Available online at: http://e-jurnal.lppmunsera.org/index.php/INTECH

Jurnal INTECH Teknik Industri Universitas Serang Raya

ISSN (Print) 2407-781X ISSN (Online) 2655-2655

Design and Development of An Optimized Automatic Flour Dosing Machine for SME Bakeries

Elsa Sri Erjuni Rumapea[1*], Hannifah Robbani[1], Ibnu Anugrah[1], Elsa Putri Pertiwi[2], Windy Wijayanti[3]

[1]Department of Industrial Engineering, Institut Teknologi Batam, Jl. Gajah Mada, Batam, Riau Islands, 29425, Indonesia

[2]Department of Engineering Management, Institut Teknologi Batam, Jl. Gajah Mada, Batam, Riau Islands, 29425, Indonesia

[3]Department of Industrial Engineering, Akademi Teknik Deli Serdang, Jl. Medan – Lubuk Pakam, Tj. Morawa, North Sumatra, 20511, Indonesia

ARTICLE INFORMATION

Article history:

Received: April 22, 2026
Revised: June 13, 2026
Accepted: June 18, 2026

Keywords

Automatic Dosing System
Design for Assembly
Load Cell Sensor
Powder Flow
Product Design and Development

ABSTRACT

This study presents the design and development of an optimized automatic flour dosing machine to improve dosing accuracy, operational usability, and repeatability for small and medium-sized bakery enterprises (SMEs). The research integrates product design and development principles with mechanical flow optimization to address the limitations of conventional manual and semi-automated dosing systems. A six-stage Engineering Design Process (EDP) was employed, encompassing user needs identification, quality function deployment (QFD)-based specification development, concept generation and selection using a Pugh matrix, prototype fabrication, and experimental validation. The proposed system integrates an HX711-coupled load cell sensor, an HC-SR04 ultrasonic proximity sensor, an Arduino Uno microcontroller, and an optimized funnel–gate dispensing mechanism to regulate powder flow. Performance was evaluated using a multi-setpoint approach (10 g, 30 g, and 50 g) with 30 independent trials per setpoint. Results demonstrate that the system achieved a mean absolute percentage error (MAPE) of 1.54%, 1.32%, and 1.83% at 10 g, 30 g, and 50 g setpoints, respectively, all below the 2% threshold and well within the 5% design specification. The coefficient of variation (CV) remained below 2.3% across all conditions, confirming stable repeatability. The modular, DfA-compliant architecture enhances manufacturability and maintainability while preserving cost-effectiveness for SME adoption. These findings indicate that dosing performance in SME-scale food production systems is influenced not only by electronic control accuracy but also by the optimization of mechanical flow behavior. The study contributes theoretically by demonstrating the role of mechanical dispensing design as a complementary determinant of dosing precision, while providing SME practitioners with a low-cost and maintainable automation framework suitable for resource-constrained production environments.

***Corresponding Author**

Elsa Sri Erjuni Rumapea
E-mail: lsa@iteba.ac.id

This is an open-access article under the CC–BY-SA license.

© 2026. Some rights reserved

1. INTRODUCTION

The rapid advancement of automation technology has fundamentally reshaped modern manufacturing systems, including the food processing sector. Among the most critical operations in bakery production is the accurate measurement of raw materials, particularly powdered ingredients such as wheat flour, as even minor deviations in ingredient proportions directly affect the texture, taste, and overall product quality (Guiné, 2022). Therefore, maintaining dosing precision is indispensable for small and medium-sized enterprises (SMEs) in the bakery sector to sustain product consistency and competitiveness.

Despite their critical importance, most SME bakery operations continue to rely on manual weighing using conventional scales. These methods are highly operator-dependent and susceptible to inconsistencies, leading to batch-to-batch quality variability. Manual dosing is also time-consuming and physically repetitive, contributing to operator fatigue and reduced throughput (Chandrasiri et al., 2022; Rosdiana et al., 2020; Taufiq et al., 2023). Measurement errors in bulk production cause raw material wastage and elevated production costs. The cumulative effect of these inefficiencies represents a significant barrier to SME productivity and scalability (Siboro et al., 2024; Chyzhykov et al., 2023).

Previous studies on automated dosing systems can generally be classified into two categories. The first category focuses on electronic control strategies, including PID-based control, sensor integration, and microcontroller optimization, aimed at improving weighing accuracy and response time (Fattulah et al., 2023; Humaira et al., 2024). Although these approaches improve measurement performance, they often assume stable material flow conditions; therefore, they provide limited solutions to powder-flow phenomena such as bridging, arching, and intermittent clogging.

The second category focuses on the mechanical

http://dx.doi.org/10.30656/intech.v12i1.12030

behavior of powder dispensing systems, where the hopper geometry, gate aperture configuration, and bulk material characteristics directly influence flow stability (Ghifary et al., 2025; Pan & Xu, 2024). In gravity-fed flour dispensing, improvements in control algorithms alone may be insufficient when flow disturbances originate from mechanical interactions between particles and dispensing geometry. Consequently, a combined approach integrating both the control architecture and mechanical flow optimization is required to achieve a reliable dosing performance.

Substantial prior research has investigated automated weighing systems that employ load cell sensors and microcontroller platforms. Load cell-based systems are widely recognized for their high accuracy and reliability across diverse measurement contexts (Montoro-Bombú et al., 2023), and advances in weighing sensor configurations have further improved their performance in powder dispensing applications (Galina, 2024; Shinde, 2025). The behavior of granular and powder materials in gravity-fed dispensing mechanisms is strongly influenced by aperture geometry, bulk density, and particle size distribution factors that must be accounted for in mechanical design to minimize dosing overshoot and variability (Ghifary et al., 2025; Santoso et al., 2025). In the SME bakery context, Humaira et al. (2024) demonstrated that an Arduino Uno-based PID-controlled bread ingredient dosing system achieved mean errors of 0–1%, while Fattulah et al. (2023) confirmed significant error reduction compared to manual methods. These findings collectively confirm the broad applicability of load cell-based Arduino Uno dosing automation in SME food production.

