 77.37%            | 0.6708        | 75.90%              | 0.7258          |
| 11    | 79.89%            | 0.6260        | 79.50%              | 0.6515          |
| 12    | 80.21%            | 0.5717        | 74.55%              | 0.7923          |
| 13    | 81.04%            | 0.5612        | 82.43%              | 0.5364          |
| 14    | 81.63%            | 0.5135        | <b>88.74%</b>       | <b>0.3274</b>   |
| 15    | 83.39%            | 0.4946        | 85.81%              | 0.4979          |

Table 2. Training Results of the CNN Model Over Fifteen Epochs.

Figure 8(a) illustrates the model achieving a training accuracy of 90.45% and a validation accuracy of 88.57%, demonstrating effective learning and generalisation. Figure 8(b) shows the loss plot, with training and validation losses steadily decreasing and minimal overfitting observed, attributed to the convergence of the curves, batch normalisation, and efficient feature extraction by the convolutional layers.

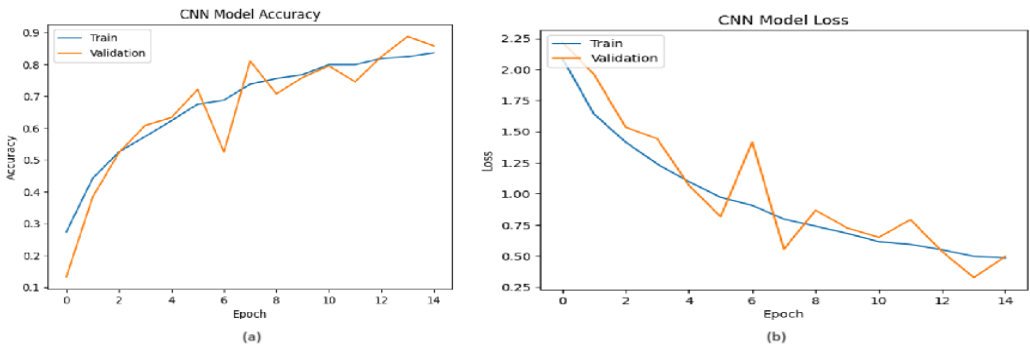


Figure 8. Graphs Illustrating the CNN Model Loss and Accuracy During Validation and Training.

The VGG16 model serves as the feature extractor and is further enhanced with additional dense layers to classify the driver distraction State Farm dataset. This architecture combines the pre-trained VGG16 convolutional layers with fully connected dense layers, batch normalisation, and dropout techniques to accomplish the final classification task, as shown in Table 3.

| VGG16 architecture                    | Layers and parameter counts                                                                                                                                                                                                              |
|---------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Input Layer</b>                    | Dimensions (256, 256, 3), 0 parameters.                                                                                                                                                                                                  |
| <b>Convolutional Layers (Block 1)</b> | Two Conv2D layers (64 filters each), totalling 38,720 parameters ( with a total of 1,792 and 36,928 parameters), followed by MaxPooling2D reducing spatial dimensions to (128, 128, 64).                                                 |
| <b>Convolutional Layers (Block 2)</b> | Two Conv2D layers (128 filters each), totalling 221,440 parameters ( with 73,856 and 147,584 parameters), followed by MaxPooling2D reducing dimensions to (64, 64, 128).                                                                 |
| <b>Convolutional Layers (Block 3)</b> | Three Conv2D layers (256 filters each), totalling 1,475,328 parameters (with 295,168, 590,080, and 590,080 parameters), followed by MaxPooling2D reducing dimensions to (32, 32, 256).                                                   |
| <b>Convolutional Layers (Block 4)</b> | Three Conv2D layers, each with 512 filters, account for a total of 5,899,776 parameters, broken down as 1,180,160, 2,359,808, and 2,359,808 respectively, followed by a MaxPooling2D layer that reduces the dimensions to (16, 16, 512). |
| <b>Flatten Layer</b>                  | Converts feature maps into a single vector (131,072 units).                                                                                                                                                                              |
| <b>Dropout Layer</b>                  | Prevents overfitting by randomly disabling neurons during training.                                                                                                                                                                      |
| <b>First Dense Layer</b>              | 128 neurons, 16,777,344 parameters, followed by Batch Normalization.                                                                                                                                                                     |
| <b>Second Dense Layer</b>             | 256 neurons, 33,024 parameters, followed by Batch Normalization.                                                                                                                                                                         |
| <b>Output Layer</b>                   | 10 neurons (final classification), 2,570 parameters.                                                                                                                                                                                     |

Table 3. VGG16 Pre-Trained Model with Dense Layers.

The model was compiled using the adam optimiser and categorical cross entropy loss. It achieved optimal performance by leveraging feature extraction and mitigating overfitting with dropout and batch normalisation. The VGG model’s performance is improved until it reached a peak training accuracy of 93.03%, a validation accuracy of 98.42%, and a low validation loss of 0.0630 by epoch 10, as shown in Table 4 and Figure 9. The early stopping mechanism ensured the model was restored to this optimal state, highlighting its ability to generalise effectively and accurately classify driver distractions.

| Epoch | Training_Accuracy | Training_Loss | Validation_Accuracy | Validation_Loss |
|-------|-------------------|---------------|---------------------|-----------------|
| 1     | 26.58%            | 2.2992        | 33.56%              | 2.2762          |
| 2     | 65.95%            | 1.0329        | 69.82%              | 0.8151          |
| 3     | 79.02%            | 0.5974        | 84.46%              | 0.4737          |
| 4     | 85.28%            | 0.4547        | 92.12%              | 0.2748          |
| 5     | 88.43%            | 0.3720        | 88.74%              | 0.3241          |
| 6     | 89.85%            | 0.3032        | 92.79%              | 0.2049          |
| 7     | 90.92%            | 0.2964        | 94.37%              | 0.1619          |
| 8     | 90.67%            | 0.2850        | 96.17%              | 0.1245          |
| 9     | 92.45%            | 0.2414        | 97.30%              | 0.1161          |
| 10    | 93.03%            | 0.2107        | <b>98.42%</b>       | <b>0.0630</b>   |
| 11    | 93.03%            | 0.2138        | 97.07%              | 0.0910          |
| 12    | 94.41%            | 0.1654        | 96.40%              | 0.0943          |
| 13    | 93.27%            | 0.2114        | 97.30%              | 0.0710          |
| 14    | 94.13%            | 0.1847        | 97.97%              | 0.0570          |
| 15    | 95.42%            | 0.1632        | 96.85%              | 0.1052          |

Table 4. Training Results of the VGG16 Model Over Fifteen Epochs.

