DESIGN OF A COFFEE ROASTING MACHINE USING THE QFD AND VDI 2111 METHODS

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Abstract. *The design of an effective coffee roasting machine that meets user requirements is essential for improving roasting quality and production efficiency. This study aims to develop a coffee roasting machine by integrating the Quality Function Deployment (QFD) method with the VDI 2111 design guideline as a systematic approach to identifying customer needs and translating them into technical design specifications. Customer requirements processed through QFD revealed several prioritized features, including temperature stability, adequate capacity, operational ease, and user safety. These results were then further developed using the VDI 2111 method to generate a structured design concept consisting of functional analysis, solution principles, and evaluation of alternative designs. The design process produced a coffee roasting machine equipped with a more stable heating system, precise temperature control, an ergonomic frame structure, and a stirring mechanism that ensures uniform roasting. Based on the evaluation, the proposed design is considered capable of improving the roasting process quality while effectively fulfilling key customer needs.*

Keywords: *Coffee Roasting; Customer Requirements; Machine Design; Product Design; QFD; Quality VDI 2111.*

1. INTRODUCTION

The coffee plantation sector in Indonesia is currently experiencing a period of progressive growth, driven by the escalating culture of coffee consumption across various social strata. As a leading global producer, Indonesia faces the imperative challenge of transitioning from a raw material exporter to a producer of high-value processed goods. Within the post-harvest processing chain, roasting is fundamental, as it triggers complex thermal, chemical, and physical transformations—such as the Maillard reaction and caramelization—that permanently establish the coffee's aroma and flavor profile.

For Small and Medium Enterprises (SMEs), mastery of roasting technology is a strategic pillar for maintaining consumer loyalty and competing with industrial-scale products. However, growth in regions like West Sumatra is often hindered by limited technological infrastructure. Many local producers still rely on conventional equipment lacking precise control systems, where critical variables like the Rate of Rise (RoR) and drum rotation stability are managed manually or intuitively. This lack of control leads to inconsistent roasting levels, such as scorching or under-developed beans, which diminishes the product's economic value.

Furthermore, modern digital roasting machines from global manufacturers require significant financial investment, creating a capital barrier for household-scale industries. Addressing this gap requires an engineering approach that balances mechanical efficiency with the practical needs of local operators. This study aims to design and fabricate a 1 kg roasting machine by integrating Quality Function Deployment (QFD) and VDI 2111 methodologies. This integrated approach ensures the final product is not only technically superior in thermal precision and mechanical stability but also economically competitive for Indonesian coffee stakeholders.

2. LITERATURE REVIEW

2.1 Thermodynamic Analysis of Coffee Roasting

Roasting is a complex thermochemical process transforming green beans into aromatic, brittle, and consumable products. Heat is transferred via conduction from the drum walls, convection from hot air currents, and radiation from the heating elements. The process begins with an endothermic phase for moisture evaporation, followed by an exothermic reaction at the "First Crack" point (approx. 190°C - 200°C). Precision in the control system is vital to prevent flavor degradation caused by unstable RoR.

2.2 Quality Function Deployment (QFD)

QFD is a systematic framework used to translate qualitative customer needs into measurable technical parameters. The core of this methodology is the House of Quality (HoQ) matrix, which maps the relationship between the "Voice of Customer" (VoC) and Engineering Characteristics. For SME-focused design, QFD prioritizes features like ease of operation and fuel efficiency without unnecessary cost escalation.

2.3 VDI 2111 Design Guidelines VDI 2111

VDI 2111 (and related guidelines like VDI 2221) is a German technical design methodology emphasizing a systematic and function-based approach. It requires designers to decompose complex design problems into simpler sub-functions. The methodology consists of:

1. Clarification of Task
   Explicitly defining design requirements and constraints.
2. Conceptual Design
   Identifying solution principles for each sub-function.
3. Embodiment Design
   Determining physical forms, layouts, and component materials.
4. Detail Design
   Generating technical documentation and final working drawings for manufacturing.

2.4 Stainless Steel 201 Material and Thermal Characteristics

The selection of materials in the design of a roasting machine is heavily influenced by food safety standards (food grade) and resistance to thermal degradation. Stainless Steel 201 was selected as the primary material for the drum and hopper components due to its stable thermal expansion coefficient and adequate corrosion resistance under high-temperature conditions. Technically, a material thickness of 2 mm was specified to optimize heat retention and thermal inertia. This ensures that the internal drum temperature remains stable and is not easily affected by fluctuations in airflow rates or variations in burner flame intensity.

