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HYBRID ANN–MCDM FRAMEWORK FOR BIG DATA-DRIVEN COMBUSTION OPTIMIZATION IN ESP32 MICROCONTROLLER-BASED SYSTEMS

This paper presents a hybrid framework that integrates Artificial Neural Networks (ANN) and Multi-Criteria Decision-Making (MCDM) methods for real-time optimization of combustion processes in microcontroller-based systems. The proposed solution is designed for low-cost hardware platforms, specifically ESP32 microcontrollers, enabling efficient processing of large-scale sensor data (Big Data) in industrial environments. The system is based on real-time data acquisition from sensors measuring temperature, humidity, CO and NOx emissions, and airflow. These data are preprocessed, normalized, and stored in a database, forming the basis for training ANN models (LSTM, GRU, and RNN). The trained models predict combustion parameters, while the MCDM module selects the optimal operating regime based on multiple criteria, including efficiency, emissions, and system stability. The framework was experimentally validated on ATI TERMING OZON boilers in the period from 2022 to 2025, with ongoing testing. The results show significant improvements, including a reduction of prediction error (MSE) by approximately 38 %, CO emissions by 18 %, NOx emissions by 12 %, and fuel consumption by 11 %. The main contribution of this research is demonstrating that low-cost microcontroller-based systems can effectively support Big Data-driven intelligent control when neural network architectures are carefully designed and optimized.

Key words: Artificial Neural Networks, Big Data, Combustion Optimization, ESP32, Microcontrollers, MCDM, LSTM, GRU, Intelligent Control Systems

1. Introduction

The rapid growth of global energy demand, combined with increasing environmental concerns and stricter regulatory requirements, has created a strong need for more efficient, intelligent, and sustainable control systems in combustion-based energy production. Industrial combustion systems, widely used in heating and power generation, are among the major contributors to greenhouse gas emissions and air pollution, particularly through the release of CO and NOx gases [1–3]. Therefore, improving their operational efficiency while simultaneously reducing emissions has become a critical research and engineering challenge [4]. Traditional control approaches, such as PID-based systems, are often insufficient in addressing these challenges due to the inherently nonlinear, time-varying, and highly dynamic nature of combustion processes. In addition, variability in fuel quality, environmental conditions, and system load introduces further complexity, making it difficult for conventional control strategies to maintain optimal operating conditions [5, 6]. As highlighted in the underlying dissertation research, these limitations lead to reduced system efficiency, increased fuel consumption, and elevated levels of harmful emissions. In recent years, significant advancements in Artificial Intelligence (AI) and Big Data technologies have opened new perspectives for overcoming these challenges. Machine learning models, particularly Artificial Neural Networks (ANN), have demonstrated strong capabilities in modeling complex nonlinear systems and extracting patterns from large-scale time-series data [7]. When integrated with real-time monitoring systems, these models enable predictive and adaptive control strategies, allowing the system to anticipate changes and respond dynamically to varying operating conditions [7, 8]. Furthermore, the emergence of low-cost, high-performance microcontroller platforms, such as ESP32, has enabled the deployment of intelligent control systems at the edge level. This paradigm shift towards edge computing allows data processing and decision-making to be performed locally, reducing latency, improving system responsiveness, and minimizing dependence on centralized computing resources. As a result, it becomes feasible to implement advanced AI-driven optimization even in resource-constrained environments.

This research builds upon these technological advancements by proposing a hybrid ANN–MCDM framework for real-time combustion optimization [6, 8]. The key idea is to combine predictive capabilities of neural networks with multi-criteria decision-making methods in order to achieve balanced optimization across multiple objectives, including energy efficiency, emission reduction, and system stability. Additionally, a particular focus of this work is to demonstrate that low-cost microcontroller-based systems can effectively support Big Data-driven intelligent control, provided that the system architecture and neural network design are carefully developed and optimized.