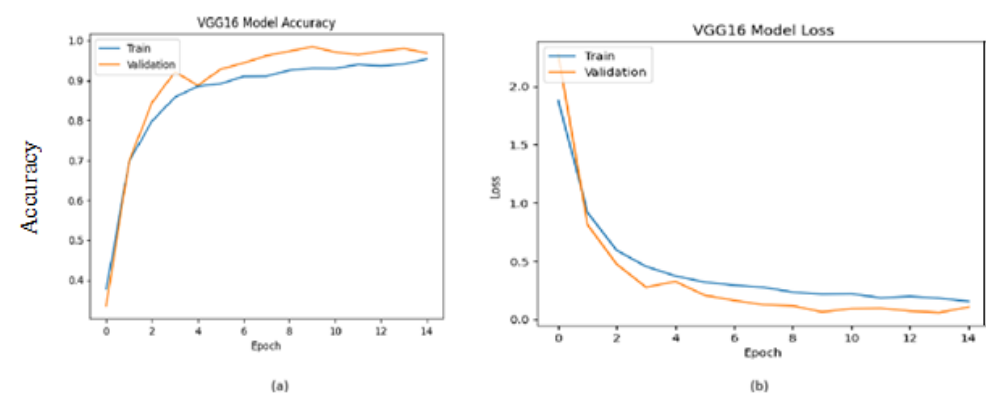


Figure 9. Graphs the Loss and Accuracy During Validation and Training for the VGG16 model.

The ResNet50 model minimises the risk of overfitting and guarantees stable training by freezing the earlier layers. To improve the stability of the ResNet50 model for driver distraction detection, five dense layers with batch normalisation were added, as seen in Table 5. Both the deep residual and the dense layers were kept frozen during the training process. The ResNet50 model effectively utilises pre-trained weights, while the last three layers are made trainable.

| ResNet50 architecture       | Output shapes and parameter counts                                                                                                                                                                                                                                                                                                                                                                                                         |
|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Input Layer                 | The model starts with an input layer of size $(256 \times 256 \times 3)$ . A ZeroPadding2D layer is applied to expand the input dimensions to $(262 \times 262 \times 3)$ .                                                                                                                                                                                                                                                                |
| Initial Convolutional Block | <ul style="list-style-type: none"><li>• A Conv2D layer with 64 filters (9,472 parameters) processes the padded input to produce a feature map of <math>(128 \times 128 \times 64)</math>.</li><li>• This process includes batch normalisation (256 parameters) and ReLU activation, which contribute to stabilising the network.</li><li>• MaxPooling2D reduces the spatial dimensions to <math>(64 \times 64 \times 64)</math>.</li></ul> |

|                               |                                                                                                                                                                                                                                                                                                                                                                                                                               |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Residual Block (conv2_block1) | <ul style="list-style-type: none"><li>• Main Path: Two Conv2D layers with 64 filters each, BatchNorm and ReLU are applied, resulting in an output of <math>(64 \times 64 \times 64)</math>.</li><li>• Shortcut Path: A Conv2D layer with 256 filters (16,640 parameters) followed by BatchNorm.</li><li>• Both paths are combined via an Add layer, producing a <math>(64 \times 64 \times 256)</math> feature map.</li></ul> |
| Advanced Convolutional Block  | <ul style="list-style-type: none"><li>• A Conv2D layer with 512 filters (524,800 parameters) generates an <math>(8 \times 8 \times 512)</math> output, followed by BatchNorm (2,048 parameters) and ReLU activation.</li><li>• The feature map is then passed through another Add layer and output <math>(8 \times 8 \times 2048)</math>.</li></ul>                                                                           |
| Flattening and Dropout        | <ul style="list-style-type: none"><li>• The feature map is flattened into a vector of 131,072 units.</li><li>• A Dropout layer is applied to reduce overfitting.</li></ul>                                                                                                                                                                                                                                                    |
| Fully Connected Layers        | <ul style="list-style-type: none"><li>• A dense layer with 128 units (16,777,344 parameters) is followed by BatchNorm (512 parameters).</li><li>• A second dense layer consisting of 256 units (33,024 parameters) is introduced, followed by Batch Normalization (1,024 parameters).</li><li>• The final output is produced by a dense layer with 10 units (2,570 parameters).</li></ul>                                     |

Table 5. The layers and parameters of the ResNet50 model.

