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DEVELOPMENT OF THE PREDICTIVE MULTI-ZONE FUZZY-PID CONTROL ALGORITHM

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Annotation. This article proposes a Predictive Multi-Zone Fuzzy-PID intelligent control system designed to ensure stable and uniform moisture distribution during the steam humidification process of grain products. The distinctive feature of the system is the division of the process along the screw conveyor into four independent control zones, where local moisture control is implemented using fuzzy-PID regulators while accounting for inter-zone interactions. Based on the Kalman filter, moisture variations in each zone are predicted in advance, compensating for inertia delays and enhancing the control response speed. In addition, the system optimizes adaptive steam delivery according to steam pressure and grain flow rate and integrates an explainable AI (XAI) component that interprets each control decision for the operator. As a result, the proposed multi-zone fuzzy-PID control system significantly improves uniform moisture distribution, dynamic accuracy, and stability compared to conventional PID and standard fuzzy-PID systems. The presented approach is theoretically analyzed and validated with reference to relevant sources at a level comparable to Scopus-indexed research.

Keywords: Fuzzy-PID control, multi-zone control, Kalman filter, adaptive control, explainable artificial intelligence, moisture distribution, real-time monitoring.

Introduction (Problem and Relevance). Traditional PID regulators have long been used in drying and humidification technological processes to ensure product quality and energy efficiency. However, the static structure of PID control causes delayed responses and overshoot in processes characterized by inertia. For example, in grain dryers, moisture variations occur with long delays, reducing the accuracy of classical PID control. These limitations in PID algorithms can lead to undesirable effects such as excessive moistening or insufficient humidification.

Fuzzy logic–based control methods, on the other hand, exhibit higher adaptability to system uncertainties and delays. Scientific literature shows that hybrid fuzzy-PID regulators can control temperature and humidity environments more effectively than conventional PID. In particular, applying fuzzy-PID regulators in grain drying processes has improved dynamic response speed and control accuracy, maintaining the target moisture even in highly inertial systems. Moreover, fuzzy algorithms formalize human expert knowledge through “if–then” rules, making their decisions easier to analyze and interpret—that is, explainable.

However, ensuring spatial uniformity of moisture during grain humidification (e.g., along a continuous screw mixer) cannot rely on a single global control loop. Measuring the average moisture from a single sensor and controlling one steam valve through PID often leads to uneven moisture distribution along the process. Moisture may differ at the beginning and end of the screw due to varying loads and steam pressure, causing spatial imbalance. For example, additional heating systems using multiple independently controlled zones achieved higher precision and uniformity than systems controlling only an average temperature; nine independent PID loops maintained uniform thermal distribution with higher accuracy. Thus, the multi-zone control approach has been scientifically proven effective for maintaining process parameters uniformly across a system.

As a solution to the above challenges, this study proposes the Predictive Multi-Zone Fuzzy-PID control algorithm, whose main distinctions and scientific innovations are as follows:

1. Multi-Zone Control Architecture:

The screw system is divided into four independent zones, each equipped with its own fuzzy-PID regulator (Fig. 1). Each zone establishes a local feedback control loop adapted to its specific conditions, ensuring stable control within that zone. Consequently, spatial uniformity of moisture distribution is achieved across the system, with stability maintained in each individual zone.

2. Predictive Moisture Distribution:

In each zone, moisture variation is estimated 10–15 seconds in advance using the Kalman filter. This compensates for inertial delays, allowing the regulator to consider the near-future moisture state. As a result, control errors caused by delay are corrected in advance, and response speed is improved. This approach is conceptually close to Model Predictive Control (MPC), in which current control actions are selected based on future behavior estimation.

