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Original Research Article

Design and Development of a Sustainable IoT-Enabled Smart Vending Machine System Using a Modified Waterfall Model and Structural Equation Modeling for Performance Evaluation

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ABSTRACT

This study developed and evaluated an Enhanced Mobile-Integrated Water Vending Machine (EMWVM) to improve operational efficiency and sustainability in water vending operations through real-time monitoring, automated dispensing, sales tracking, and mobile integration. The system was developed using a Modified Waterfall Model covering requirements analysis, design, implementation, testing, deployment, and maintenance. The Integrated Garvin-Based Product Quality Structural Model (IGPQ-SEM) was used to examine relationships among product quality dimensions, Product Quality, Product Standards, Overall Product Quality, and Business Outcomes. Using a quantitative-descriptive SEM approach, results showed high evaluations for Conformance (M =4.70), Serviceability (M=4.53), and Performance (M=4.48), indicating strong functionality, reliability, and maintainability. Measurement results confirmed acceptable reliability and validity for most constructs, but Product Standards showed less reliability and convergent validity, requiring refinement. SEM model fit indices indicated acceptable but improvable fit (CMIN/DF=1.635, CFI=0.852, TLI=0.811, RMSEA=0.097), suggesting moderate model fitness. Overall, the EMWVM is functional, user-friendly, efficient, and commercially promising.

KEYWORDS

Internet of Things (IoT), Smart Vending Machine, Sustainable Development, Garvin's Quality Dimensions, Automation

INTRODUCTION

In today's fast-paced urban and semi-urban environment, demand for safe, accessible, and affordable drinking water is steadily increasing. This demand is fuelled by rapid urbanization and industrial growth [1]. Traditional water distribution systems often struggle to meet this demand, creating opportunities for innovative business models. As a result, water vending machines have emerged as a practical solution by providing on-demand access to clean water. This technology addresses the need for water accessibility [2] to safe drinking water to enhance public health resilience against waterborne diseases [3]. The water vending machines operate on a pay-per-use basis, allowing users to insert coins to purchase water. The water is then dispensed into the user's container, whether it's a reusable water bottle or a jug. Water vending machines are becoming increasingly popular in the Philippines to provide people with access to clean drinking water. This is particularly important in a country where many people do not have access to safe drinking water. Globally, 2.1 billion people lack access to safe drinking water, which can lead to a range of health problems, including waterborne diseases [4]. Water vending machines are a cost-effective and convenient alternative to bottled water, which can be

expensive and environmentally damaging. To address the broader issue of water security, which is challenged by diminishing resources and industrial waste [5]. By using water vending machines, people can avoid the cost of bottled water while also reducing their environmental impact.

However, traditionally designed water vending machines are useful; they have notable limitations. For instance, they often suffer from frequent breakdowns, irregular spare part availability, and slow response times to user complaints [6]. Most units are equipped with only a single 12-liter bottle, which quickly runs out of water and requires frequent refilling. This results in operational inefficiency, increased maintenance effort, and potential revenue loss due to service interruptions. The dependence on manual refilling introduces potential delays and labor costs that can significantly impact operational expenditure and diminish profitability [7]. Likewise, operators often struggle to monitor the water level of each unit. As a result, machines frequently also run empty, leaving bottles unfilled and disrupting service. This not only reduces customer satisfaction but also leads to significant revenue losses for the business operator. Furthermore, operators also face difficulties in monitoring the sales performance of each unit. Since the machines rely on 1-peso coins, operators are required to manually count each coin, which is time-consuming, tedious, and inefficient. This manual process not only delays revenue tracking but also hinders operators from making timely business decisions and optimizing profitability. Such limitations necessitate the development of more advanced water vending solutions that incorporate real-time monitoring and automated inventory management to enhance efficiency and profitability [6].