The ResNet50 model is trained over 15 epochs and demonstrated significant improvement. The training accuracy rose from 17.73% to 65.24%, while the validation accuracy reached 74.55%. Additionally, the validation loss decreased notably from 11.1845 in the first epoch to 0.7474 by the 10th epoch, highlighting the effectiveness of transfer learning. However, performance plateaued after the 10th epoch, suggesting a potential need for further adjustments, like fine-tuning a learning rate or incorporating regularisation to enhance stability, as shown in Table 6.

| Epoch | Train Accuracy | Train Loss | Validate Accuracy | Validate Loss | Time per Epoch (s) |
|-------|----------------|------------|-------------------|---------------|--------------------|
| 1     | 0.1773         | 2.6027     | 0.0968            | 11.1845       | 550                |
| 2     | 0.3429         | 1.8421     | 0.1104            | 4.9851        | 564                |
| 3     | 0.4342         | 1.6166     | 0.1779            | 5.1718        | 535                |
| 4     | 0.4462         | 1.5588     | 0.3761            | 1.8280        | 534                |
| 5     | 0.5051         | 1.4173     | 0.2973            | 5.7755        | 512                |
| 6     | 0.5176         | 1.3586     | 0.3941            | 2.1522        | 531                |
| 7     | 0.5462         | 1.2807     | 0.4054            | 1.8823        | 530                |
| 8     | 0.5844         | 1.1987     | 0.5991            | 1.1240        | 528                |
| 9     | 0.5766         | 1.1884     | 0.6937            | 0.8567        | 528                |
| 10    | 0.6211         | 1.1193     | 0.7680            | 0.7474        | 506                |
| 11    | 0.6125         | 1.1163     | 0.6982            | 0.8633        | 518                |
| 12    | 0.6296         | 1.0709     | 0.7275            | 0.8295        | 578                |
| 13    | 0.6458         | 1.0442     | 0.7793            | 0.6865        | 560                |
| 14    | 0.6400         | 1.0412     | 0.6802            | 0.9194        | 559                |
| 15    | 0.6524         | 1.0025     | 0.7455            | 0.7572        | 565                |

Table 6. Training of the ResNet50 model across 15 epochs.

Figure 10 illustrates the ResNet50 model's consistent improvement in training and validation accuracy over 15 epochs, ultimately reaching 65% and 74%, respectively. Additionally, there is a steady reduction in loss. However, the early epochs showed minor fluctuations in validation performance; the model stabilised by epoch 10, achieving a test accuracy of 77.58%. This demonstrates its strong potential for classifying driver behaviour, with opportunities for further enhancement through fine-tuning.

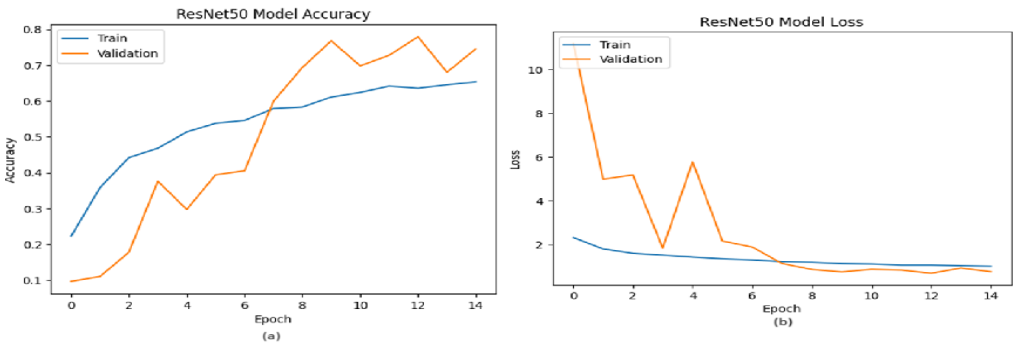


Figure 10. Graphs the Loss and Accuracy During Validation and Training for the ResNet50 model.

The YOLOv8 model was fine-tuned using the State Farm dataset, which includes ten behaviour classes for distracted drivers labelled from c0 to c9 to achieve effective detection. The model utilised pre-trained weights from the yolov8n-cls.pt file. Its architecture incorporates convolutional layers and C2f blocks to enhance feature extraction. The Adam optimiser regulates the learning rate and momentum, ensuring optimal performance.

Table 7 outlines the architecture of the YOLOv8 model, which consists of 99 layers, 1,451,098 trainable parameters, and a computational cost of 3.4 GFLOPs. This streamlined architecture, featuring Conv2D layers and C2f blocks, enables lightweight yet highly accurate detection of driver distractions.

| Layer_Number | Layer_Type      | Output_Shape         | Parameters |
|--------------|-----------------|----------------------|------------|
| 0            | Conv2D          | (None, 112, 112, 16) | 464        |
| 1            | Conv2D          | (None, 56, 56, 32)   | 4,672      |
| 2            | C2f             | (None, 56, 56, 32)   | 7,360      |
| 3            | Conv2D          | (None, 28, 28, 64)   | 18,560     |
| 4            | C2f             | (None, 28, 28, 64)   | 49,664     |
| 5            | Conv2D          | (None, 14, 14, 128)  | 73,984     |
| 6            | C2f             | (None, 14, 14, 128)  | 197,632    |
| 7            | Conv2D          | (None, 7, 7, 256)    | 295,424    |
| 8            | C2f             | (None, 7, 7, 256)    | 460,288    |
| 9            | Classify (Head) | (None, 10)           | 343,050    |

Table 7. Provides an overview of the YOLOv8 model's architecture.

Figure 11 shows a steady decrease in both training and validation loss over 15 epochs. This trend demonstrates the effectiveness of the YOLOv8 model in learning and its strong ability to generalise. The gradual convergence of these loss metrics towards low values indicates reduced overfitting and indicates strong performance in detecting driver distraction.