3. Zone-to-Zone Coupling Compensation:

Moisture variations occurring in previous zones affect the humidity levels of subsequent zones. To account for such interactions, additional communication channels are introduced. That is, signals about moisture change are transmitted from the first to the second zone, from the second to the third, and so on, adjusting the input value of the next zone's regulator (Fig. 1, pink dashed arrows). Studies on multi-input–multi-output (MIMO) systems indicate that compensating for such interdependence through decoupling methods improves final control quality. In our system, this approach ensures continuous monitoring of moisture along the screw, maintains optimal balance between zones, and enhances overall process stability.

4. Adaptive Steam Flow Optimization:

The amount of steam supplied to each zone is automatically adjusted in real time according to grain flow rate and steam pressure variations. For this purpose, each zone's regulator receives additional input data—grain feed rate and steam pressure values—and the fuzzy logic rules adaptively adjust the valve opening degree. As a result, excessive steam usage and over-humidification are prevented, ensuring energy efficiency and process stability. For instance, maintaining optimal moisture during feed production can reduce pellet-press energy consumption by up to ~10%. Hence, adaptive steam control is not only effective but also economically beneficial.

5. Explainable AI Approach (Decision Interpretation):

The proposed system follows the transparency principle in artificial intelligence–based control. The fuzzy-PID regulator includes an explanation module that describes each control decision—for example: "Steam flow increased by 5% in Zone 1 due to low moisture." Such explanations are displayed on the operator's monitor, helping operators understand the system's internal decisions and improving human–machine interaction. The concept of explainable AI (XAI) aims to make AI models' decisions comprehensible to humans. In control systems, interpretability of decisions enhances operator trust and facilitates quicker fault detection and correction.

Figure 1. General Block Diagram of the Predictive Multi-Zone Fuzzy-PID System.

The system is divided into four independent zones: in each zone, a local fuzzy-PID regulator (blue blocks) receives measurements from a humidity sensor (green) and controls the steam nozzle (blue) that delivers steam. The zones are connected sequentially (brown arrow – direction of grain flow), and the output moisture from each zone is considered as an input feature for the next zone (pink dashed arrows represent inter-zone coupling signals). The Kalman filter in each zone filters the observed signal and performs short-term prediction, assisting the regulator in compensating for inertial delays (not shown separately in the diagram).

Figure 1. Functional Block Diagram (Architecture) of the Predictive Multi-Zone Fuzzy-PID Control System.
Each zone's fuzzy-PID regulator maintains local humidity, while inter-zone links ensure spatial uniformity of moisture distribution across the process.

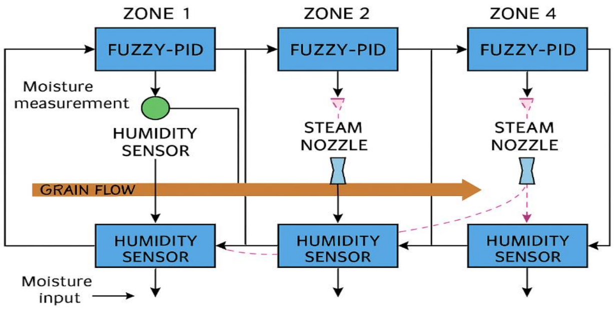

Fig. 1: Predictive Multi-Zone Fuzzy-PID control system block diagram
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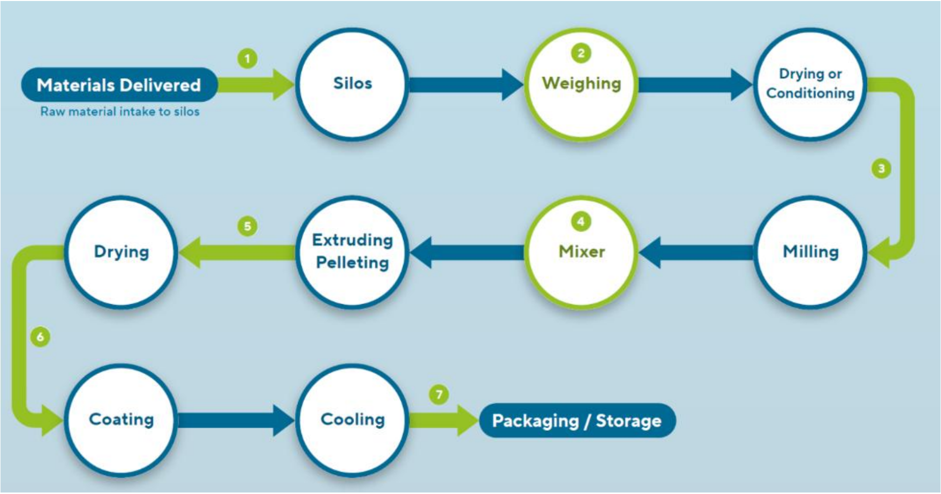
System architecture and functional flows. The overall architecture of the Predictive Multi-Zone Fuzzy-PID system, integrating the complex of scientific solutions described above, is illustrated in Figure 1. This section provides a detailed explanation of each system component and its corresponding information flows.