2. Research Problem

The combustion process in industrial boiler systems represents a highly complex nonlinear dynamic system influenced by a wide range of interacting variables and external conditions [9]. These systems operate under continuously changing regimes, where parameters such as fuel composition, air supply, temperature distribution, and environmental conditions significantly affect the overall performance and stability of the process. The inherent nonlinearity of combustion reactions, coupled with time-dependent behavior and delayed system responses, makes accurate modeling and control particularly challenging. In a general form, the combustion system can be described as a nonlinear dynamic system:

$$y(t) = f(x(t), u(t), t)$$

where $y(t)$ represents the system outputs (e. g., temperature, emissions), $x(t)$ denotes the internal state variables, and $u(t)$ corresponds to control inputs such as fuel supply and air flow. The function $f(\cdot)$ is nonlinear and often unknown or only partially known, which significantly complicates the application of classical control methods [10]. One of the primary challenges lies in the variability of fuel quality, especially in systems that utilize biomass or mixed fuel sources, where calorific value, moisture content, and chemical composition can vary significantly over time. This variability directly impacts combustion efficiency and emission levels, making it difficult to maintain optimal operating conditions using static or predefined control strategies. In addition, the combustion process itself exhibits strong nonlinear characteristics, meaning that small changes in input parameters can lead to disproportionately large and often unpredictable changes in system behavior [11].

Another important limitation arises from the use of classical control systems, such as PID controllers, which are typically designed for linear or near-linear systems with relatively stable operating conditions. In mathematical terms, such controllers assume a simplified linear approximation of the system:

$$y(t) = Ax(t) + By(t)$$

which is insufficient to capture the complex nonlinear dependencies present in real combustion systems [10]. As a result, these controllers often fail to maintain optimal performance, particularly under transient conditions or in the presence of disturbances. Furthermore, modern industrial requirements demand real-time adaptive optimization, where control systems must continuously adjust operating parameters in response to changing inputs and system states. This requires not only fast data acquisition and processing, but also predictive capabilities that can estimate future system behavior:

$$\hat{y}(t+1) = f_{ANN}(y(t), y(t-1), \ldots, u(t))$$

where f_{ANN} represents a trained neural network model capable of learning complex temporal dependencies [12]. According to experimental findings from the underlying dissertation research, conventional control approaches are unable to adequately respond to rapid changes in system conditions, leading to reduced efficiency, increased fuel consumption, and higher levels of harmful emissions such as CO and NOx [6, 8]. These limitations highlight the need for advanced intelligent control strategies capable of handling nonlinear dynamics, large-scale data, and multi-objective optimization in real time. Addressing this research problem requires the integration of modern AI-based methods with robust data acquisition and decision-making frameworks, which forms the central motivation for the hybrid ANN–MCDM approach proposed in this paper.

3. Methodology

The methodology applied in this research is based on an integrated experimental and theoretical approach that combines real-time data acquisition, machine learning modeling, and intelligent control system design within a unified framework. The proposed system is developed as a closed-loop architecture that connects Internet of Things (IoT) technologies, Big Data processing, Artificial Neural Networks (ANN), and Multi-Criteria Decision-Making (MCDM) methods in order to achieve efficient and adaptive optimization of combustion processes. Experimental validation is conducted on industrial boiler systems (ATI TERMING OZON series), where a custom-designed sensor network continuously collects real-time data, including temperature, humidity, gas emissions such as CO and NOx, and airflow parameters. These data are acquired through a microcontroller-based platform, specifically utilizing Arduino and ESP32 technologies, which enable edge-level signal processing, filtering, and reliable transmission to a centralized database. The collected dataset, characterized by high volume and temporal variability, is structured and prepared for further analysis through preprocessing procedures that include noise reduction, normalization, and feature extraction, ensuring data consistency and improving model performance.