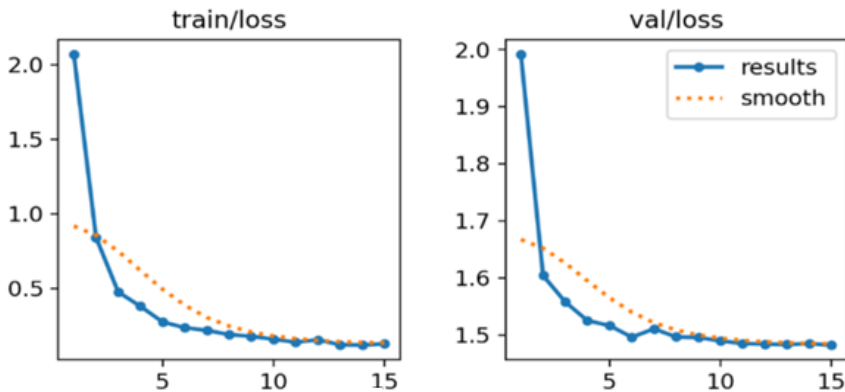


Figure 11. Graphs the Loss During Training and Validation for the YOLOv8 model

Figure 12 demonstrates that the YOLOv8 models top-1 accuracy steadily increases, approaching nearly 99% by the 10th epoch. Meanwhile, the top-5 accuracy reaches 100% within the first few epochs. This robust and consistent performance highlights the model's high reliability for detecting driver distraction.

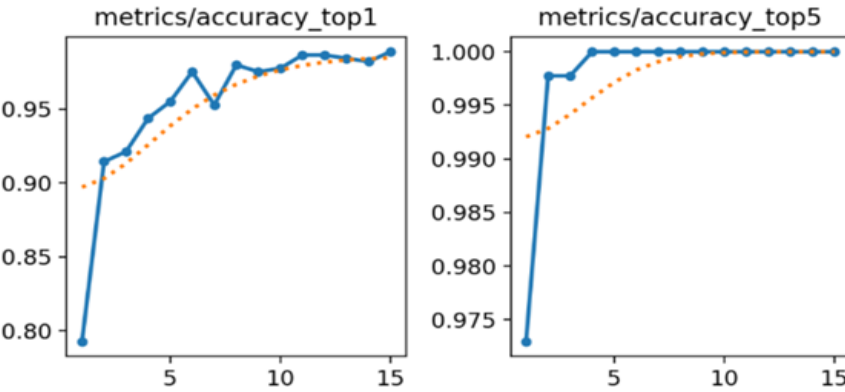


Figure 12. Graphs the Accuracy During Training and Validation of the YOLOv8 Model.

Figure 13 illustrates the normalised confusion matrix indicates for the State Farm dataset that the YOLOv8 model achieved nearly flawless classification, attaining 100% accuracy in most classes (c1, c2, c3, c4, c5, c7, and c9). There were only minor misclassifications in classes c0, c6, and c8, leading to an overall test accuracy of 99.44%. This matrix underscores the model's strong predictive performance, as evidenced by the prominent diagonal values representing accurate detection for each category, thereby validating the reported accuracy.

Figure 14 shows the models YOLOv8, VGG16, and ResNet50 applied to DMD. YOLOv8 outperforms the other models, recording a Top-1 accuracy of 97.7%. Its validation loss stabilises at approximately 1.06, making it highly reliable for real-time detection of driver behaviours such as distraction, drowsiness, or phone usage. Next, the VGG16 model returns a confidence of 96.3% and a slightly higher validation loss of 1.45, which makes for a nice compromise of performance and calculation cost. On the other hand, ResNet50 has the lowest accuracy rate at Top-1 (92.9%) and the highest validation loss of 1.25, indicating less generalisation and overfitting. From these results, YOLOv8 is the ideal selection for DMD applications that need a high level of precision and robustness.

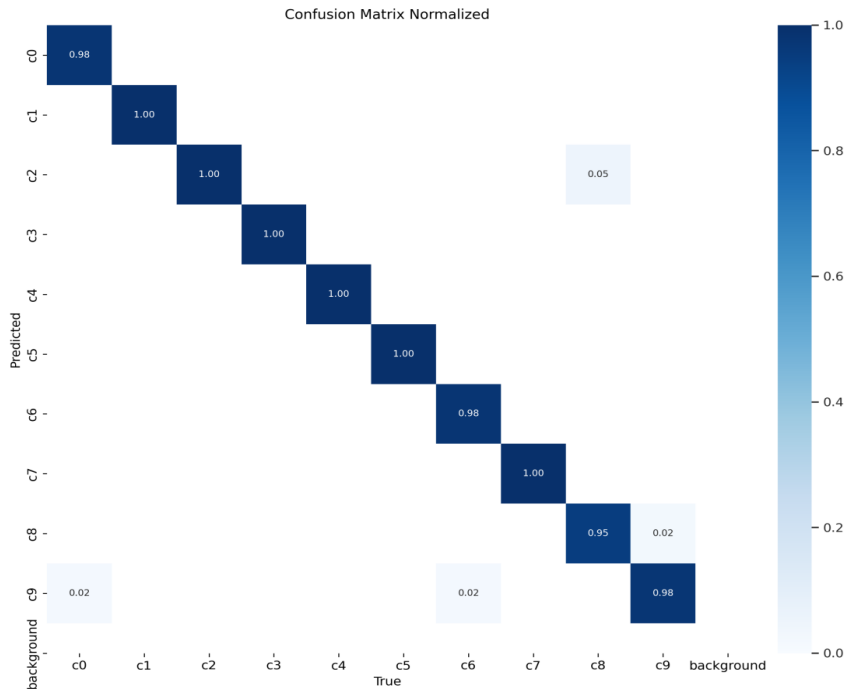


Figure 13. The YOLOv8 model confusion matrix.

