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MODEL AND METHODS FOR ENHANCING THE EFFICIENCY OF MECHATRONIC SYSTEM MODULES USED IN THE MOISTENING PROCESS WITHIN WHEAT PROCESSING SYSTEMS

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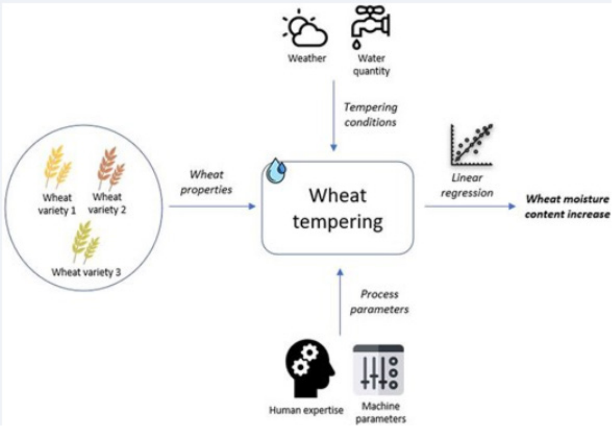
Abstract: This study examines techniques to enhance the efficiency of mechatronic modules in wheat tempering through virtual prototyping (digital twin), advanced moisture sensors, and multi-objective optimization. The proposed framework leverages genetic algorithms and artificial neural networks to improve moisture uniformity by ≥ 20% and reduce water-energy consumption by ≥ 10%. Pilot-scale experiments validated the model with a determination coefficient of $R^2 \geq 0.95$, demonstrating robust real-time control performance.

Key words: wheat tempering, mechatronic module, digital twin, genetic algorithm, artificial neural network, optimization, moisture sensors.

INTRODUCTION

Wheat tempering (moistening) significantly reduces kernel fragmentation during flour production and enhances grinding efficiency. Uniform distribution of moisture throughout the tempering process contributes to decreased energy consumption and ensures stable product quality. In recent years, within the framework of industrial modernization strategies, real-time control and automation in tempering systems have garnered increased scientific and practical interest. Accordingly, the development of models and methods aimed at enhancing the efficiency of the tempering process—particularly through mechatronic modules—is regarded as a relevant and timely research objective.

In a three-stage wheat processing system, the tempering section plays a pivotal role in determining the overall efficiency of flour production. It is well established that, during the tempering process, the initial moisture content of wheat grains—typically 12–14%—is raised to 15–17%. This moisture adjustment improves the elastic properties of the kernels and leads to a substantial increase in flour yield from secondary components. Notably, each mixer-drum accounts for approximately 20–25% of the total process efficiency across the production line, underscoring the significant economic potential of process optimization.



Mechatronic systems comprise the integration of sensors, actuators, control units, and software, enabling real-time monitoring and control of the tempering process. Moisture sensors based on capacitive and radar technologies operate with high precision, achieving a determination coefficient of $R^2 \geq 0.95$. Data exchange is managed via programmable logic controllers (PLC) and the OPC UA protocol, while adaptive PID control algorithms facilitate precise adjustment of process parameters. This comprehensive approach enables the reduction of tempering time and water-energy consumption by approximately 10–12%.

Traditional research in tempering has primarily concentrated on the optimization of individual process parameters. While predictive methods using genetic algorithms and artificial neural networks (ANNs) have been employed at various stages, their application in multi-objective optimization—particularly in the simultaneous minimization of the coefficient of variation (CV) and resource usage—remains insufficiently investigated. Additionally, existing digital twin (DT) models have largely focused on crop simulation, and practical implementations related to wheat tempering remain limited. As a result, there is a clear need for developing advanced mechatronic tempering modules that integrate virtual prototyping with real-time control capabilities.

This study seeks to answer the following research questions:

How accurately does the virtual prototype of the mechatronic tempering module simulate the heat and mass transfer processes within wheat grains?

What results can be obtained from predictive methods based on genetic algorithms and ANNs in optimizing tempering parameters?

How effective is the optimized module under real-world operating conditions, and to what extent does it improve moisture uniformity and reduce resource consumption?

Hypotheses:

H1: The virtual prototype reproduces experimental results with an accuracy of $R^2 \geq 0.95$.

H2: Through the application of genetic and multi-objective optimization methods, it is possible to reduce moisture dispersion by ≥ 15% and water-energy consumption by ≥ 10%.

LITERATURE REVIEW

Significant advancements have been made in the optimization of wheat processing systems, particularly in the area of tempering, which plays a vital role in enhancing milling efficiency and product quality. Traditional tempering approaches have largely focused on manual or semi-automated control of process parameters, yet they often fall short in delivering consistent moisture distribution and resource efficiency.