Nevertheless, significant research gaps persist. First, most existing studies prioritize control algorithms and electronic measurement, whereas the mechanical design of the dispensing mechanism, which directly governs the material flow behavior and dosing accuracy, remains comparatively unexplored. Second, few studies adopt a structured product design and development methodology incorporating modularity and Design for Assembly (DfA) principles, which are indispensable for ensuring manufacturability, maintainability, and scalability in resource-constrained SMEs (Monetti et al., 2025; Reinert & Gontijo, 2017; Savio, 2025). Furthermore, commercially available automated dosing equipment is often designed for large-scale industrial production and typically involves high acquisition costs, complex maintenance procedures, and prolonged downtime during component replacement. These limitations present significant barriers for SMEs in developing economies, where technical support resources are limited. Therefore, incorporating Design for Assembly (DfA) principles into product architecture is important not only for manufacturability but also for reducing maintenance complexity, shortening repair time, and improving long-term operational sustainability. Third, experimental validation is frequently confined to a single setpoint or a small number of trials, limiting the generalisability of reported accuracy (Wiyatno et al., 2024)

To address these gaps, the present study proposes the design and development of an optimized automatic flour dosing machine that integrates mechanical flow control with a structured engineering design process (EDP). The system features a funnel-gate dispensing mechanism with a dual-mode flow strategy for high-flow dispensing to 90% of the target mass, followed by a trickle-flow mode to minimize overshoot combined with Arduino-based load cell feedback control. The modular frame architecture adheres to DfA principles to reduce assembly complexity and support maintenance. System performance was evaluated using a multi-setpoint experimental design (10 g, 30 g, and 50 g) with 30 independent trials per setpoint, yielding statistically robust performance data.

This study contributes to the literature by integrating mechanical flow optimization, QFD, Pugh Matrix, DfA principles, and Arduino-based automation within a unified framework for SME-scale flour dosing systems. In contrast to prior studies that focused predominantly on electronic control, this study demonstrates that mechanical design and product architecture are equally decisive factors in determining dosing accuracy and practical usability.

2. RESEARCH METHODS

This study adopted an engineering design process (EDP) to systematically develop and evaluate the proposed automatic flour dosing machine. The engineering design process is widely used in product design and development to translate user needs into functional and manufacturable solutions (Reinert & Gontijo, 2017). The process consists of several stages: (1) planning, (2) concept development, (3) system-level design, (4) detail design, (5) testing and refinement, and (6) share solution (Fig. 1).

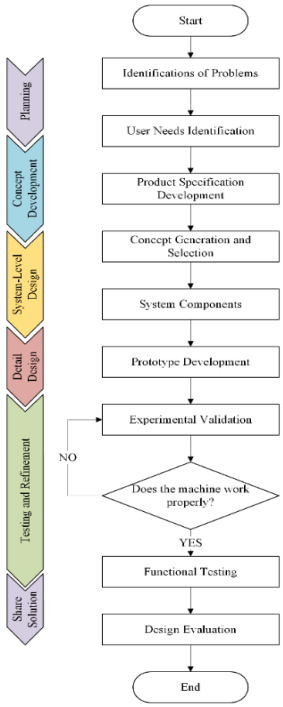


Fig. 1. Research flowchart illustrating the six-stage engineering design process

2.1. User Needs Identification

User needs were identified through structured interviews and direct observation involving five SME bakery practitioners in Tiban, Batam. The interview respondents consisted of bakery owners, production supervisors, and machine operators with more than three years of operational experience. Prior to data collection, the interview instrument was reviewed by two industrial engineering lecturers and one bakery practitioner to ensure content validity and relevance. Practitioners were questioned regarding current dosing workflows, pain points associated with manual weighing, and desired features for an automated system. Key needs identified included high dosing accuracy, ease of operation, minimal maintenance requirements, and affordability of components. These needs were subsequently translated into measurable engineering requirements.

2.2. Product Specification Development

User needs were converted into quantifiable engineering specifications using a Quality Function Deployment (QFD) approach (Rumapea & Hartanto, 2023). The critical specifications established were a target dosing accuracy of MAPE ≤ 5%, dosing range of 10–100 g, maximum dosing cycle time of 30 seconds, and component compatibility with low-cost microcontroller platforms. Design for Assembly (DfA) metrics, including part count, assembly time, and ease of disassembly for maintenance were included as explicit design targets (Monetti et al., 2025). The importance ratings were assigned by the participating SME practitioners during the interview stage using a five-point Likert scale, where 1 indicates very low importance and 5 indicates very high importance. The final importance score for each customer requirement was obtained by averaging the ratings provided by all respondents. The mapping of customer requirements to engineering specifications is summarized in Table 1**.**

Customer requirement importance ratings were determined using a five-point Likert scale based on practitioner responses. The ratings were subsequently translated into engineering characteristics using a House of Quality (HoQ). Relationship strengths between customer requirements and technical characteristics were assessed using the standard QFD scale (9 = strong, 3 = moderate, 1 = weak). Technical priorities were then calculated to determine the most critical engineering specifications. The resulting technical priority values were obtained by multiplying the importance rating of each customer requirement by the corresponding relationship score and then summing the results across all customer requirements. Engineering specifications with higher priority values were considered more critical during concept generation and concept evaluation. These priorities subsequently informed the weighting process used in the Pugh Matrix and guided the selection of the final dispensing system configuration.

2.3. Concept Generation and Selection

Multiple design concepts were generated for both the mechanical dispensing mechanism and the electronic control subsystem. Concept generation was conducted using a morphological chart approach, in which independent design parameters were identified for each functional subsystem, and alternative solutions were mapped across each parameter. For the dispensing mechanism, three principal alternatives were evaluated: (a) a screw-auger feeder, which uses a helical screw to advance powder along a barrel, offering high flow consistency but requiring a motor drive and presenting cleaning difficulties for food-grade applications; (b) a vibratory tray feeder, which uses oscillation to convey powder gradually, suitable for fragile granules but prone to flow irregularity with fine powders such as flour; and (c) a funnel–gate gravity-fed mechanism, which relies on gravity to drive powder flow through an aperture controlled by a servo-actuated gate, offering simplicity, low part count, and direct compatibility with DfA design targets. For the electronic control subsystem, three alternatives were considered: relay-based binary switching, which provides only on/off gate control with no intermediate flow modulation; stepper-motor gating, which allows precise angular positioning but requires additional driver circuitry and introduces mechanical complexity; and pulse-width modulation (PWM) servo actuation, which enables continuous and programmable angular positioning with minimal additional hardware, directly compatible with the Arduino Uno platform.