Fig. 1. End-to-End Architecture of a Hybrid ANN-Control System for Real-Time Combustion Optimization

The core of the methodology is based on the application of recurrent neural network architectures, including LSTM, GRU, and standard RNN models, selected due to their capability to capture nonlinear dynamics and temporal dependencies inherent in combustion systems. These models are trained using supervised learning techniques within a Python-based environment, where performance is evaluated through standard metrics such as Mean Squared Error and related statistical indicators. The predictive outputs generated by the ANN models are subsequently integrated with a Multi-Criteria Decision-Making module, which evaluates multiple conflicting objectives, including energy efficiency, emission reduction, and operational stability, in order to determine the optimal operating regime. This hybrid ANN–MCDM approach enables more balanced and realistic decision-making compared to traditional single-objective optimization methods. The final stage of the methodology involves the implementation of a real-time control loop, where system parameters such as air supply, fan operation, and fuel dosing are continuously adjusted based on predictive and decision-making outputs, allowing the system to dynamically respond to changing operating conditions. The effectiveness of the proposed methodology is validated through experimental testing under real operating conditions, demonstrating improvements in prediction accuracy, emission reduction, and overall system efficiency. A key methodological contribution of this research lies in demonstrating that advanced AI-based optimization techniques can be successfully implemented on low-cost microcontroller platforms, provided that the neural network architecture is carefully designed and properly integrated within the overall system structure.

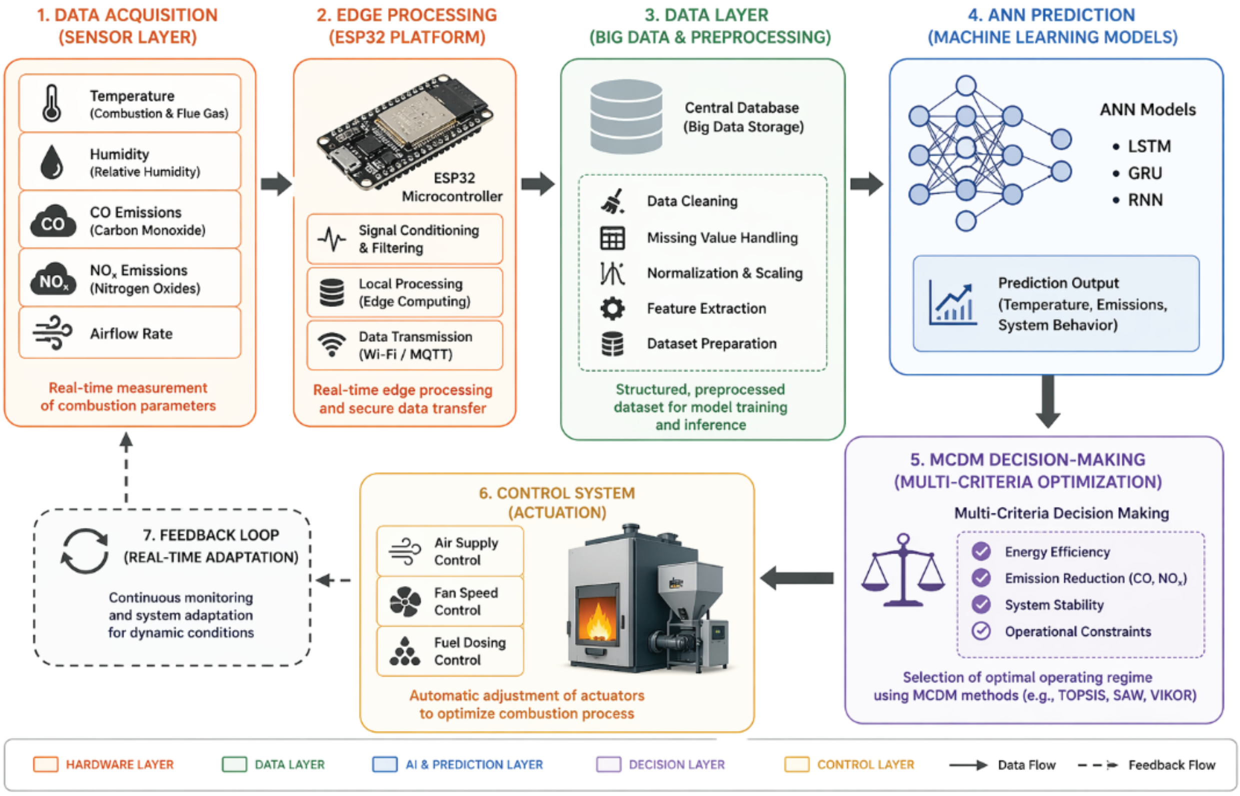

Fig. 2. Hybrid ANN–MCDM framework for real-time combustion optimization based on IoT data acquisition and intelligent control