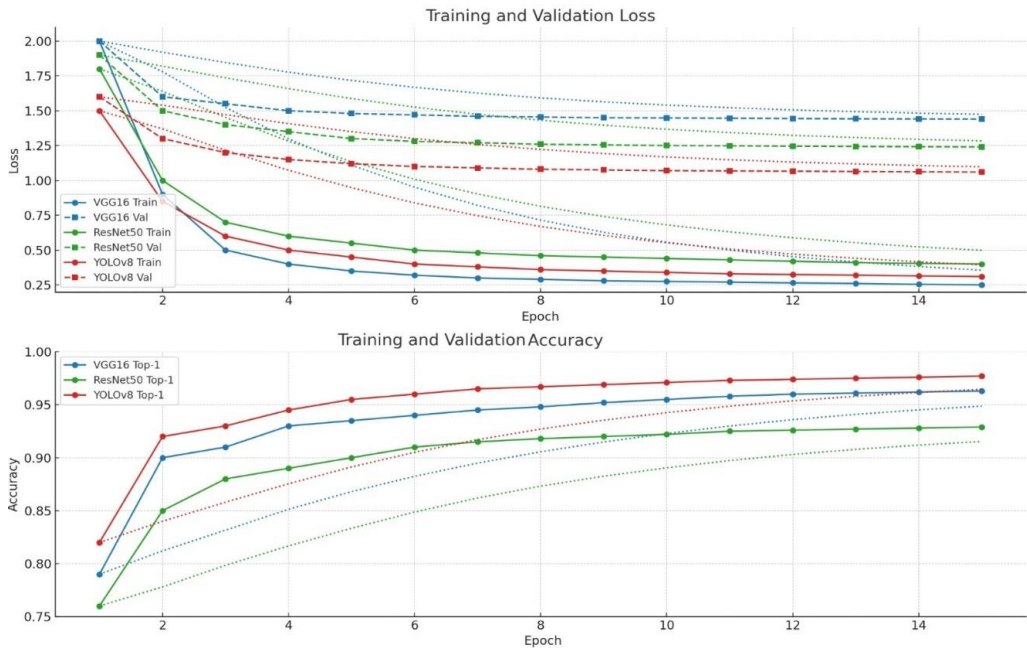


Figure 14. Comparison of VGG16, ResNet50, and YOLOv8 Models in DMD: Training and Validation Losses and Accuracy.

As shown in Figure 15, the proposed YOLOv8's performance on DMD images demonstrates its ability to detect crucial behaviours, including eye status (open/closed), smoking, and seatbelt wearing, in real-time under varying lighting and angles. This validates the effectiveness and reliability of YOLOv8 for practical usage in monitoring drivers.

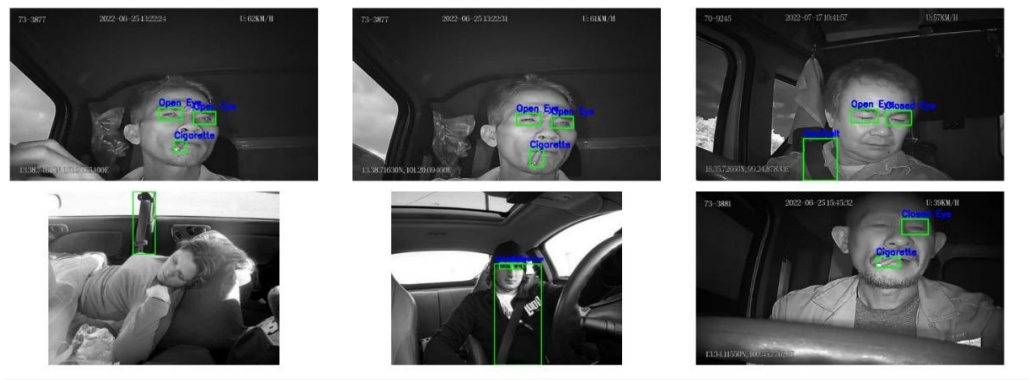


Figure 15. Real-Time Detection of Driver Behaviours Using YOLOv8 in DMD

The Figure 16 displays confusion matrices for VGG16, ResNet50, and YOLOv8, which are evaluated on DMD in five classes: open eye, closed eye, cigarette, phone, and seatbelt. VGG16 exhibits strong overall accuracy, although it occasionally confuses visually similar classes, particularly between the open eye and closed eye. The ResNet50 performs poorly with increased abortion and low precision, especially in phone and seatbelt categories. On the other hand, YOLOv8 achieves the best results, displaying the highest true positive rates and minimal confusion between squares. This underscores its robustness and suitability for real-time driver behaviour detection.

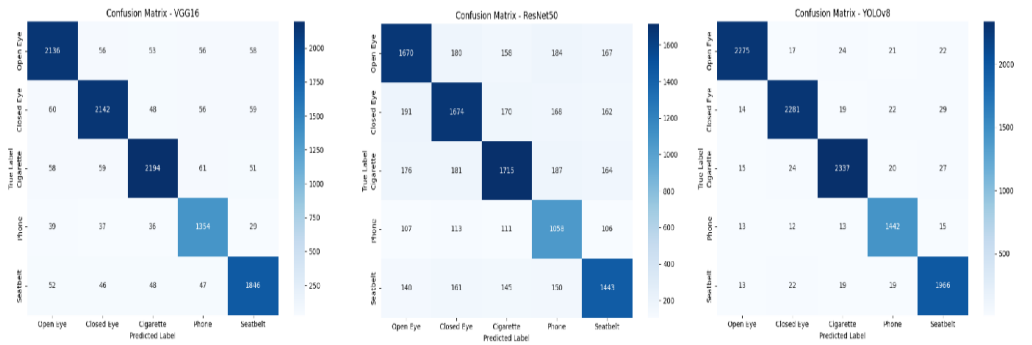


Figure 16. Confusion Matrices of VGG16, ResNet50, and YOLOv8 Models on the DMS Dataset

Figure 17 compares the performance of four models for driver distraction detection across two datasets: the State Farm and the Driver Monitoring. In the State Farm dataset, the accuracy attained the highest percentage in YOLOv8 with 98.46 %, while VGG16 recorded 97.58%, showing that both models are robust in the feature extraction performance. A CNN model was accuracy-wise scored 82.20% which means that increasing its complexity or the tuning process fine-tuning could potentially improve its performance. The ResNet50 model achieved a performance accuracy of 77.80%. However, when evaluated on the DMD, all models experienced a drop in performance reflecting the increased difficulty or variability within the DMD images. YOLOv8 remained the top performer with 96.46%, maintaining high robustness across both datasets. VGG16 also showed strong generalisation with 90.58%, while CNN and ResNet50 saw larger declines, achieving 67.24% and 70.80%, respectively. These results highlight YOLOv8's superior adaptability and confirm its effectiveness for real-world driver behaviour detection tasks.