A Pugh concept selection matrix was applied to evaluate each concept against the established engineering specifications. Each alternative was scored on a 1–5 scale across five weighted criteria derived from the QFD specifications: dosing accuracy, flow controllability, assembly complexity (DfA score), component cost, and maintenance accessibility (Table 2). The Pugh matrix evaluation was conducted by a panel consisting of two industrial engineering lecturers and one practitioner from the participating SME bakery. Scores were assigned on a five-point scale based on the degree to which each concept satisfied the engineering specifications established in the QFD stage. The weighting factors correspond directly to the importance ratings obtained from the customer requirements. Final scores were calculated using the weighted-sum approach and agreed upon through consensus discussions among the evaluators.

The funnel-gate gravity-fed mechanism achieved the highest weighted score among the mechanical alternatives (87), primarily because of its superior ratings for dosing accuracy, assembly simplicity, and maintenance accessibility, all critical criteria for SME deployment. The screw-auger scored substantially lower (52) because of its high assembly complexity and maintenance difficulty, while the vibratory tray received an intermediate score (57) reflecting limitations in flow consistency with fine powder materials. For the control subsystem, PWM servo actuation achieved the highest score (86), driven by its excellent dosing accuracy rating and low assembly complexity. The stepper-motor option scored lowest (55) owing to its high complexity and cost. Based on these results, the funnel–gate mechanism combined with PWM servo actuation was selected as the basis for prototype development. This combination offers the optimal trade-off between performance, cost, and maintainability for the target SME application.

http://dx.doi.org/10.30656/intech.v12i1.12030

Table 1. Quality function deployment mapping of customer requirements to engineering specifications

Customer Requirement	Importance (1–5)	Engineering Specification	Target Value
High dosing accuracy	5	Mean Absolute Percentage Error (MAPE)	≤ 5%
Flexible dosing range	4	Dosing range	10–100 g
Fast dosing cycle	4	Maximum dosing cycle time	≤ 30 s
Low component cost	5	Low-cost microcontroller-compatible components	Arduino-compatible
Easy assembly & maintenance	4	DfA metrics: part count, assembly time, disassembly ease	Minimized part count; tool-free disassembly
Safe operation (no-container lockout)	5	Ultrasonic container detection interlock	Detection range 2–15 cm
Real-time user feedback	3	LCD I2C display with status & weight readout	16×2-character LCD

Table 2. Pugh concept selection matrix for mechanical and control subsystem alternatives

Criterion	Weight	Screw Auger	Vibratory Tray	Funnel–Gate (selected)	Relay Switch	Stepper Gate	Servo (selected)
Dosing accuracy	5	3	3	5	3	4	5
Flow controllability	4	4	3	4	3	4	4
Assembly complexity (DfA)	4	2	3	5	4	2	4
Component cost	3	2	3	4	5	2	4
Maintenance accessibility	4	2	3	5	4	3	4
Weighted Score		52	57	87	70	55	86

2.4. System Components

The selected design integrates three functionally distinct but interdependent subsystems, each responsible for a specific aspect of the dosing process. The first subsystem is the mechanical dispensing unit, which constitutes the core innovation of this study. It comprises a conical hopper fabricated from an acrylic sheet for visual monitoring of the flour level, an adjustable gate aperture at the hopper base, and a material collection platform mounted directly above the load cell. The gate is actuated by an SG90 servo motor, which controls the aperture angle in two modes: a high-flow mode at 90° and a trickle-flow mode at a reduced angle to minimize dispensing overshoot as the target mass is approached. The second subsystem is the sensing and control unit, centered on an Arduino Uno R3 microcontroller (ATmega328P, 16 MHz) that receives real-time mass data from the load cell via the HX711 24-bit analog-to-digital converter module and container proximity data from the HC-SR04 ultrasonic sensor. The control logic executes a threshold-based gate closure algorithm: the servo remains at the high-flow angle until the measured mass reaches 90% of the target and then switches to the trickle-flow angle until the exact target is detected, at which point the gate closes to 0°. The third subsystem is the human–

Table 3. Key components, specifications, and system functions

No.	Component	Specification	Function in System
1	Arduino Uno R3	ATmega328P, 14 digital I/O, 6 PWM, 16 MHz	Central microcontroller; processes sensor data and generates actuator control signals
2	Load Cell + HX711 Module	Capacity: 1 kg; resolution: 0.01 g (with HX711 24-bit ADC)	Measures dispensed mass in real-time; triggers gate closure at target mass
3	HC-SR04 Ultrasonic Sensor	Range: 2–400 cm; accuracy: ±3 mm	Container presence detection; safety interlock preventing dispensing without container
4	SG90 Servo Motor	Torque: 1.8 kg·cm; rotation: 0°–180°; 4.8–6 V	Gate actuator controlling funnel aperture for high-flow and trickle-flow dispensing modes
5	LCD I2C 16×2	I²C interface (SDA/SCL); 16 characters × 2 rows	User interface displaying system status, container detection state, and dispensed mass
6	Push Buttons (START/STOP)	Momentary tactile switches; digital input	Operator control for initiating and halting the dosing cycle
7	Power Supply (DC)	5V USB output, ≥2 A	Portable DC power supply for all electronic subsystems

machine interface (HMI), comprising a 16×2 character LCD I2C display and two momentary push-button switches (START and STOP). The LCD continuously presents system status messages ("System Inactive," "System Active," "Container Detected," "Done – [X] g"), enabling the operator to monitor the dosing process without additional instrumentation. The START/STOP and STOP buttons provide direct operator control, with the STOP button functioning as an emergency interrupt at any point in the dosing cycle. The structural frame was fabricated from plywood panels, which were selected for their low cost and ease of machining, consistent with the DfA principle of minimizing manufacturing complexity. The complete set of components, their specifications, and functions within the system are summarized in Table 3**.**

2.5. Prototype Development

The prototype frame was fabricated using plywood panels to support all system components, with acrylic sheets used for the hopper and funnel enclosure to facilitate visual monitoring during operation. The mechanical dispensing unit comprised a conical hopper, an adjustable gate aperture controlled by the SG90 servo motor, and a material collection platform positioned above the load cell.