Thus, various water vending machine innovations have been developed, primarily designed by integrating sensors and communication modules. A study of a water vending machine integrated with two sensors to measure environmental temperature [8] and weight, along with a smartphone [9]. Another study uses an RGB camera and a Raspberry Pi board to identify the presence of a container and manage the water flow in real time [10]. Conversely, consumers were reluctant to consume water if electronic components were placed inside the water bottle, while ensuring water is safe for consumption to avoid health issues. Additionally, various systems for monitoring water quality using wireless communication technology, such as WIFI and Zigbee, focus on real-time data acquisition of parameters like pH, temperature, and dissolved oxygen for comprehensive water management [11]. However, each of these advancements has its limitations, as most existing systems focus primarily on water quality while failing to provide effective solutions that improve operational efficiency and revenue generation.

Hence, this study developed a mobile application-based monitoring system for Water Vending Machines, enhancing efficiency, sustainability and profitability through real-time sales and supply tracking. The design contains 4 bottles with an effortless refilling system, allowing for an extended duration before depleting the water supply, reducing the need for frequent refills. Additionally, the system integrates sensors to track the water level in real time, with data displayed on both an LCD panel and a mobile application. This feature enables operators to conveniently monitor the water supply status anytime and anywhere, reducing downtime, improving efficiency, and protecting revenue by ensuring uninterrupted service. Likewise, the system is equipped with sensors to track every 1-peso coin inserted, providing operators with real-time visibility of cash flow and sales. This ensures accurate revenue monitoring, reduces manual counting, and allows operators to manage their business more efficiently anytime and anywhere using their mobile phone.

As a result, supply-focused and hassle-free designed, combined with real-time monitoring of water levels and sales using the mobile application, providing interactive support to users [12] anytime and anywhere, enhances operational efficiency, minimizes downtime, and ultimately drives higher revenue for the business. The implementation of this solution offers

high market potential and scalable business opportunities, positioning it as a profitable venture that can attract and secure investor confidence. It also creates significant value for the vending industry by strengthening business sustainability and long-term profitability.

MATERIALS AND METHODS

This section presents the system context to support the understanding of the development concepts used in designing and developing an innovative, responsive, and secure vending machine system [13]. It also presents a two-part methodological framework consisting of the system development method and the prototype evaluation method. The development method utilized a Modified Waterfall Model to ensure a systematic and sequential approach [14] to the proposed system. Likewise, the evaluation method employed Garvin's product quality dimensions, which are essential in assessing the performance of IoT-enabled vending machines [15], using a descriptive-correlational and causal-predictive approach through Structural Equation Modeling (SEM) via AMOS. Furthermore, ChatGPT was utilized as an aid tool to enhance the presentation of figures, improve sentence construction, and refine the overall clarity and coherence of the study.

Context of the core functional modules of EMWVM

This context highlights the two core components of the system: the water level monitoring module and the coin-tracking module, both of which were developed to support real-time status tracking and accurate revenue monitoring.