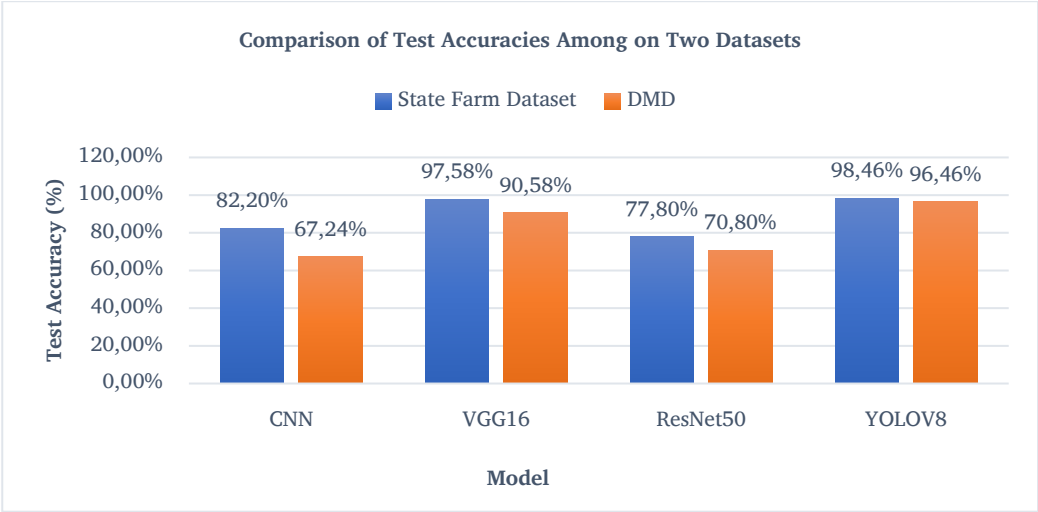


Figure 17. Test Accuracy Results for the proposed work.

The figure 18 illustrates the real-time implementation of the trained YOLOv8-based driver monitoring system. The algorithm was applied using a standard webcam to detect and classify driver behaviours across multiple individuals and scenarios. The system successfully identifies various states such as normal driving, texting right, drinking, and smoking, in addition to critical indicators like open eyes, phone usage, and seatbelt status. By providing real-time detections, the model demonstrates its worth and efficiency for practical situations, successfully establishing behavioural patterns in several scenarios. This confirms the model's readiness for deployment in live driver assistance systems aimed at improving road safety.



Figure 18. illustrates the outcomes of the real-time identification of normal driving, texting, drinking, open eyes, phone usage, and seatbelt status.

## 7. Conclusion

Distracted driving is now a major concern in recent years. This study examines three neural network architectures: VGG16, YOLOv8, and ResNet50, to detect distracted drivers using two open-source datasets to provide diversity in the number of classes as well as to predict distracted driving in different lighting conditions, day and night and different camera angles. The total data trained in the system exceeds 33,000 images. The dataset was augmented and preprocessed to improve performance and transfer learning was used to train models over fifteen categories of distracted driving. The results show that YOLOv8 performed better than other models once implemented on the State Farm dataset with a resulting test accuracy of 98.46%. VGG16 was followed with great precision with accuracy rate of 97.58%, where effective transfer learning and feature extraction techniques were used. Despite the fact that CNN and ResNet50 models delivered fairly good results, YOLOv8 was faster and more accurate. YOLOv8 maintained its best performance after applying it to the DMD dataset, achieving 96.46%. VGG16 also demonstrated strong generalisation, achieving 90.58%, while CNN and ResNet50 achieved 67.24% and 70.80%, respectively. In totality, speed and precision in YOLOv8 make it the best tool for driver monitoring systems. YOLOv8 facilitates the timely detection of distracted behaviours, applied to real-time images captured from a camera and identifies different driver distraction categories successfully, supporting seamless integration into modern car dashboards that ultimately enhance road safety.

The limitation of this study is that we found the VGG16 model outperforms ResNet50 when applied to two types of datasets. Despite ResNet50 being deeper and more complex, with over 23 million parameters, it requires more training epochs and better learning rate scheduling to achieve optimal performance. In our work, we utilised a relatively short training duration of only 15 to 20 epochs.

Future research could consider different deep learning architectures, specifically their capacity to learn from a limited number of images, in order to add accuracy with fewer samples. This area has received little research attention. Learning based on Sample-Based Learning (SBL) has shown potential in improving accuracy with fewer samples. Additionally, there is a need for careful investigation into the ability to predict human behaviour using visual features, such as mouth movements, or physiological indicators that can identify anomalies in data. A hybrid approach to detecting driver distraction could be developed by combining deep learning techniques with an embedded search strategy.