Fig. 2 and Fig. 3 shows the wiring diagram of the automatic flour dosing machine, comprising seven components: (1) START/STOP push buttons as the operator interface; (2) HC-SR04 ultrasonic sensor for container detection; (3) Arduino Uno R3 microcontroller as the central processing unit; (4) LCD I²C 16×2 display for real-time status and weight readout; (5) SG90 servo motor controlling the funnel gate aperture; (6) load cell and HX711 module for real-time mass measurement and gate closure triggering; and (7) mini breadboard as the power distribution hub.

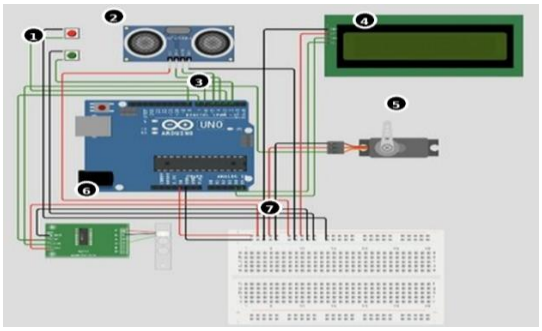


Fig. 2. Wiring diagram of the automatic flour dosing machine

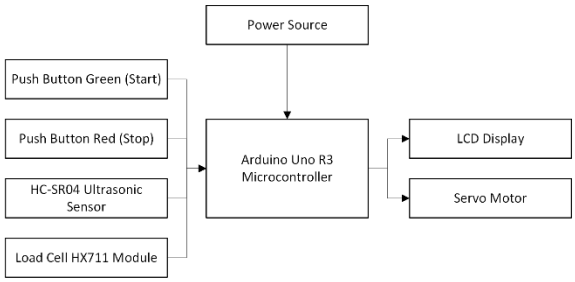


Fig. 3. System communication diagram

The gate actuation algorithm employs a dual-mode dispensing strategy: the servo opens to 90° (high-flow mode) until the load cell reading reaches 90% of the target mass, then reduces to a trickle-flow angle until the target is reached, at which point the gate closes to 0°. This two-stage approach was specifically designed to minimize overshoot.

The HMI comprises an LCD I2C 16×2 display that presents real-time system status, container detection state, and dispensed mass, alongside START/STOP push buttons for operator control. Container presence is verified by the HC-SR04 ultrasonic sensor; dispensing is blocked if no container is detected within the 2–15 cm valid range, providing an effective safety interlock. The assembled prototype is presented in Fig. 4**.**



Fig. 4. Assembled automatic flour dosing machine prototype

2.6. Experimental Validation

System performance was evaluated using a multi-setpoint experimental design at target masses of 10 g, 30 g, and 50 g. At each setpoint, 30 independent dosing trials were conducted under controlled laboratory conditions using wheat flour as the test material. The actual dispensed mass for each trial was recorded using a calibrated reference scale (resolution: 0.01 g). Prior to trials, the load cell was calibrated using a reference object of known mass (90 g) to ensure accurate baseline readings repeated three times (Fig. 5 and Fig. 6). Prior to experimentation, the load cell was calibrated using a certified 90 g reference mass. Calibration was repeated three times, and the average calibration factor generated by the HX711 library was adopted for subsequent measurements. The calibration error was verified to remain below ±0.05 g before experimental testing commenced.



Fig. 5. Load cell calibration process

http://dx.doi.org/10.30656/intech.v12i1.12030

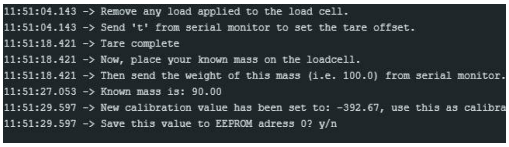


Fig. 6. Load cell program calibration

Performance was assessed using four metrics: (i) mean absolute percentage error (MAPE), calculated as the average of absolute percentage deviations between dispensed and target mass across all trials; (ii) standard deviation (SD), reflecting intra-setpoint variability; (iii) coefficient of variation (CV), expressed as the ratio of SD to mean dispensed mass; and (iv) maximum error (%), the highest individual trial error recorded per setpoint. These metrics collectively provide a comprehensive characterization of both systematic accuracy and trial-to-trial repeatability. The mathematical definitions of each metric are given in Equations (1)–(4).

Equation (1) — Mean Absolute Percentage Error (MAPE):

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\frac{|Ai - Ti|}{Ti} \times 100\% \quad (1)$$

where n = number of trials (n = 30 per setpoint); Ai = actual dispensed mass of trial i (g); Ti = target setpoint mass (g). MAPE below 5% satisfies the design specification; values below 2% indicate high dosing precision.

Equation (2) — Standard Deviation (SD):

$$\text{SD} = \sqrt{\frac{\sum_{i=1}^{n}(Ai - \bar{A})^2}{n-1}} \quad (2)$$

where Ai = dispensed mass of trial i (g); $\bar{A}$ = mean dispensed mass across all n trials (g); denominator uses $n - 1$ (sample standard deviation). A lower SD indicates greater trial-to-trial consistency within a setpoint.

Equation (3) — Coefficient of Variation (CV):

$$\text{CV}\,(\%) = \frac{SD}{\bar{A}} \times 100\% \quad (3)$$

where SD = standard deviation of dispensed mass (g) from Equation (2); $\bar{A}$ = mean dispensed mass (g). The CV normalizes the variability relative to the mean, enabling a direct comparison of the repeatability across setpoints of different magnitudes. A CV below 5% is generally accepted as indicating adequate repeatability in food dosing applications.

Equation (4) — Maximum Individual Trial Error (Max Error):

$$\text{Max Error}\,(\%) = \max\left(\frac{|Ai - Ti|}{Ti}\right) \times 100\% \quad (4)$$

where Ai and Ti are as defined in Equation (1). Max Error identifies the worst-case dosing deviation within a setpoint and is used alongside MAPE to assess whether any individual trial breaches the 5% design specification boundary. All Max Error values remained close to the 5% design target. The highest observed error was 5.20% at the 50 g setpoint, indicating that one trial slightly exceeded the design target while the overall system performance remained acceptable for practical SME bakery applications.

3. RESULTS AND DISCUSSION

3.1. Functional Testing Results

Prior to quantitative dosing trials, a series of functional tests were conducted to verify the correct operation of each subsystem component. The test conditions, expected behaviors, and observed results are summarized in Table 4.