4. Results and Validation

The proposed hybrid ANN–MCDM framework was evaluated through experimental testing on real industrial boiler systems (ATI TERMING OZON series) over an extended operational period from 2022 to 2025, with ongoing testing. The validation process was conducted under varying operating conditions, including fluctuations in fuel quality, air supply, and system load, in order to assess the robustness and adaptability of the proposed approach. The performance of the system was evaluated using both predictive accuracy metrics and operational efficiency indicators. The results demonstrate that the application of recurrent neural network models, particularly LSTM-based architectures, enables highly accurate prediction of combustion parameters. The prediction performance was quantified using the Mean Squared Error (MSE), which was reduced by approximately 38 % compared to baseline models, indicating a significant improvement in modeling accuracy.

In addition to prediction performance, the implementation of the hybrid ANN–MCDM framework resulted in measurable improvements in system operation. Experimental results show a reduction in carbon monoxide (CO) emissions by approximately 18 % and nitrogen oxides (NOx) emissions by around 12 %, demonstrating the environmental benefits of the proposed approach. Furthermore, fuel consumption was reduced by approximately 11 %, confirming the effectiveness of the optimization process in improving energy efficiency.

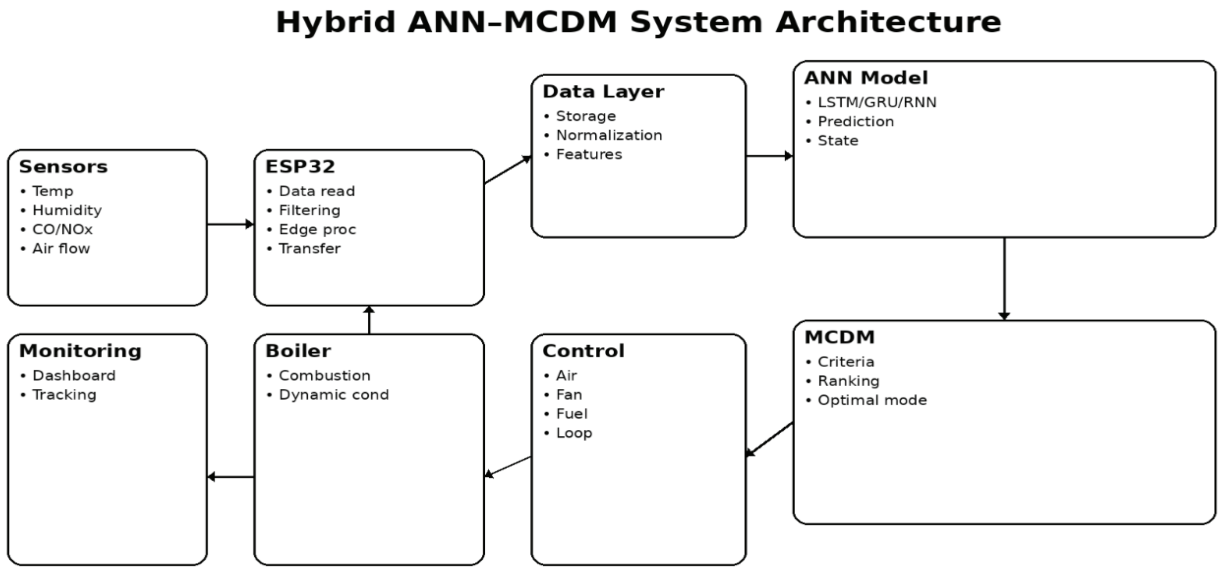

Fig. 3. Hybrid ANN–MCDM system architecture

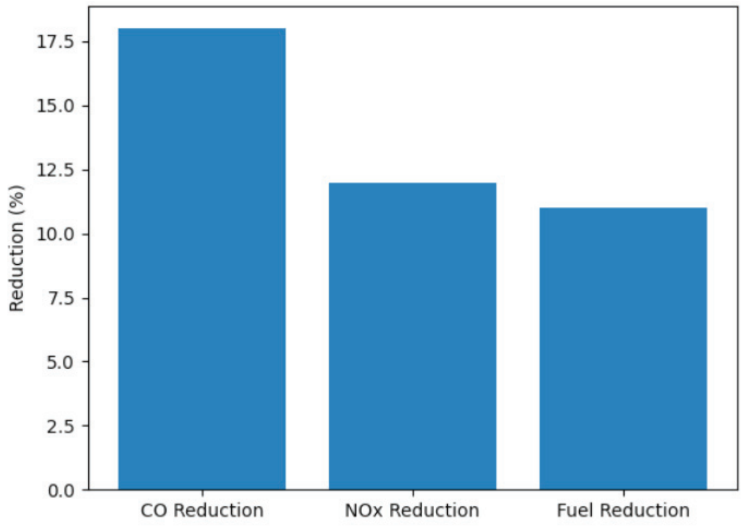

Fig. 4. Performance Improvements of the Hybrid ANN–MCDM Framework

A comparison between predicted and measured values reveals a high degree of correlation, indicating that the ANN models successfully capture the nonlinear dynamics of the combustion process. This alignment between real and predicted data validates the reliability of the model and its suitability for real-time application. Moreover, the integration of MCDM methods enabled the system to balance multiple objectives simultaneously, ensuring that improvements in efficiency did not come at the expense of increased emissions or reduced system stability. This multi-objective optimization capability represents a key advantage over traditional control approaches.