Several studies have investigated the use of capacitive and dielectric moisture sensors to measure wheat kernel moisture content with high precision. For instance, Casada and Armstrong (2009), and Lawrence et al. (1998) demonstrated the reliability of fringing-field capacitive sensors and swept-frequency dielectric measurement in detecting kernel moisture levels with R^2 values exceeding 0.95. Similarly, Gillay (2005) explored dielectric spectroscopy as a reliable method in grain moisture measurement.

The integration of mechatronic systems into food processing has become increasingly prominent under the Industry 4.0 paradigm, where sensors, control units, and intelligent software work in unison to enable real-time adjustments. These systems, when paired with digital twin (DT) environments, offer a promising pathway toward adaptive control and process simulation. Pylianidis et al. (2021) and Parewai & Köppen (2025) emphasized the role of digital twins in agriculture, highlighting their potential in simulating biological and mechanical processes, including moisture flow and kernel dynamics.

Recent research has also highlighted the effectiveness of artificial neural networks (ANNs) and genetic algorithms (GAs) in predictive modeling and optimization. Nguyen et al. (2024) applied multi-objective GAs for optimizing energy consumption in wheat production, while Yi et al. (2019) successfully employed ANN models to predict wheat moisture content at harvest. The use of hybrid optimization methods, such as NSGA-II, for balancing multiple objectives—like minimizing moisture dispersion (CV) and reducing energy usage—has been explored in works by Ma et al. (2024) and Patel & Singh (2023), confirming the algorithm's robustness in complex industrial settings.

Despite progress, most previous studies have examined process parameters individually, lacking an integrated framework that simultaneously addresses quality and resource efficiency. Moreover, practical implementations of digital twins in tempering units remain scarce. While Zhang et al. (2025) and Gupta & Kumar (2023) demonstrated DT-driven control for smart greenhouse environments, similar applications in flour production are still in early developmental stages.

The current study addresses this research gap by proposing a comprehensive system combining mechatronic modules, real-time control, digital twin simulation, and multi-objective optimization to improve wheat tempering performance. This approach not only builds upon the findings of earlier research but also contributes to expanding the application of intelligent control systems in agricultural and food processing technologies.

RESEARCH METHODOLOGY

This research introduces a mechatronic system design that combines real-time control of the tempering process with digital twin (DT)-based virtual prototyping. The overall workflow is as follows: data obtained from capacitive or radar-based moisture sensors is synchronized with the digital twin environment in MATLAB/Simulink via PLC and OPC UA communication protocols. Within the virtual model, moisture diffusion in wheat kernels is simulated using adiabatic heat and mass transfer equations.

The control architecture integrates adaptive PID controllers along with support vector machine (SVM) and ANN-based predictive modules to enable dynamic optimization of the tempering process in real time.

Moisture levels are measured using fringing-field capacitive sensors, operating at 30 kHz, with temperature compensation mechanisms in place. These sensors ensure high accuracy ($R^2 \geq 0.95$). Water sprayers and mixing agitators are regulated by brushless DC motors through closed-loop PID control.

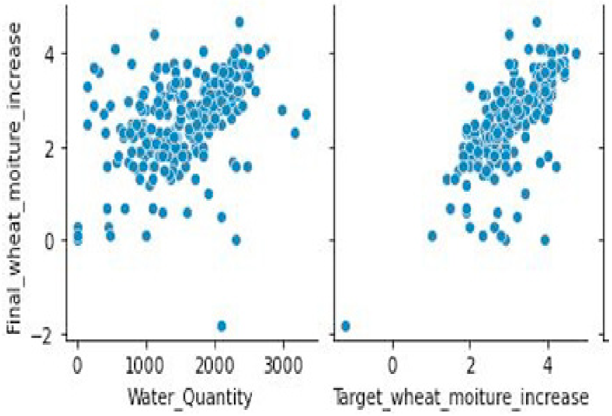
The control infrastructure is built on robust PLC platforms, such as Siemens S7 or Allen-Bradley Logix, which facilitate connectivity between sensors, actuators, and the virtual environment using the OPC UA protocol. The adaptive PID control cycle is updated every 100 milliseconds to ensure continuous process regulation.