Table 4. Functional testing results for all system components

Test Condition	Expected Behavior	Observed Result
Power ON (no start command)	System standby; servo at 0°; LCD: "System Inactive"	Confirmed — system waits for user input; no actuator motion is observed.
START button pressed	System activates; LCD: "System Active"	Confirmed: The system transitions to the active state without measurable delay.
STOP button pressed during operation	Process halts; servo returns to 0°; LCD: "System Inactive"	Confirmed — emergency stop responsive; gate closed within one servo cycle.
Container within 2–15 cm (ultrasonic)	LCD: "Container Detected"; dispensing permitted	Confirmed — container reliably detected across the full valid range.
Container absent or >15 cm	LCD: "Container Not Detected"; dispensing blocked	Confirmed — effective safety interlock preventing dispensing without a container.
Target mass reached (load cell)	Servo closes to 0°; LCD: "Done – [X] g"	Confirmed — gate closure responsive; no significant overshoot post-closure.
LCD real-time display at normal flow rate	Display incremental weight updates	Limited — display shows final status only at full gate aperture owing to high flow rate; accuracy unaffected (Section 3.4).

All primary functional tests were performed without measurable delay or failure. The LCD real-time display at the full gate aperture was the sole limitation, but did not affect dosing accuracy, as the load cell continued to read and trigger gate closure at the target mass. This limitation is attributable to the gate aperture size rather than the sensor capability and is addressed in the

prototype improvement recommendations (Section 3.4).

3.2. Dosing Accuracy Results

The detailed trial-by-trial results for each setpoint are presented in Table 5, Table 6, and Table 7. The aggregated summary statistics are presented in Table 8.

Table 5. Trial-by-trial dosing results for 10 g setpoint (n = 30)

Trial	Measured (g)	|Error| (g)	Trial	Measured (g)	|Error| (g)
1	9.82	0.18	16	10.08	0.08
2	10.05	0.05	17	10.20	0.20
3	9.83	0.17	18	9.93	0.07
4	9.81	0.19	19	10.02	0.02
5	9.86	0.14	20	10.17	0.17
6	9.97	0.03	21	9.98	0.02
7	9.97	0.03	22	10.44	0.44
8	9.89	0.11	23	10.21	0.21
9	9.96	0.04	24	9.83	0.17
10	10.28	0.28	25	9.71	0.29
11	9.66	0.34	26	9.96	0.04
12	10.07	0.07	27	10.26	0.26
13	9.66	0.34	28	9.91	0.09
14	10.22	0.22	29	10.18	0.18
15	9.95	0.05	30	10.14	0.14

Summary:
Mean = 10.001 g
Standard Deviation (SD) = 0.191 g
Coefficient of Variation (CV) = 1.91%
MAPE = 1.54%

Table 6. Trial-by-trial dosing results for 30 g setpoint (n = 30)

Trial	Measured (g)	|Error| (g)	Trial	Measured (g)	|Error| (g)
1	29.90	0.10	16	29.86	0.14
2	29.64	0.36	17	30.08	0.08
3	28.82	1.18	18	30.60	0.60
4	30.02	0.02	19	30.58	0.58
5	30.55	0.55	20	30.33	0.33
6	30.23	0.23	21	30.20	0.20
7	29.97	0.03	22	30.86	0.86
8	29.67	0.33	23	30.72	0.72
9	29.91	0.09	24	29.53	0.47
10	31.09	1.09	25	29.77	0.23
11	30.19	0.19	26	30.99	0.99
12	29.66	0.34	27	29.80	0.20
13	30.02	0.02	28	29.21	0.79
14	29.98	0.02	29	29.80	0.20
15	30.58	0.58	30	29.68	0.32

Summary:
Mean = 30.075 g
Standard Deviation (SD) = 0.515 g
Coefficient of Variation (CV) = 1.71%
MAPE = 1.32%

As shown in Table 8, the system achieved MAPE values of 1.54%, 1.32%, and 1.83% at the 10 g, 30 g, and 50 g setpoints, respectively. These average errors were substantially below the 5% design specification and indicate high dosing precision across the evaluated operating range. The mean dispensed mass closely tracked the target at each setpoint (10.001 g, 30.075 g, and 49.821 g), indicating negligible systematic bias across the tested dosing range. The 95% confidence intervals were also estimated for each setpoint mean. The confidence intervals contained the respective target values, indicating that no statistically significant systematic bias was observed across the evaluated dosing range.

Table 7. Trial-by-trial dosing results for 50 g setpoint (n = 30)

Trial	Measured (g)	|Error| (g)	Trial	Measured (g)	|Error| (g)
1	50.32	0.32	16	50.66	0.66
2	48.78	1.22	17	48.50	1.50
3	50.23	0.23	18	50.16	0.16
4	49.08	0.92	19	48.20	1.80
5	50.20	0.20	20	49.79	0.21
6	50.80	0.80	21	51.16	1.16
7	50.89	0.89	22	50.11	0.11
8	51.08	1.08	23	48.44	1.56
9	50.68	0.68	24	48.38	1.62
10	51.30	1.30	25	49.81	0.19
11	48.34	1.66	26	49.14	0.86
12	51.35	1.35	27	47.40	2.60
13	50.31	0.31	28	49.77	0.23
14	49.62	0.38	29	48.40	1.60
15	51.82	1.82	30	49.90	0.10

Summary:
Mean = 49.821 g
Standard Deviation (SD) = 1.130 g
Coefficient of Variation (CV) = 2.27%
MAPE = 1.83%

The SD increased with setpoint magnitude from 0.191 g at 10 g to 0.515 g at 30 g and 1.130 g at 50 g, reflecting the greater absolute flow volume at higher targets and the increased influence of gate opening duration on the final dispensed mass. The CV values of 1.91%, 1.71%, and 2.27% confirm that relative variability remained low and consistent across all conditions, indicating stable system repeatability suitable for production applications.