The results also confirm that the system is capable of real-time adaptive behavior, continuously adjusting control parameters in response to changing operating conditions. This demonstrates the practical applicability of the proposed framework in industrial environments.

5. Discussion

The obtained results clearly demonstrate that the proposed hybrid ANN–MCDM framework provides significant improvements in both predictive accuracy and operational performance of the combustion system. The reduction in prediction error confirms that the applied neural network models are capable of effectively capturing the nonlinear and time-dependent behavior of the combustion process, which is consistent with the theoretical assumptions presented in the research problem. In particular, the superior performance of recurrent architectures highlights the importance of incorporating temporal dependencies when modeling dynamic industrial systems. Beyond prediction accuracy, the observed reductions in CO and NOx emissions, as well as fuel consumption, indicate that the proposed approach successfully translates improved modeling into practical system optimization. This is especially important in real-world industrial environments, where even modest percentage improvements can result in substantial economic savings and environmental benefits over extended periods of operation. The results confirm that the integration of predictive modeling with control strategies enables a more efficient and sustainable operation compared to conventional approaches. A key aspect of the proposed framework is the integration of Multi-Criteria Decision-Making methods, which allows the system to balance multiple, often conflicting objectives. Unlike traditional control systems that typically focus on a single performance metric, the hybrid ANN–MCDM approach considers efficiency, emissions, and system stability simultaneously. This multi-objective perspective is particularly relevant in combustion systems, where optimizing one parameter can negatively impact another. The inclusion of MCDM ensures that the selected operating regime represents a globally optimal compromise rather than a locally optimized solution.