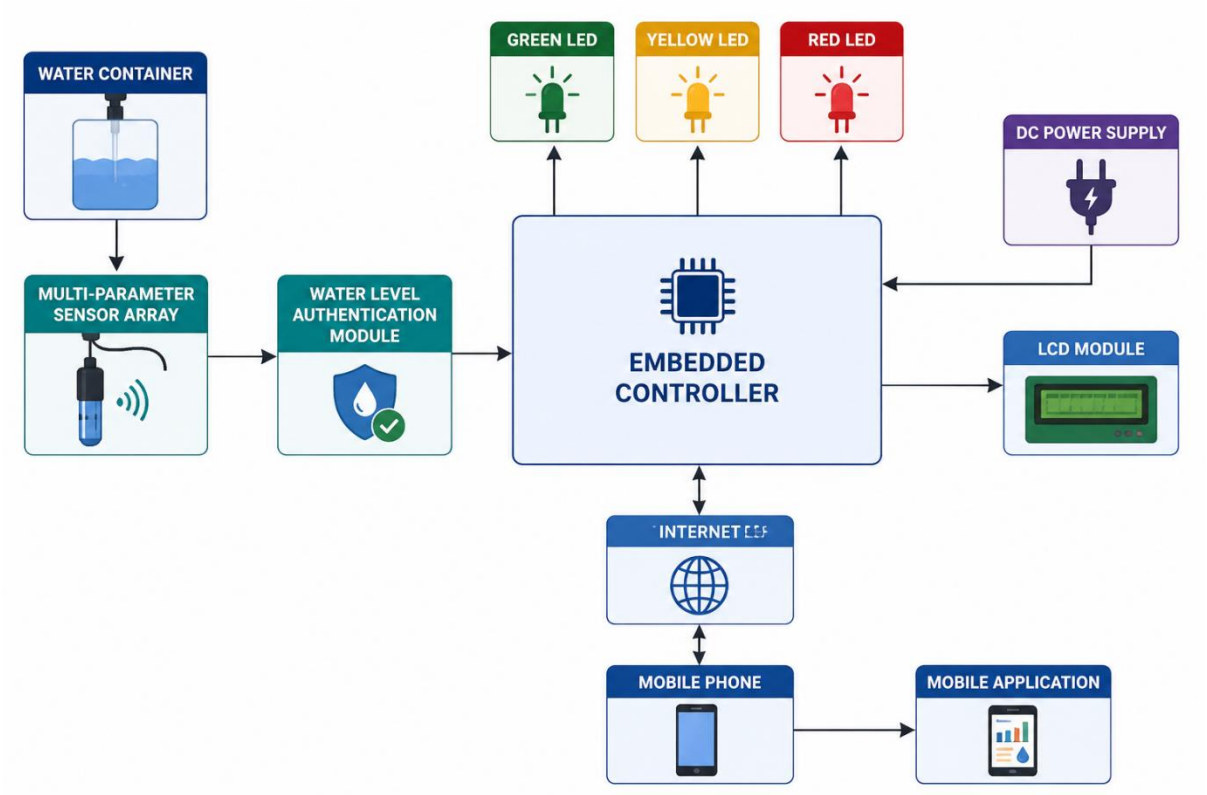


Figure 1. The context of water level tracking systems for EMWVM, with visualization assistance from OpenAI ChatGPT

Figure 1 illustrates the water level tracking system, which is composed of input/output components and a network interface. The microcontroller manages and processes the overall system operation, while a sensor detects the water level inside the water container and transmits the corresponding signal to the microcontroller. The LCD module receives signals from the microcontroller and displays the water level status labeled as "Full," "Half," or "Near Empty." Similarly, a set of LEDs also receives electrical signals from the microcontroller and provides visual indicators of the water level: green for "Full," yellow for "Half," and red for "Near Empty". Moreover, an internet connection serves as the wireless communication link between the microcontroller and the mobile phone. Through this connection, the mobile application delivers real-time remote monitoring, showing the number of water containers present in the vending unit, the percentage level of water available, and the corresponding status label ("Full," "Half," or "Near Empty"). A DC power supply provides the necessary electrical energy to operate the microcontroller and the LCD module.