The highest individual trial error occurred at the 50 g setpoint (5.20% at Trial 27), attributable to the larger gate aperture required for higher flow volumes and the amplifying effect of flour particle irregularities and minor mechanical vibrations at wider aperture angles. The 30 g setpoint yielded the lowest MAPE (1.32%), consistent with its role as the system calibration target and the intermediate flow regime in which the funnel–gate

Table 8. Summary of dosing accuracy performance across all setpoints (n = 30 per setpoint)

Setpoint (g)	Mean (g)	95% CI	SD (g)	CV (%)	MAPE (%)	Max Error (%)
10	10.001	9.93 – 10.07	0.191	1.91	1.54	4.40
30	30.075	29.88 – 30.27	0.515	1.71	1.32	3.93
50	49.821	49.40 – 50.24	1.130	2.27	1.83	5.20

http://dx.doi.org/10.30656/intech.v12i1.12030

Table 9. Comparison of dosing accuracy with related studies

Study	Control Method	Accuracy Metric	Best Result	Key Distinction
Humaira et al. (2024)	PID control	Mean error	0–1%	Sophisticated closed-loop; higher computational cost
Fattulah et al. (2023)	Arduino microcontroller	Error reduction vs manual	Significant reduction	No quantified MAPE; single-setpoint validation
Santoso et al. (2025)	Arduino + servo	Accuracy improvement	Qualitative	Sugar dosing; no multi-setpoint statistical validation
(Pan & Xu, 2024)	Dual ARM core	Powder dispensing accuracy	Not directly comparable	Industrial-grade; higher cost; not SME-targeted
Present study	Threshold-based load cell feedback	MAPE (n=30 per setpoint)	1.32–1.83%	Mechanical optimisation + DfA + multi-setpoint validation

mechanism operates most stably.

3.3. Comparison with Related Literature

The dosing accuracy performance obtained in this study is contextualized against related work in Table 9**.** The present system, operating without PID control, achieved MAPE values between 1.32% and 1.83%, demonstrating that a well-optimized mechanical dispensing mechanism combined with threshold-based load cell feedback can deliver near-equivalent accuracy at substantially lower implementation complexity, an important consideration for SME adoption. The accuracy levels obtained also satisfy the practical tolerance standards for bakery ingredient measurement, where deviations below 2–3% are generally considered acceptable for maintaining product quality (Guiné, 2022).

3.4. Design Evaluation and Limitations

The collective findings of this study, spanning functional testing (Section 3.1), multi-setpoint dosing accuracy trials (Section 3.2), and literature benchmarking (Section 3.3), provide a coherent and substantive basis for evaluating the proposed system against the research objectives and engineering specifications established in Section 2.2. This section synthesizes these findings into an integrated discussion addressing system performance, design effectiveness, theoretical contributions, practical implications, and directions for future development.

3.4.1. *Dosing Accuracy and Repeatability*

The system achieved MAPE values of 1.54%, 1.32%, and 1.83% across the 10 g, 30 g, and 50 g setpoints, respectively, all within the 2% high-precision threshold and well below the 5% design specification. These results confirm that the primary engineering objective of dosing accuracy was fully met across a representative range of bakery ingredient quantities. The CV values (1.91%, 1.71%, 2.27%) further demonstrate that variability was not only low in absolute terms but also stable relative to the dispensed mass, indicating that the system exhibited consistent behavior regardless of the target quantity. This is a critical attribute for SME bakery operations, where batch-to-batch consistency directly determines product quality.

The observed trend of increasing SD and CV with setpoint magnitude from 0.191 g at 10 g to 1.130 g at 50 g is physically consistent with the greater absolute flour mass in motion at higher targets, which amplifies the effect of flow irregularities, such as particle bridging, wall adhesion, and minor servo positional variation. This phenomenon is well-documented in gravity-fed powder dispensing systems, where aperture size and bulk density interact to produce flow rate variability (Ghifary et al., 2025; Pan & Xu, 2024)

The dual-mode flow strategy transitioning from high-flow to trickle-flow at 90% of the target was specifically designed to mitigate this effect by reducing momentum at the critical mass-approach phase. The improvement in MAPE at the 30 g setpoint relative to both the 10 g and 50 g setpoints (1.32% vs 1.54% and 1.83%) validates this design choice: at 30 g, the system operates within the intermediate flow regime where the transition point falls at 27 g, giving the trickle-flow phase sufficient time to stabilize before closure. At 10 g, the trickle-flow phase begins at 9 g, leaving a narrower margin; at 50 g, the larger aperture angle required in high-flow mode generates greater residual momentum that is harder to fully attenuate during the trickle phase.

3.4.2. *Role of Mechanical Design in System Performance*

The central argument of this study is that mechanical design optimization plays an equally decisive role in dosing accuracy as electronic control strategy. The results support this argument. The funnel–gate mechanism, selected through the Pugh matrix for its superior flow controllability and DfA score, directly enabled the dual-mode dispensing algorithm to function effectively. Without a gate mechanism capable of reliable partial closure at the trickle-flow angle, the threshold-based load cell feedback loop would be insufficient to prevent overshoot.

This interdependence between mechanical design and control strategy is consistent with observations by Shinde (2025) who note that sensor accuracy alone cannot compensate for poor mechanical integration in weighing system design. The present study extends this insight to the powder dispensing context: the accuracy achieved here without PID control a result of mechanical optimization is comparable to that reported by Humaira et al. (2024) using a PID-controlled system.

This suggests that for SME-scale dosing at the gram level, thoughtful mechanical design can substitute for algorithmic complexity, substantially reducing implementation cost and maintenance burden. The modular, DfA-compliant frame architecture further

reinforces this argument: by reducing the part count and enabling tool-free disassembly, the prototype achieves not only mechanical performance but also operational practicality for resource-constrained SME environments (Monetti et al., 2025; Reinert & Gontijo, 2017).

3.4.3. *System Limitations and Root Cause Analysis*

Two limitations were identified during the experimental evaluation. First, the LCD could not display incremental weight updates at the full gate aperture during normal operation, instead transitioning directly to the completion status. Root cause analysis attributes this to the high volumetric flow rate of flour at 90° gate opening, which causes the dispensed mass to reach the target before the LCD refresh cycle completes. Critically, this does not constitute a functional failure: the load cell reads continuously at the hardware sampling rate of the HX711 (up to 80 samples per second), and gate closure is triggered by the microcontroller logic independently of the display update cycle.