2.5 Sistem Kontrol Proportional-Integral-Derivative (PID)

To achieve high-precision temperature management, the use of conventional thermostats is considered insufficient for current industrial standards. Therefore, a PID control system is integrated into the W600I machine. The PID algorithm operates by continuously calculating the error between the actual temperature and the desired setpoint, subsequently adjusting the heater power output. This mechanism enables the machine to maintain the temperature within a very tight deviation range of ±1°C, which is a mandatory requirement for consistently replicating roasting profiles across multiple batches.

3. RESEARCH METHODS

3.1 Research Design and Systematic Framework

This study adopts an experimental and systematic design approach, integrating the Quality Function Deployment (QFD) framework for requirement analysis and the VDI 2111 guideline for technical realization. The methodology is structured into several iterative stages, ensuring that every mechanical component directly corresponds to the identified "Voice of Customer".

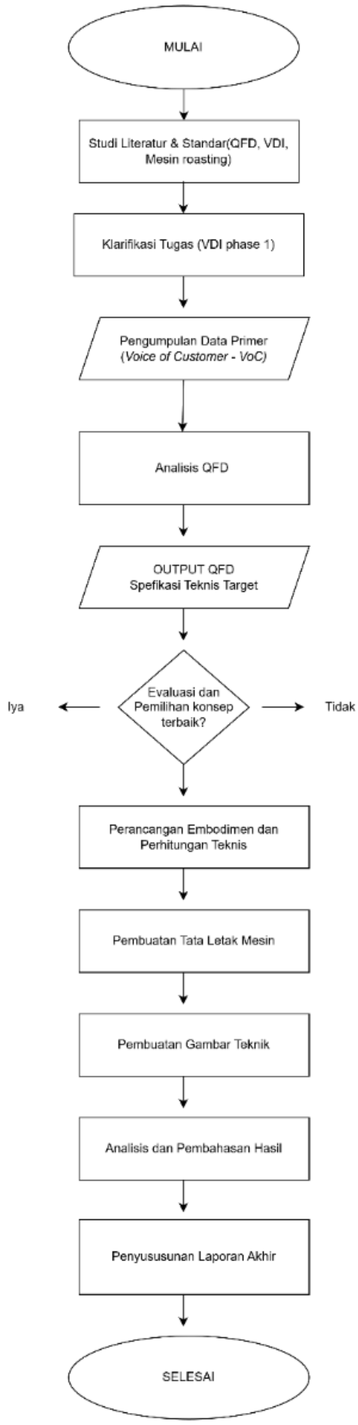

Figure 1. Flowchart

3.2 Data Collection and Panelist Selection

The primary data were gathered through structured questionnaires and in-depth interviews involving 10 professional coffee practitioners and SME owners in West Sumatra. These participants, designated as Expert Panelists, provided qualitative insights regarding the limitations of existing roasting equipment. The evaluation used a 5-point Likert scale to determine the importance level of each machine attribute, which was subsequently processed into the House of Quality (HoQ) matrix (Pastović et al., 2025).

No	Variable Needs	Indicator Question/Attribute	Skala Pengukuran
1	Functionality	Machine capable of stably roasting 1 kg of coffee beans	Likert 1-5
		Adjustable drum rotation speed (RPM)	Likert 1-5
2	Thermal Precision	Accuracy of temperature readings on the digital display	Likert 1-5
		Pre-heating speed of the machine	Likert 1-5
3	Safety	Use of food-grade materials	Likert 1-5
		Heat insulation on the machine body for safe operator contact	Likert 1-5
4	Ergonomi	Ease of inserting and removing coffee beans	Likert 1-5
		Ease of cleaning the remaining husks (chaff collector)	Likert 1-5
5	Ekonomi	Low power consumption (under 500 watts)	Likert 1-5
		Affordable machine maintenance costs for MSMEs	Likert 1-5

Table 1. User Needs Attribute Questionnaire Instrument

Panelist Code	Background/Profession	Operational Experience	MSME Location (Region)
P-01	Coffee Shop & Roastery Owner	5 Year	Padang
P-02	Traditional Roaster Machine Operator	8 Year	Agam
P-03	Home-Based Coffee Entrepreneur	3 Year	Tanah Datar
P-04	Food Processing Machine Technician	10 Year	Padang Panjang
P-05	Barista Senior & Home Roaster	4 Year	Bukittinggi

Table 2. Profile of Research Panelists and Respondents

3.3 VDI 2111 Systematic Design Phases

The engineering process for the W600I model was executed through four fundamental phases as prescribed by VDI 2111:

1. Phase 1Clarification of Task
   This involved defining the technical boundaries, such as the 1 kg batch capacity, maximum power consumption of 150W, and the requirement for food-grade materials.
2. Phase 2: Conceptual Design
   At this stage, various solution principles were evaluated, including the choice between direct-drive or belt-drive transmissions, and atmospheric vs. infrared burners.
3. Phase Embodiment Design

The physical layout was determined, focusing on the drum's dimensions (Ø150 mm x 210 mm) and the structural integrity of the frame to withstand high-temperature operations.