## References

- [1] E. Michelaraki, C. Katrakazas, S. Kaiser, T. Brijs, and G. Yannis, "Real-time monitoring of driver distraction: State-of-the-art and future insights," *Accid Anal Prev*, vol. 192, p. 107241, 2023, doi: <https://doi.org/10.1016/j.aap.2023.107241>.
- [2] K. Khan, S. B. A. Zaidi, and A. Ali, "Evaluating the Nature of Distractive Driving Factors towards Road Traffic Accident," *Civil Engineering Journal*, vol. 6, pp. 1555–1580, Aug. 2020, doi: 10.28991/cej-2020-03091567.
- [3] A. Muthuswamy, M. A. A. Dewan, M. Murshed, and D. Parmar, "Driver Distraction Classification Using Deep Convolutional Autoencoder and Ensemble Learning," *IEEE Access*, vol. 11, pp. 71435–71448, 2023, doi: 10.1109/ACCESS.2023.3293110.
- [4] A. Misra, S. Samuel, S. Cao, and K. Shariatmadari, "Detection of Driver Cognitive Distraction Using Machine Learning Methods," *IEEE Access*, vol. 11, pp. 18000–18012, 2023, doi: 10.1109/ACCESS.2023.3245122.
- [5] A. N. Jaafar, "Enhancement of Breast Cancer Classification Using Bat Feature Selection with Recurrent Deep Learning.," *J. Comput. Inf. Technol.*, vol. 32, no. 3, pp. 195–215, 2024, [Online]. Available: <http://cit.fer.hr/index.php/CIT/article/view/5801>
- [6] A. Kashevnik, R. Shchedrin, C. Kaiser, and A. Stocker, "Driver Distraction Detection Methods: A Literature Review and Framework," *IEEE Access*, vol. 9, pp. 60063–60076, 2021, doi: 10.1109/ACCESS.2021.3073599.
- [7] M. Al-Bayati, "Deep Learning Model for Predicting Spreading Rates of Pandemics, 'COVID-19 as Case Study,'" *Journal of information and organizational sciences*, vol. 48, pp. 253–262, Dec. 2024, doi: 10.31341/jios.48.2.1.
- [8] M. H. Alkinani, W. Z. Khan, and Q. Arshad, "Detecting Human Driver Inattentive and Aggressive Driving Behavior Using Deep Learning: Recent Advances, Requirements and Open Challenges," *IEEE Access*, vol. 8, pp. 105008–105030, 2020, doi: 10.1109/ACCESS.2020.2999829.

- [9] J. Wang *et al.*, “A Survey on Driver Behavior Analysis From In-Vehicle Cameras,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 8, pp. 10186–10209, 2022, doi: 10.1109/TITS.2021.3126231.
- [10] V. Yaloveha, D. Hlavcheva, and A. Podorozhniak, “Spectral Indexes Evaluation for Satellite Images Classification using CNN,” *Journal of information and organizational sciences*, vol. 45, pp. 435–449, Dec. 2021, doi: 10.31341/jios.45.2.5.
- [11] Y. Chen, Y. Chen, S. Fu, W. Yin, K. Liu, and S. Qian, “VGG16-based intelligent image analysis in the pathological diagnosis of IgA nephropathy,” *J Radiat Res Appl Sci*, vol. 16, no. 3, p. 100626, 2023, doi: <https://doi.org/10.1016/j.jrras.2023.100626>.
- [12] Y. Chen *et al.*, “Automated Alzheimer’s disease classification using deep learning models with Soft-NMS and improved ResNet50 integration,” *J Radiat Res Appl Sci*, vol. 17, no. 1, p. 100782, 2024, doi: <https://doi.org/10.1016/j.jrras.2023.100782>.
- [13] S. D, S. J, A. S, A. K, S. P, and P. K, “Proactive Headcount and Suspicious Activity Detection using YOLOv8,” *Procedia Comput Sci*, vol. 230, pp. 61–69, 2023, doi: <https://doi.org/10.1016/j.procs.2023.12.061>.
- [14] R. Girshick, J. Donahue, T. Darrell, and J. Malik, “Rich Feature Hierarchies for Accurate Object Detection and Semantic Segmentation,” in *2014 IEEE Conference on Computer Vision and Pattern Recognition*, 2014, pp. 580–587. doi: 10.1109/CVPR.2014.81.
- [15] J. Redmon, S. Divvala, R. Girshick, and A. Farhadi, “You Only Look Once: Unified, Real-Time Object Detection,” in *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2016, pp. 779–788. doi: 10.1109/CVPR.2016.91.
- [16] R. Girshick, “Fast R-CNN,” in *2015 IEEE International Conference on Computer Vision (ICCV)*, 2015, pp. 1440–1448. doi: 10.1109/ICCV.2015.169.
- [17] A. D. Alvarez, F. S. Garcia, J. E. Naranjo, J. J. Anaya, and F. Jimenez, “Modeling the Driving Behavior of Electric Vehicles Using Smartphones and Neural Networks,” *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 3, pp. 44–53, 2014, doi: 10.1109/MITS.2014.2322651.
- [18] N. Vaegae, K. Pulluri, K. Bagadi, and O. Oyerinde, “Design of an Efficient Distracted Driver Detection System: Deep Learning Approaches,” *IEEE Access*, vol. 10, pp. 116087–116097, Nov. 2022, doi: 10.1109/ACCESS.2022.3218711.
- [19] A. Dhiman, A. Varshney, F. Hasani, and B. Verma, “A Comparative Study on Distracted Driver Detection Using CNN and ML Algorithms,” in *Proceedings of International Conference on Data Science and Applications*, M. Saraswat, C. Chowdhury, C. Kumar Mandal, and A. H. Gandomi, Eds., Singapore: Springer Nature Singapore, 2023, pp. 663–676.
- [20] M. Aljasim and R. Kashef, “E2DR: A Deep Learning Ensemble-Based Driver Distraction Detection with Recommendations Model,” *Sensors*, vol. 22, p. 1858, Feb. 2022, doi: 10.3390/s22051858.
- [21] A. V Jamsheed, B. Janet, and U. S. Reddy, “Real Time Detection of driver distraction using CNN,” in *2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT)*, 2020, pp. 185–191. doi: 10.1109/ICSSIT48917.2020.9214233.
- [22] H. Mittal and B. Verma, “CAT-CapsNet: A Convolutional and Attention Based Capsule Network to Detect the Driver’s Distraction,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 9, pp. 9561–9570, 2023, doi: 10.1109/TITS.2023.3266113.
- [23] C. Guo, H. Liu, J. Chen, and H. Ma, “Temporal Information Fusion Network for Driving Behavior Prediction,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 9, pp. 9415–9424, 2023, doi: 10.1109/TITS.2023.3267150.
- [24] K. Alshalfan and M. Zakariah, “Detecting Driver Distraction Using Deep-Learning Approach,” *Computers, Materials & Continua*, vol. 68, pp. 689–704, Feb. 2021, doi: 10.32604/cmc.2021.015989.
- [25] S. Liu, Y. Wang, Q. Yu, H. Liu, and Z. Peng, “CEAM-YOLOv7: Improved YOLOv7 Based on Channel Expansion and Attention Mechanism for Driver Distraction Behavior Detection,” *IEEE Access*, vol. 10, pp. 129116–129124, 2022, doi: 10.1109/ACCESS.2022.3228331.