Therefore, dosing accuracy was unaffected, as confirmed by the consistent MAPE and CV values across all 90 trials. The display limitation is attributable solely to aperture geometry and can be resolved in future iterations by reducing the maximum gate opening angle or implementing a display update interrupt separate from the main control loop. Second, the maximum individual trial error at the 50 g setpoint reached 5.20% (Trial 27:47.40 g). Although the maximum observed error slightly exceeded the 5% design target (5.20%), it occurred only once among the 30 trials and did not materially affect the overall dosing performance. Analysis of the trial data shows that this outlier occurred under conditions of potential flour bridging at the gate edge, a known phenomenon in gravity-fed powder systems characterized by intermittent flow interruption followed by sudden release (Ghifary et al., 2025).

According to Janssen's Silo Theory, vertical stress within granular materials does not increase linearly with fill height because a portion of the load is transferred to the hopper walls through friction. Under higher mass loads, the interaction between wall friction and inter-particle friction may promote arch formation (bridging) near the gate opening. The unusually high error observed in Trial 27 (5.20%) may therefore be attributed to temporary flow interruption followed by the sudden release of flour, resulting in under-dosing behavior. The current prototype employs a vertical gate profile that introduces a sharp transition at the outlet boundary. Such geometry may increase local shear resistance and encourage particle interlocking near the aperture edge. Future studies may investigate beveled or chamfered gate geometries, which theoretically reduce shear stress concentration and facilitate a more uniform mass-flow pattern, thereby decreasing the likelihood of bridging and intermittent discharge.

3.4.4. *Practical Implications for SME Adoption*

The results of this study have direct practical implications for SME bakery operators. Manual weighing using conventional scales the current standard in most SME bakery operations in Indonesia introduces inconsistency through operator variability, fatigue, and parallax error (Farihin et al., 2021; Firdaus et al., 2024). The present system eliminates these sources of variability by automating the full dosing cycle, from container detection through dispensing to automatic gate closure, with no operator intervention required beyond pressing the START button.

The safety interlock via the HC-SR04 sensor further reduces the risk of flour spillage in the absence of a container, addressing a common source of raw material waste in SME environments (Rosdiana et al., 2020). In terms of economic feasibility, the total component cost of the prototype comprising an Arduino Uno R3, HX711 module, HC-SR04 sensor, SG90 servo, LCD I2C, and structural materials remains well within typical SME equipment procurement budgets, making this solution accessible without capital investment. The modular design further supports adoption by enabling component-level replacement and maintenance without specialized tools, a critical consideration for SME operators who may lack technical support infrastructure. Taken together, these attributes position the proposed system as a practical, scalable, and economically viable automation solution for the SME food production sector in Indonesia and comparable emerging market.

3.4.5. *Future Research Directions*

Several directions were identified for future research. First, the system was evaluated exclusively with wheat flour under controlled laboratory conditions; future work should test the performance with powdered sugar, cocoa powder, baking soda, and other bakery ingredients of varying particle size, cohesion, and bulk density, as these properties directly influence gravity-fed flow behavior.

Second, the incorporation of a PID or fuzzy logic control layer could further reduce the maximum individual trial error at the 50 g setpoint, particularly under high-variability material conditions; however, this must be balanced against the associated increase in implementation complexity and cost relative to the SME deployment context.

Third, the integration of IoT connectivity, for example via an ESP8266 or ESP32 Wi-Fi module, would enable remote monitoring of dosing counts, cumulative material consumption, and system status, supporting data-driven production management in SME bakeries. Fourth, a structured time-motion study comparing dosing cycle times between the automated and manual methods would provide the empirical efficiency data needed to fully substantiate the productivity improvements claimed qualitatively in this study. Fifth, scalability testing in a live SME bakery production environment, beyond the controlled laboratory setting, is necessary to validate system performance under real-world conditions, including ambient temperature variation, flour moisture content fluctuation, and continuous multi-hour operation.

4. CONCLUSION

This study successfully designed, developed, and experimentally validated an optimized automatic flour dosing machine by integrating a structured engineering design process with mechanical flow control optimization. The system combines a load cell-based

http://dx.doi.org/10.30656/intech.v12i1.12030

measurement subsystem, Arduino Uno microcontroller logic, and an optimized funnel–gate dispensing mechanism with a dual-mode flow strategy to overcome the limitations of manual and semi-automated dosing processes.

Experimental evaluation across three setpoints (10 g, 30 g, and 50 g) with 30 independent trials per condition demonstrated MAPE values of 1.54%, 1.32%, and 1.83%, respectively, all substantially below the 5% design specification and within a 2% threshold suitable for production use. The CV remained below 2.3% across all conditions, confirming stable trial-to-trial repeatability. Functional testing confirmed the correct operation of all system components, including effective container detection safety interlock and responsive gate actuation. The automated dispensing process eliminates manual handling steps, which is expected to reduce the per-cycle operator time relative to conventional scale-based weighing; quantification of this improvement is recommended as a priority for future work. Several limitations should be acknowledged. The experimental validation was conducted using only wheat flour, a single hopper geometry, and under laboratory conditions. Long-term durability and industrial-scale performance were not evaluated.

The findings demonstrate that mechanical design optimization plays an equally decisive role in dosing system performance as electronic control design, a dimension frequently underemphasized in prior work. The structured EDP methodology, incorporating QFD-based specifications, Pugh matrix concept selection, DfA-compliant modular design, and multi-setpoint statistical validation, provides a replicable methodological framework for future research in low-cost food production automation. The system offers SME operators a cost-effective, maintainable, and accurate dosing solution that enhances product consistency and operational efficiency. To the best of the authors' knowledge, this study is the first to systematically integrate DfA-compliant modular mechanical design with multi-setpoint load cell dosing validation (n = 30 per setpoint) in the SME bakery context, providing a replicable and low-cost automation framework directly applicable to resource-constrained food production environments.

ACKNOWLEDGEMENT

This study received no external funding. The authors would like to thank the Institut Teknologi Batam for the facilities and academic support, as well as the lecturers and laboratory staff of the Industrial Engineering Program for their guidance. Appreciation is also extended to SME bakery practitioners in Tiban, Batam, for their valuable input during the user needs identification stage and to all team members involved in this research.