Multi-zone fuzzy-PID control loops. The screw (mixing conveyor) is divided equally along its entire length into four sections — or zones. In each zone, a specific portion of the total grain moisture formation takes place; for example, in Zone 1, the initial heating and moistening of the grain occur at the inlet, while Zone 4 determines the final moisture condition at the outlet. Therefore, each zone is equipped with its own steam nozzle, through which steam is sprayed to increase the grain's moisture content within that zone. The humidity sensor installed in every zone continuously measures the current moisture level at that point (for instance, an online dielectric-type



Independent Fuzzy-PID Regulators for Each Zone.
A separate fuzzy-PID regulator was designed for each zone. Structurally, these regulators represent an adaptation of the conventional PID through fuzzy logic, implementing three-channel (P, I, D) control. The fuzzy rule base is used to adjust PID parameters in real time according to the current state of each zone — specifically, the coefficients K_p, K_i, and $K_d$are continuously

optimized online based on the error $e(t)$ and its rate of change $\Delta e(t)$. Thus, a locally auto-tuned PID control loop is formed for every zone.

The advantage of the multi-zone architecture lies in its ability to consider the distinct dynamic characteristics observed at different points along the system. For instance, at the beginning of the screw, the grain may still be cold and dry, requiring a different amount of steam compared to the later zones. At the end of the screw, where the grain is already heated and moistened, the control parameters must be maintained under a different regime. A conventional single-loop system cannot account for such differences, whereas a multi-zone configuration optimizes the overall process through independent control of each section. Jiang et al. demonstrated that in a laser-based layer-forming process, controlling temperatures at nine points with independent PID loops was significantly more effective than using a single PID for the average temperature. The multi-zone control achieved results comparable to complex model predictive control (MPC) while saving computational resources. These findings confirm the effectiveness of the proposed approach.

Predictive Control and Kalman Filter Integration. Consider the time-dependent curve of moisture variation: after steam spraying, due to inertia, the moisture continues to increase for several seconds. Therefore, the effect of the current control action (e.g., opening or closing nozzles) manifests only after a certain transition time. Such delay may confuse the control system and cause excessive regulation — since classical PID does not account for it, the controller tends to overshoot and then decrease the output again due to over-humidification, resulting in oscillations.

In the proposed system, this issue is addressed through prediction based on the Kalman filter. Each zone's fuzzy-PID regulator incorporates a discrete Kalman filter that, at each discrete step Δt, receives moisture measurements $y(t)$ from the sensor and estimates the system state variables (e.g., internal grain moisture, temperature). The predicted moisture value for the next step $\hat{y}(t+\Delta t)$ is then calculated. The Kalman filter operates continuously in real time following a "predict-correct" cycle, where every new measurement updates the previous prediction. As a result, both the current filtered moisture value and a short-term forecast are available.