- [26] B. B. Traore, B. Kamsu-Foguem, and F. Tangara, "Deep convolution neural network for image recognition," *Ecol Inform*, vol. 48, pp. 257–268, 2018, doi: <https://doi.org/10.1016/j.ecoinf.2018.10.002>.
- [27] R. Yamashita, M. Nishio, R. K. G. Do, and K. Togashi, "Convolutional neural networks: an overview and application in radiology," *Insights Imaging*, vol. 9, no. 4, pp. 611–629, 2018, doi: [10.1007/s13244-018-0639-9](https://doi.org/10.1007/s13244-018-0639-9).
- [28] B. Baheti, S. Gajre, and S. Talbar, "Detection of Distracted Driver Using Convolutional Neural Network," in *2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, 2018, pp. 1145–11456. doi: [10.1109/CVPRW.2018.00150](https://doi.org/10.1109/CVPRW.2018.00150).
- [29] K. He, X. Zhang, S. Ren, and J. Sun, "Deep Residual Learning for Image Recognition," in *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2016, pp. 770–778. doi: [10.1109/CVPR.2016.90](https://doi.org/10.1109/CVPR.2016.90).
- [30] C. Tan, F. Sun, T. Kong, W. Zhang, C. Yang, and C. Liu, "A Survey on Deep Transfer Learning," in *Artificial Neural Networks and Machine Learning – ICANN 2018*, V. Kůrková, Y. Manolopoulos, B. Hammer, L. Iliadis, and I. Maglogiannis, Eds., Cham: Springer International Publishing, 2018, pp. 270–279.
- [31] Y. Gao and K. Mosalam, "Deep Transfer Learning for Image-Based Structural Damage Recognition," *Computer-Aided Civil and Infrastructure Engineering*, vol. 33, Apr. 2018, doi: [10.1111/mice.12363](https://doi.org/10.1111/mice.12363).
- [32] T. T. Huynh, H. T. Nguyen, and D. T. Phu, "Enhancing Fire Detection Performance Based on Fine-Tuned YOLOv10," *Computers, Materials and Continua*, vol. 81, no. 2, pp. 2281–2298, 2024, doi: [10.32604/cmc.2024.057954](https://doi.org/10.32604/cmc.2024.057954).
- [33] J. Deng, W. Dong, R. Socher, L.-J. Li, K. Li, and L. Fei-Fei, "ImageNet: A large-scale hierarchical image database," in *2009 IEEE Conference on Computer Vision and Pattern Recognition*, 2009, pp. 248–255. doi: [10.1109/CVPR.2009.5206848](https://doi.org/10.1109/CVPR.2009.5206848).
- [34] X. Lu, H. Wang, J. Zhang, Y. Zhang, J. Zhong, and G. Zhuang, "Research on J wave detection based on transfer learning and VGG16," *Biomed Signal Process Control*, vol. 95, p. 106420, 2024, doi: <https://doi.org/10.1016/j.bspc.2024.106420>.
- [35] P. K. Mannepalli, A. Pathre, G. Chhabra, P. A. Ujjainkar, and S. Wanjari, "Diagnosis of bacterial leaf blight, leaf smut, and brown spot in rice leaves using VGG16," *Procedia Comput Sci*, vol. 235, pp. 193–200, 2024, doi: <https://doi.org/10.1016/j.procs.2024.04.022>.
- [36] K. Srinivasan et al., "Performance Comparison of Deep CNN Models for Detecting Driver's Distraction," *Computers, Materials & Continua*, vol. 68, pp. 4109–4124, Apr. 2021, doi: [10.32604/cmc.2021.016736](https://doi.org/10.32604/cmc.2021.016736).
- [37] L. Ali, F. Alnajjar, H. Jassmi, M. Gochoo, W. Khan, and M. Serhani, "Performance Evaluation of Deep CNN-Based Crack Detection and Localization Techniques for Concrete Structures," *Sensors*, vol. 21, p. 1688, Mar. 2021, doi: [10.3390/s21051688](https://doi.org/10.3390/s21051688).
- [38] Y. Gong, Z. Chen, W. Deng, J. Tan, and Y. Li, "Real-Time Long-Distance Ship Detection Architecture Based on YOLOv8," *IEEE Access*, vol. PP, p. 1, Jan. 2024, doi: [10.1109/ACCESS.2024.3445154](https://doi.org/10.1109/ACCESS.2024.3445154).
- [39] R.-Y. Ju and W. Cai, "Fracture detection in pediatric wrist trauma X-ray images using YOLOv8 algorithm," *Sci Rep*, vol. 13, no. 1, p. 20077, 2023, doi: [10.1038/s41598-023-47460-7](https://doi.org/10.1038/s41598-023-47460-7).
- [40] F. Solimani et al., "Optimizing tomato plant phenotyping detection: Boosting YOLOv8 architecture to tackle data complexity," *Comput Electron Agric*, vol. 218, p. 108728, 2024, doi: <https://doi.org/10.1016/j.compag.2024.108728>.



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