REFERENCES

Chandrasiri, S., Wijenayake, A., & Arachchige, U. (2022). Development of automated systems for the implementation of food processing. *Journal of Research Technology and Engineering*, *3*, 8–18. https://www.jrte.org/wp-content/uploads/2022/01/Development-of-automated-systems-for-the-implementation-of-food.pdf

Chyzhykov, D., Widziewicz-Rzońca, K., Błaszczak, M., Rogula-Kopiec, P., & Słaby, K. (2023). Automatic weighing system vs. manual weighing precision comparison in PM-loaded filter measurements under different humidity conditions. *Environmental Monitoring and Assessment*, *195*(11), 1393. https://doi.org/10.1007/s10661-023-11939-7

Farihin, M. M., Priambodo, J., & Khindi, B. Al. (2021). Sistem Penakar Bahan Baku Premix Roti Manis Menggunakan Metode PID. *Jurnal Teknik ITS*, *10*(2), 121–126. http://ejurnal.its.ac.id/index.php/teknik/article/view/68131

Fattulah, A., Rahman, S., & Lubis, I. (2023). Prototype Mesin Penakar Gula Pasir Berbasir Ardiuno Uno Pada UMKM. *SNASTIKOM*, *10*, 29–40. https://prosiding.snastikom.com/index.php/SNASTIKOM2020/article/view/69

Firdaus, L. H., Ramdan, F., Angga, A., Fajar, J., & Prasetio, I. (2024). Rancang Bangun Sistem Penimbangan Tepung pada Silo Secara Kontinyu yang Terintegrasi dengan Sistem Monitoring Online. *Journal of Mechanical Engineering*, *1*(4), 1. https://doi.org/10.47134/jme.v1i4.3271

Galina, M. (2024). Design and Implementation of Home Industrial-Based Automatic Granulated Food Weighing Machine. *JURNAL INFOTEL*, *16*(3). https://doi.org/10.20895/infotel.v16i3.1168

Ghifary, N. M., Primananda, R., & Setiawan, E. (2025). Rancang Bangun Sistem Takaran Otomatis Biji Kopi Blend (Arabika Dan Robusta) Pada Mesin Grinder Kopi Berbasis Load Cell Pada Arduino. *Jurnal Teknologi Informasi Dan Ilmu Komputer*, *12*(4), 843–850. https://jtiik.ub.ac.id/index.php/jtiik/article/view/9789

Guiné, R. P. F. (2022). Textural Properties of Bakery Products: A Review of Instrumental and Sensory Evaluation Studies. *Applied Sciences*, *12*(17), 8628. https://doi.org/10.3390/app12178628

Humaira, N., Dewatama, D., & Gillang Al Azhar. (2024). Optimalisasi Sistem Penakar Bahan Baku Roti Otomatis Menggunakan Kontrol PID. *Jurnal Elektronika Dan Otomasi Industri*, *11*(1), 85–94. https://doi.org/10.33795/elkolind.v11i1.3298

Monetti, F. M., Lundström, A., & Maffei, A. (2025). Integrating design for assembly in modular product architecture: barriers, insights, and a framework for early-stage guidance. *Production & Manufacturing Research*, *13*(1). https://doi.org/10.1080/21693277.2025.2566066

Montoro-Bombú, R., Gomes, B. B., Santos, A., & Rama, L. (2023). Validity and Reliability of a Load Cell Sensor-Based Device for Assessment of the Isometric Mid-Thigh Pull Test. *Sensors*, *23*(13), 5832. https://doi.org/10.3390/s23135832

Pan, S., & Xu, D. (2024). Design of an Automatic Powder Dosing Control System Based on Dual

ARM Core. *Academic Journal of Science and Technology*, *13*(1), 168–174. https://doi.org/10.54097/ar0wf055

Reinert, F., & Gontijo, L. A. (2017). The consideration of human factors in product design at the engineering programmes of a Brazilian university. *Journal of Engineering Design*, *28*(10–12), 709–730. https://doi.org/10.1080/09544828.2017.1393656

Rosdiana, Y. M., Iriyadi, I., & Wahyuningsih, D. (2020). Pendampingan Peningkatan Efisiensi Biaya Produksi UMKM Heriyanto Melalui Analisis Biaya Kualitas. *Jurnal Abdimas Dedikasi Kesatuan*, *1*(1), 1–10. https://doi.org/10.37641/jadkes.v1i1.311

Rumapea, E. S. E., & Hartanto, A. (2023). Perancangan Ulang Hand Blender Menggunakan Metode Quality Function Deployment. *In Talenta Conference Series: Energy and Engineering (EE)* , 809–821. https://talentaconfseries.usu.ac.id/index.php/ee/article/view/1897

Santoso, L. H., Anwari, A., & Subagja, R. (2025). Rancang Bangun Alat Pengemasan Gula Pasir Otomatis Berbasis Mikrokontroler. *Jurnal Infotex*, *4*(1), 1–13. https://ojs.stttexmaco.ac.id/index.php/infotex/article/view/183

Savio, R. D. (2025). Modular Assembly Systems: Benefits, challenges, Opportunities, Case studies and Best Practices. *Technium: Romanian Journal of Applied Sciences and Technology*, *30*, 176–189. https://doi.org/10.47577/technium.v30i.13037

Shinde, N. S. (2025). Design and Implementation of a Microcontroller-Based Digital Weight Measurement System Using Gefran Load Cell. *International Journal for Research in Applied Science and Engineering Technology*, *13*(4), 3724–3731. https://doi.org/10.22214/ijraset.2025.69086

Siboro, B. A. H., Manik, Y., Tampubolon, G. M., Situmorang, E. D. V., & Sinaga, H. (2023). Penciptaan Teknologi Tepat Guna untuk Peningkatan Kualitas dan Produktifitas Produksi Produk Turunan Jahe Merah di Sumatera Utara. *International Journal of Community Service Learning*, *7*(4), 384-392. https://doi.org/10.23887/ijcsl.v7i4.67881

Taufiq, A. J., Miftahuddin, M. A., & Wibowo, T. N. (2023). Penerapan Teknologi Tepat Guna pada Perajin Tepung Bumbu Serbaguna di Desa Pagedangan Bojongsari Purbalingga. *Jurnal Pengabdian Teknik Dan Sains (JPTS)*, *3*(02). https://doi.org/10.30595/jpts.v3i02.18721

Wiyatno, T. N., Kurnia, H., Putri, I. M. M., & Nugroho, R. (2024). The combination of the kaizen approach with the Design of Experiment (DoE) method for improving quality of the bread and donut products in SMEs. *OPSI*, *17*(1), 12. https://doi.org/10.31315/opsi.v17i1.11108

http://dx.doi.org/10.30656/intech.v12i1.12030