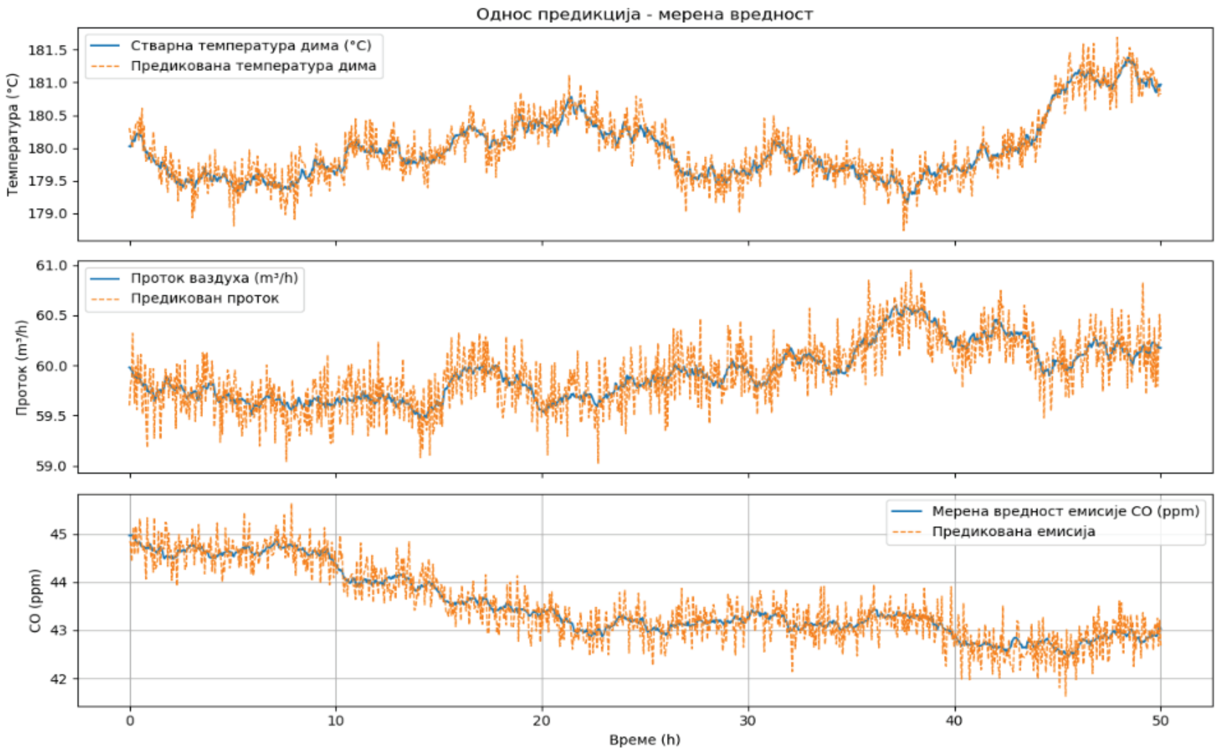

Fig. 5. The observed prediction accuracy directly contributes to the reduction of control error and improvement of system efficiency

Overall, the discussion confirms that the proposed hybrid ANN–MCDM framework represents a robust and practical solution for real-time combustion optimization, combining theoretical rigor with real-world applicability.

7. Conclusion

This paper presented a hybrid ANN–MCDM framework for real-time optimization of combustion processes in industrial boiler systems, with a particular focus on implementation using low-cost microcontroller platforms such as ESP32. The proposed approach integrates IoT-based data acquisition, Big Data processing, artificial neural network modeling, and multi-criteria decision-making into a unified closed-loop control system. The obtained results demonstrate that the proposed framework significantly improves both predictive accuracy and operational performance. The application of ANN models, particularly recurrent architectures, enabled accurate modeling of nonlinear and time-dependent combustion dynamics, while the integration of MCDM methods ensured balanced optimization across multiple objectives, including efficiency, emission reduction, and system stability. Experimental validation confirmed measurable improvements, including reductions in CO and NOx emissions, as well as fuel consumption, highlighting both environmental and economic benefits.

An important contribution of this research lies in demonstrating that advanced AI-based optimization can be effectively implemented on low-cost hardware platforms. This finding opens new opportunities for scalable and economically viable deployment of intelligent control systems in industrial applications, especially in resource-constrained environments.

However, despite the promising results, certain limitations must be acknowledged. Although the developed ANN models achieved a relatively high coefficient of determination ($R^2 \approx 0.93$), indicating strong predictive capability, there remains room for further improvement in model accuracy and generalization. The observed discrepancies between predicted and measured values suggest that additional refinement of the model architecture, expansion of the dataset, and inclusion of additional input variables could further enhance performance. Future research should therefore focus on improving model robustness through larger and more diverse datasets, exploring more advanced deep learning architectures, and integrating adaptive or reinforcement learning approaches. Additionally, further optimization of the MCDM component, including dynamic weighting of criteria, may contribute to even more effective decision-making. In conclusion, while the proposed system demonstrates strong potential for real-time combustion optimization, it also provides a foundation for further development toward more precise, adaptive, and intelligent energy systems.

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