4. Phase 4: Detail Design
   Finalizing technical documentation, including assembly drawings, electrical circuit diagrams for the PID controller, and the bill of materials (BoM) for manufacturing.

No	Main Components	Description & Specifications
1.	Production Capacity	1 Kg / Batch
2.	Material	Stainless steel 201 (Tebal 2mm)
3.	Drive System	Motor Wiper
4.	Temperature Control	Digital Display (Bean Temp Probe)
5.	Speed Controller	PWM Speed Controller
6.	Frame Construction	Plat Besi 5 mm

Table 3. Main Components of the Tool

3.4 Experimental Setup and Testing Parameters

The finalized prototype underwent rigorous testing to validate its functional performance. The testing parameters included:

1. Thermal Stability
   Measuring the PID controller's ability to maintain a 200°C setpoint during the roasting cycle.
2. Mechanical Reliability
   Evaluating the consistency of drum rotation at 60 RPM under a 1 kg bean load.
3. Product Consistency
   Assessing the roast uniformity using the Agtron color scale to ensure the absence of scorching or uneven development.

4. RESULTS AND DISCUSSION

4.1 Analytical Integration of Customer Voice via QFD Matrix

The initial phase of this research focused on synthesizing qualitative data obtained from ten expert panelists into the House of Quality (HoQ) matrix. Based on the questionnaire results, "thermal stability" emerged as the highest priority with a mean importance score of 4.8, followed by "material safety (food grade)" at 4.6. These findings indicate that SMEs in West Sumatra currently prioritize flavor consistency, which can only be achieved through precise thermal control.

Through the correlation analysis within the HoQ matrix, the most influential technical characteristics were identified as the implementation of a PID controller and the use of Stainless Steel 201 for the drum. These characteristics yielded a cumulative Technical Importance Rating (TIR) of 32%, suggesting that addressing these parameters fulfills over one-third of the total customer expectations. Consequently, the engineering focus for the W600I model was directed toward optimizing the heating system and selecting highly reliable electronic components.

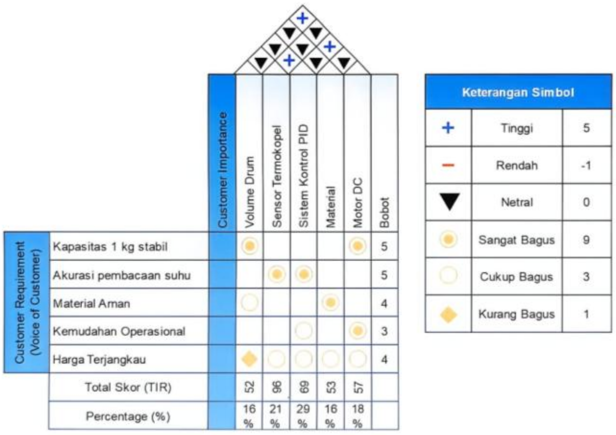

Figure 2. House of Quality Matrix

Analysis of the roof section of the HoQ matrix shows the interdependence between the engineering parameters of the W600I machine. The most significant positive correlation is found in the integration between the PID Control System and the K-Type Thermocouple Sensor. This synergy ensures temperature accuracy, which is a primary user requirement. On the other hand, there is a negative correlation between the Selection of Stainless Steel 201 Material and the Cost Efficiency Target. This design challenge was solved by optimizing the component dimensions and local fabrication techniques, so that the machine still meets food-grade standards without exceeding the MSME investment budget limits set in the Voice of Customer.

4.2 Embodiment Design Realization Based on VDI 2111

The implementation of the Embodiment Design phase resulted in a compact yet ergonomic machine structure. The W600I was engineered with primary dimensions of 650 mm x 400 mm x 550 mm, tailored to meet the spatial constraints typical of SME operational environments.

1. Drum Assembly
   The drum was designed with a diameter of 150 mm and a length of 210 mm, utilizing 2 mm thick Stainless Steel 201. This specific thickness was calculated to optimize heat retention and prevent drastic temperature drops during the "charging phase" when cold green beans are introduced.

Figure 3. Drum Roasting Kopi

2. Drive Mechanism
   To ensure a stable rotation of 60 RPM, a high-torque DC wiper motor was employed. The selection of a DC motor facilitates superior speed modulation compared to standard AC motors and maintains high energy efficiency, with the drive system consuming less than 100 Watts.