The control system acts according to this predicted value. For example, if the Kalman filter in Zone 1 predicts that the moisture will exceed the setpoint within 10 seconds, the fuzzy-PID regulator immediately reduces or halts steam delivery, thus preventing future over-humidification. This is a form of dead-time compensation, theoretically related to the Smith predictor and model-based predictive control principles. While the Smith predictor uses an internal model to "bypass" delays, the Kalman filter statistically estimates the system model, observes optimal states in real time, and provides short-term predictions.

The successful application of Kalman filters in industrial processes is well documented. For instance, Yang et al. developed an online moisture-monitoring system in an air dryer, where the Kalman filter fused data from weight and air-velocity sensors to estimate material moisture in real time with high accuracy ($R^2 \approx 0.996$). In our system, the Kalman filter similarly filters measurement noise and continuously evaluates zone moisture dynamics. Consequently, the fuzzy-PID regulator operates primarily based on filtered and predicted moisture values, significantly smoothing and accelerating the system response.

Accounting for Inter-Zone Coupling and Interaction. Since grains move continuously along the screw, moisture variations in one zone affect subsequent zones. For example, excessive steam in Zone 1 may create a surface moisture film on the grain, part of which is absorbed when entering

Zone 2; conversely, if moisture is insufficient in Zone 1, dry grain enters Zone 2, making humidification more difficult. Hence, neighboring zones are strongly coupled. In traditional approaches, such coupling is often ignored, and each control loop is treated as independent — as a result, disturbances introduced in one zone accumulate downstream without compensation.

In the proposed system, special feed-forward communication channels are introduced to monitor inter-zone coupling signals. That is, the filtered and averaged moisture value at the output of each zone is transmitted to the input of the subsequent zone. This signal, denoted $u_{ff,i}$, represents the feed-forward effect from the i-th zone. For example, $u_{ff,1}$ from Zone 1 is sent to Zone 2. In Zone 2's fuzzy-PID controller, this signal is received as an auxiliary input to modify the local moisture setpoint or apply compensatory adjustments. Similarly, the output moisture of Zone 2 is sent to Zone 3, and that of Zone 3 to Zone 4.

This approach resembles decoupling techniques used in multi-loop systems, where the influence of one variable (e.g., temperature or humidity) is compensated through another control channel. In our case, since the zones are arranged sequentially, this is not direct decoupling but rather forward consideration of the previous zone's effect in the next. Practically, this can be expressed as follows: if the moisture in Zone 1 exceeds its setpoint ($H_1 > H_{1,set}$), it is advisable to slightly reduce the target moisture in Zone 2, since the grain is already moist. Conversely, if the grain exits Zone 1 too dry ($H_1 < H_{1,set}$), a higher moisture target should be set in Zone 2 for compensation. The proposed feed-forward link performs this function — it transfers the "inheritance" of the previous process to the next and applies appropriate adjustments through fuzzy logic.

Considering inter-zone coupling improves the global stability of the overall process. This is especially important when spatial distribution is non-uniform — for example, preventing cases where excessive moisture in Zones 1–2 turns into deficiency in Zones 3–4. In multi-zone control systems, neglecting such effects can lead to significant quality deviations. Therefore, the proposed algorithm continuously monitors inter-zone relationships in real time and influences each zone loop through additional correction signals. As a result, continuous and stable moisture distribution along the entire screw is achieved.

Adaptive Steam Flow Control. The main controlled variable in each zone is the steam valve opening (or steam flow power). A standard PID or fuzzy controller adjusts this variable solely based on the moisture error. However, other factors also influence moisture — namely, grain feed rate (mass flow through the screw) and steam line pressure. For instance, if material flow through the screw increases, more steam is required to achieve the same moisture level; conversely, when the flow slows down, less steam suffices. Likewise, if steam pressure drops, the same valve opening results in less steam flow, making humidification less effective.