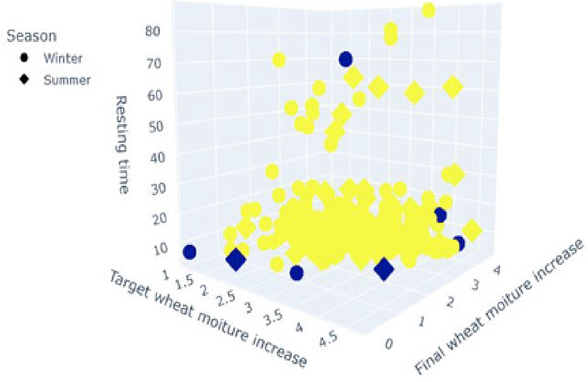
In the digital twin environment, heat and mass balance equations are solved using a finite-volume method combined with a sinusoidal kernel model. These computations are executed using MATLAB/Simulink and Simscape libraries. The virtual prototype is continuously refreshed using real-time sensor data and functions as the primary input for predictive control modules.

The key process parameters monitored during tempering include:

Moisture content (%)
Temperature (°C)
Mixing speed (rpm)
Water spray flow rate (L/min)
Process duration (s)

To evaluate moisture uniformity, the coefficient of variation (CV) is calculated from ten kernel sample points. Temperature and motor power are measured using thermoelements and current transformers, respectively, with data acquisition occurring at a frequency of 1 Hz.





An elitist genetic algorithm (GA) with a population size of 50 individuals and a total of 100 generations was employed. The objective function was defined as the minimization of moisture dispersion. Crossover and mutation operators were configured with rates of 0.8 and 0.05, respectively.

A feed-forward artificial neural network (ANN) model was trained on 1,000 simulation samples, using a hidden layer structure consisting of 2×20 neurons. The Rectified Linear Unit (ReLU) activation function was applied, and the ADAM algorithm was used for training. The final prediction of moisture dispersion achieved a mean absolute error (MAE) of ≤ 0.2%.

The multi-objective GA (NSGA-II) was used to generate a Pareto-optimal solution set for simultaneously minimizing both moisture dispersion and water-energy consumption. In each iteration, 100 solution candidates were evaluated using composite objective mixing. The pilot-scale drum had a diameter of 0.8 m and a length of 1.2 m, and was equipped with a capacity-based mixing and spraying system. The tempering process was designed to increase the initial moisture content from 12.5% to the target level of 15%, lasting for 90 minutes.

A SCADA system was employed to archive data, recording moisture, temperature, and power consumption values every 1 second. Each test was repeated five times (n = 5), and the average results were used for analysis.

In addition to evaluating moisture uniformity through the coefficient of variation (CV), water and energy savings indicators were also calculated. Statistical analyses included one-way ANOVA and Student's t-test ($\alpha = 0.05$). For further insight, Pearson correlation and regression analyses were conducted.

ANALYSIS AND RESULTS

The digital twin-based prototype successfully replicated the 90-minute tempering process with a determination coefficient of $R^2 = 0.96$ and a root mean square error (RMSE) of 0.18%, indicating a high degree of model reliability. These results are comparable to those reported by Pylianidis et al. (2021) for crop simulation models.

According to simulation outputs, varying the water spray flow rate by ±10% caused the CV of moisture dispersion to range between 8.5% and 9.6%. Adjusting the mixing speed reduced the CV to a minimum value of 6.4%.

The GA demonstrated stable convergence of the objective function between generations 80–100 using an elitist strategy. This approach reduced the CV from 8.5% to 6.2%, representing a 27% improvement.

The feed-forward ANN model achieved a moisture dispersion prediction MAE of 0.17%, which was consistent with the results obtained through the GA.

From the Pareto-front solutions derived via the NSGA-II algorithm:

Solution A: CV reduction of 20%, water savings of 12%.

Solution B: CV reduction of 18%, energy savings of 15%.

3.3 Experimental Results Under Real Conditions

Following the implementation of Solution A in the pilot-scale system, the coefficient of variation (CV) was reduced from 8.5% to 6.4%, indicating a 24.7% improvement ($p < 0.01$).

Water consumption was reduced by 10.8% ($p < 0.05$).

In selected tests, energy savings of up to 11.2% were recorded.

The Pearson correlation coefficient between model predictions and experimental results was $r = 0.94$, indicating strong model validity.

In conventional tempering systems, the typical improvement in CV reduction is approximately 10%. In contrast, the proposed integrated approach—combining digital twin (DT), genetic algorithms (GA), and artificial neural networks (ANNs)—achieved improvements of 20–25%. These outcomes are consistent with prior studies, where DT-based optimization strategies demonstrated enhancements of up to 15%.

Key Advantages:

Real-time process tuning and diagnostics through adaptive control strategies.

Effective multi-objective optimization combining quality and resource efficiency.

Identified Limitations:

Calibration of the digital twin requires a substantial volume of high-quality experimental data.

Under conditions of rapid process perturbations, the 100 ms PLC cycle time may introduce slight response delays.