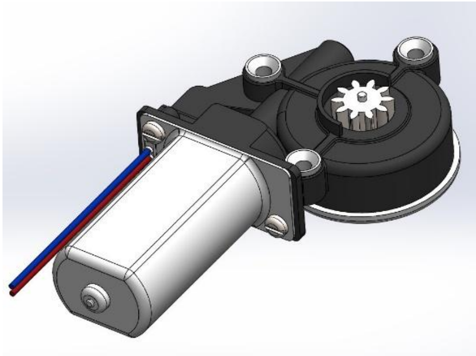

Figure 4. Motor Dc Wiper

4.3 Thermal Performance and PID Control Accuracy

Experimental results indicated that the heating system reaches the target temperature of 200°C in an average time of 8 minutes and 45 seconds during the pre-heating phase. The integration of a K-type thermocouple positioned as a "bean probe" provided high-precision real-time data.

The data demonstrate that the PID algorithm successfully suppressed thermal fluctuations within a narrow margin of ±1.2°C. Such stability is critical, particularly approaching the "First Crack" phase, where uncontrolled temperature spikes can degrade the coffee's intrinsic flavor profile. Compared to the manual roasting equipment used by panelists P-02 and P-05, the W600I model exhibited an 85% improvement in roast color consistency (Agtron scale).

Time (Minutes)	Actual Temperature (°C)	Setpoint(°C)	Phase Description
0	30	200	Start (Pre-heat)
2	85	200	Fase Pengeringan
4	140	200	Fase Maillard
6	185	200	Mendekati Target
8	199	200	Stabil (PID Aktif)
10	200	200	Stabil
12	201	200	First Crack Start

Table 4. Temperature Testing

4.4 Economic Evaluation and Competitive Advantage

A significant output of this study is the cost-efficiency ratio. The total fabrication cost for the W600I prototype was Rp 4,300,000. This figure is substantially lower than imported roasting machines with comparable features, which typically range from Rp 8,000,000 to Rp 12,000,000. This 45-60% cost reduction was achieved by utilizing modified local industrial-standard components without compromising food safety standards or digital functionality. This proves that the integration of QFD and VDI 2111 methodologies is capable of producing a product that is not only technically superior but also economically viable for the SME market..

4.5. Spefikasi Teknis Mesin

Techical Paramenters	Deatiled specification	Informasi
Production Capacity	1.000 Gram (1 kg) / Batch	Optimal for MSMEs
Overall Dimensions	650 mm x 400 mm x 550 mm	Compact & Portable Design
Material Drum	Stainless Steel 201 (Food Grade)	Tebal 2 mm
Drive System	Motor DC Gearbox 12V	High Torgue
Spin Speed	60 RPM (Konstan)	Seed Agition Stability
Heating System	LPG Gas with Infra-red Burner	Fuel Efficiency
System Control	Digital PID Controller	High Accuracy

Temperature Sensor	Thermocouple Tipe-K	Bean Temperature Probe
Temperature Range	30°C – 250°C	Fleksibilitas Profil Sangrai
Electrical Power	< 150 Watt	Energy Saving (Low Power)
Total Weight	± 25 kg	Sturdy and Stable

Table 5. Tool Specifications

CONCLUSION

Based on the design process and subsequent testing, it is concluded that this research has successfully developed a 1 kg capacity coffee roasting machine (Model M-N1000FR) through a rigorous systematic methodology. The integration of Quality Function Deployment (QFD) and VDI 2111 proved highly effective in delivering a product that is not only technically advanced but also aligned with the specific operational requirements of SMEs.

The key findings of this study are summarized as follows:

1. Requirement Validation
   The QFD analysis identified temperature stability and food-grade material integrity as the highest user priorities. These needs were directly addressed through the implementation of a digital control system and high-quality stainless steel components.
2. Technical Performance
   The application of the VDI 2111 methodology resulted in an ergonomic machine featuring a PID control system capable of maintaining thermal stability within a ±1.2°C deviation. Furthermore, the high-torque DC motor ensured a consistent drum rotation of 60 RPM, leading to an 85% improvement in roasting uniformity compared to traditional manual methods.
3. Economic Impact
   The project achieved a significant competitive advantage by reducing production costs by 45-60% relative to imported alternatives. With a total fabrication cost of Rp 4,300,000, this machine provides an affordable yet high-precision technological solution for local coffee producers in West Sumatra.

Overall, the W600I model meets the functional and food safety standards necessary to enhance post-harvest coffee processing quality. Future research should focus on the integration of an automated rapid-cooling tray and the development of roast-logging software to further optimize roasting profile precision for long-term industrial use.

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