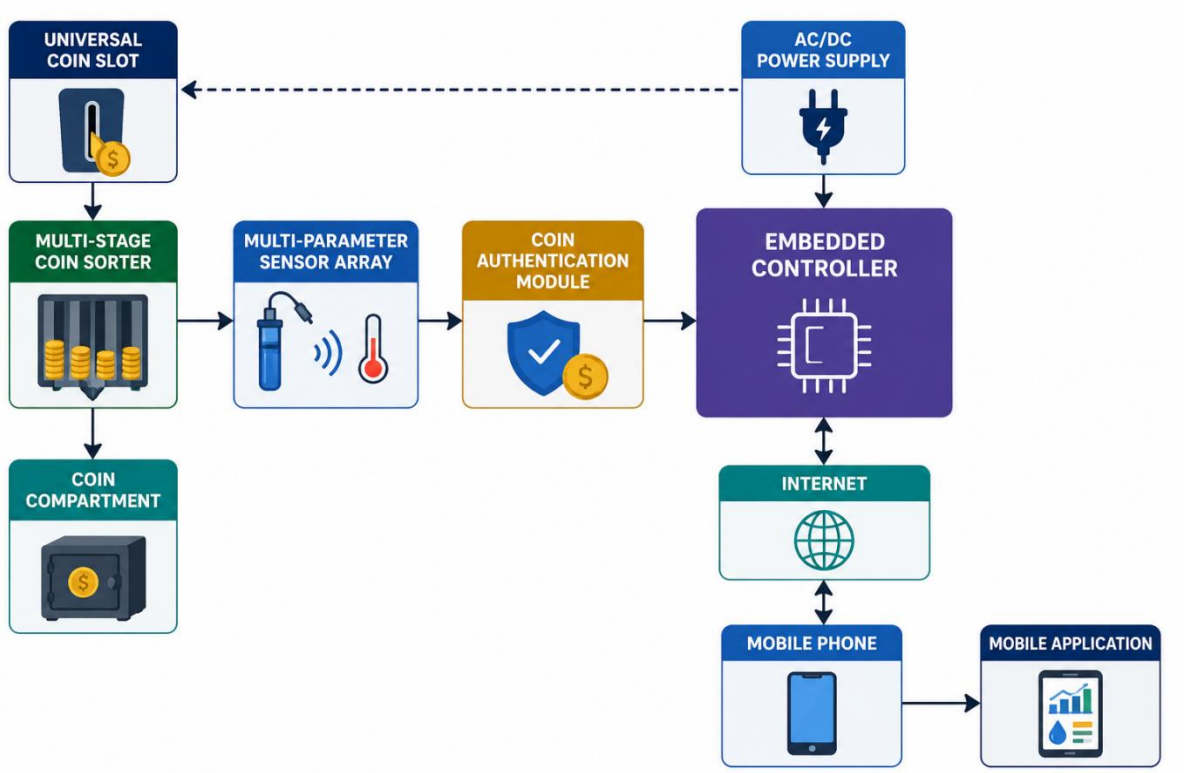


Figure 2. The context of coin counting systems for EMWVM, with visualization assistance from OpenAI ChatGPT

Figure 2 presents the coin sorting and counting system. The system consists of input/output components and a network interface, all controlled by a microcontroller, which manages the overall system operation. The plurality of sensors detects each inserted coin as it passes from the universal coin slot through the coin sorter tray and into its designated storage compartment. Once the microcontroller receives and processes the electrical pulses generated by the sensors, it transmits the processed data to the mobile application installed on the mobile phone via an internet connection. The internet thus serves as the wireless communication link between the microcontroller and the mobile device. Through this connection, the mobile application provides real-time remote monitoring, displaying the count and total accumulated coins.

Development and evaluation framework of EMWVM

This part illustrates the development methods adopted in this study using a Modified Waterfall Model and the evaluation method of the prototype using Garvin's 8 quality dimensions. The model follows a structured and sequential approach to systematic development, progressing through distinct phases such as requirements analysis, design, implementation, and testing [16], resulting in a functional prototype of the EMWVM. Additionally, the system was assessed based on Garvin's Eight Dimensions of Product Quality. This approach provides a comprehensive evaluation of both technical and user-oriented quality attributes of the developed prototype to ensure that the system not only meets its specifications but also provides a robust, user-friendly experience, addressing factors such as performance efficiency, usability, and security [17].