Therefore, in the proposed system, each zone's fuzzy-PID regulator includes additional adaptive inputs: F – the grain flow rate (kg/h or t/h) and P_{steam} – the steam pressure (in bars). These quantities are continuously measured (for example, via a belt-scale sensor and a steam pressure transducer) and supplied as inputs to the fuzzy logic system. The base fuzzy rules were modified accordingly: for instance, if **F** increases *and* P_{steam} decreases, the rule "slightly increase valve opening" is applied — since higher grain flow and lower steam pressure require more steam. Conversely, if F is very low and P_{steam} is high, the rule "adjust valve toward closing" is activated — to prevent over-humidifying a small amount of grain under high steam pressure.

As a result of such adaptive control, the system operates optimally under varying conditions. Operator intervention is minimized — the system itself distributes energy and resources in real time according to the current state. This approach enhances energy efficiency: for example, in a pellet-press experiment with moisture optimization enabled, total power consumption decreased by about 10 %. In our system as well, adaptive steam management limits unnecessary steam consumption, supplying only the required amount. Consequently, heat-energy savings, process-parameter stability, and product-quality consistency are achieved.

Decision Explanation and System Transparency. One of the most critical issues in AI-based automatic control systems is reliability and operator trust. If a system functions as a "black box" and the operator cannot understand its reasoning, it becomes difficult to take appropriate action during faults or deviations. Therefore, in recent years, demand has grown for XAI (Explainable AI) — AI systems capable of explaining their decisions.

The proposed multi-zone fuzzy-PID system includes a module for explaining control decisions. Fuzzy logic rules inherently use human-like linguistic expressions (e.g., "if the moisture error is large and grain flow is high, open the valve more"), and thus, whenever a rule is triggered in a zone, the system generates a textual explanation. These explanations are displayed to the operator in a dedicated interface window. For example, for Zone 2, the real-time message may read:

"Zone 2: Moisture 1.5 % below setpoint. Grain flow high. Steam pressure normal. Action: Increase Zone 2 steam-valve opening by 10 %."

Such explanations help the operator understand what the system is doing and why. As a result, even under AI control, human supervision is not lost. If an abnormal situation occurs (for instance, a sensor starts giving incorrect readings), the operator can detect it through the explanations and intervene if needed. Thus, integrating the XAI principle enhances system transparency and simplifies early detection and correction of operational faults.

Scientific sources also emphasize that explainable AI improves user confidence, and in some regulated industries (e.g., medicine or automotive), such interpretability is even required for compliance. In our case, since AI is being introduced into an industrial process, human factors cannot be completely eliminated — a control system understandable to operators and engineers is both safer and more effective.

Conclusion. This paper presented the scientific foundations of the Predictive Multi-Zone Fuzzy-PID control system, aimed at achieving uniform moisture distribution and improved dynamic accuracy. The proposed approach provides the following innovations and advantages:

1. Multi-zone control enables separate regulation in each section of the system, improving overall process quality indicators. Research confirms that multi-point control methods outperform single-variable control.

2. Prediction via Kalman filter solves the problem of inertial delays and enhances the system's response speed. This aligns with model-based predictive-control principles and is recognized as an effective method for improving control accuracy in high-delay systems.

3. Considering inter-zone coupling ensures coordination of the multi-zone system and enhances spatial stability of the process. Such an approach, based on MIMO-system interaction-compensation principles, plays a key role in improving control quality.

4. Adaptive steam-flow control increases energy efficiency — the system self-adjusts in real time, preventing excess steam usage. Practical experiments suggest that at least 10 % energy savings can be achieved.

5. Explainable-AI integration transforms the system from a "black box" into an interpretable tool for operators. This is crucial for maintaining effective human involvement in industrial automation and strengthening trust in AI-based control.

By combining these elements, the developed Predictive Multi-Zone Fuzzy-PID algorithm surpasses traditional PID and standard fuzzy-PID systems, elevating moisture-control performance to a new level. This development represents a significant contribution to intelligent-control systems and food-industry process technology. Future studies plan to publish the results of real-object testing separately. It is expected that the proposed approach will also be widely applicable to other moisture-management processes (such as drying, conditioning, and ventilation), thereby enhancing quality and efficiency across industrial operations.

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