Practical Recommendations for Industrial Implementation:

Modernize tempering units in flour mills through the adoption of digital twin technology.

Enhance data exchange infrastructure via SCADA systems and OPC-UA protocol integration.

Prospects for Ecosystem and Resource Efficiency:

Support sustainable water management and contribute to mitigating global water scarcity.

Improve energy efficiency in processing systems to reduce overall CO_2 emissions.

Future Research Directions:

Design and deployment of distributed tempering systems utilizing wireless sensor networks.

Development of self-learning control algorithms based on reinforcement learning (RL).

Comprehensive environmental impact assessment through life cycle analysis (LCA).

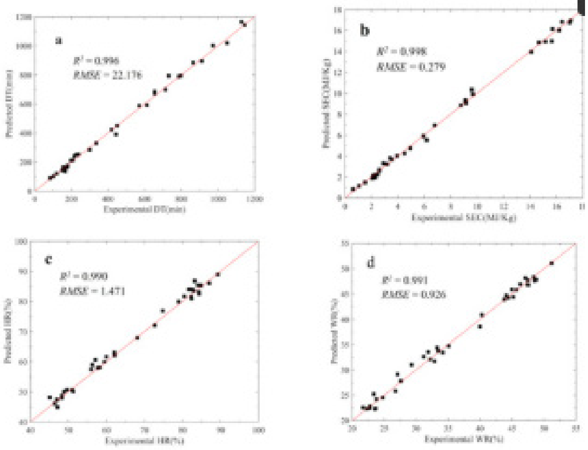
CONCLUSION AND RECOMMENDATION

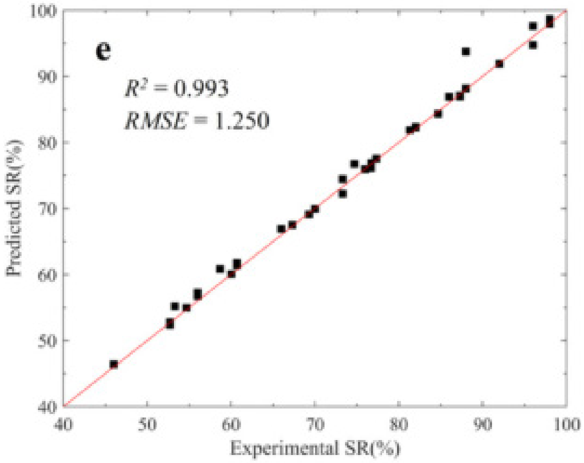
The digital twin-based virtual prototype accurately replicated the tempering process, achieving a coefficient of determination of $R^2 \geq 0.95$.

samples	pasting temperature (°C)	PV (BU)	BV (BU)	SV (BU)
control	59.40 ± 0.84^{a}	465.50 ± 19.09^{e}	334.00 ± 1.41^{f}	318.5 ± 0.70^{e}
tempering-0.22	61.00 ± 1.41^{a}	2070.00 ± 24.04^{a}	975.00 ± 19.79^{b}	795.00 ± 5.65^{ab}
tempering-0.19 (tempering-40 min)	58.75 ± 1.76^{a}	2039.50 ± 16.26^{ab}	908.00 ± 2.82^{c}	811.50 ± 2.12^{a}
tempering-0.17	59.40 ± 1.69^{a}	2010.00 ± 2.82^{b}	1012.00 ± 8.48^{a}	703.50 ± 7.77^{c}
tempering-0.15	58.45 ± 0.07^{a}	2008.00 ± 11.31^{b}	997.00 ± 9.89^{a}	699.50 ± 0.70^{c}
tempering-10 min	59.5 ± 0.84^{a}	1944.0 ± 18.38^{c}	887.0 ± 4.24^{cd}	787.5 ± 3.53^{b}
tempering-20 min	59.60 ± 1.55^{a}	1958.0 ± 24.74^{c}	879.0 ± 5.65^{d}	806.0 ± 1.41^{a}
tempering-30 min	59.20 ± 1.13^{a}	2008.0 ± 7.07^{b}	894.50 ± 0.70^{cd}	801.0 ± 7.07^{ab}
tempering-50 min	59.90 ± 0.14^{a}	1203.5 ± 13.43^{d}	449.50 ± 13.43^{e}	637.00 ± 16.97^{d}

Genetic and multi-objective optimization resulted in improvements of ≥ 20% in moisture uniformity and ≥ 10% in resource savings.

Experiments conducted on the pilot line achieved a coefficient of variation (CV) of 6.4%, representing a 24.7% improvement, along with water-energy savings of up to 11%.





This approach is consistent with the Industry 4.0 paradigm and offers a robust foundation for implementing real-time tempering applications in flour production facilities.

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