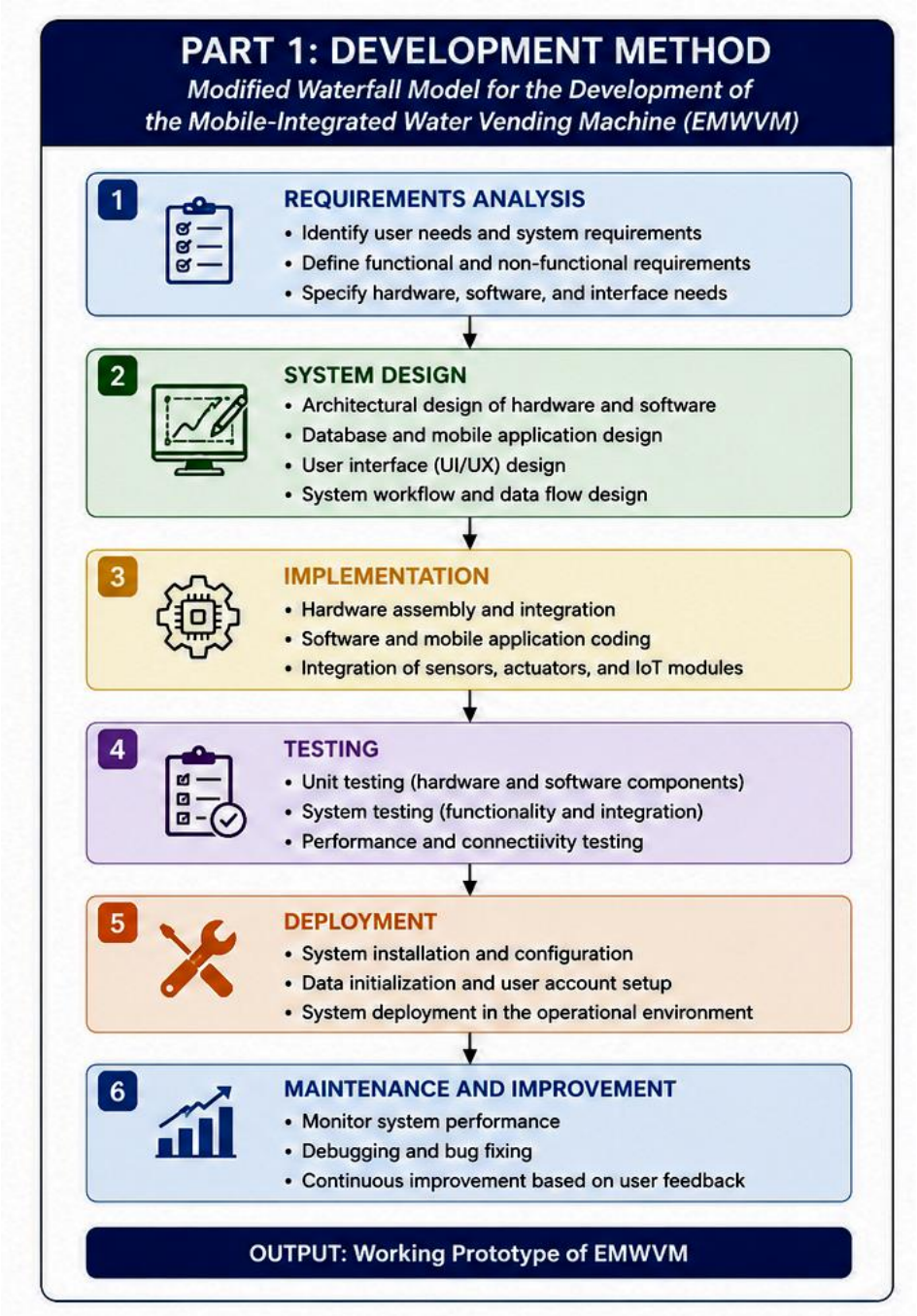


Figure 3. Part 1 System development framework based on Waterfall Model, with visualization assistance from OpenAI ChatGPT

The first phase, requirement analysis, focused on identifying user needs and defining both functional and non-functional system requirements. This stage included determining the necessary hardware, software, database, and communication interface requirements essential for the operation of the mobile-integrated water vending machine. Thus, requirement analysis begins several months after the extension project on "Water Vending Machine Making" in Holistic International for Love and Share Ministry, Incorporated (HIALSMI), the developer conducted a focus group discussion to assess issues and concerns with the water vending machines. From the feedback gathered, solutions were analysed, leading to the identification of both functional and non-functional requirements to improve performance and ensure business sustainability. Consequently, the transitions of the prototype functional output highlight the core operational capabilities of the system, such as real-time water level monitoring, mobile application integration with status alerts, and automated coin detection with sales tracking, with a user-friendly construction design for effortless refilling, and an expanded capacity with four bottles. The non-functional focused on ensuring efficiency, enabling operators to manage and monitor operations anytime and anywhere, while also improving the refilling experience for users. Users initiate the transaction by inserting coins, which triggers the dispensing process monitored by sensors that track water levels across multiple bottles. The system ensures accurate dispensing and displays real-time water levels, preventing downtime caused by empty bottles. Simultaneously, the IoT application collects data on total sales and water levels, providing owners with real-time visibility into both cash flow and supply status. This integration reduces the need for manual monitoring, eliminates tedious coin counting, and minimizes operational inefficiencies. These activities were conducted in the testing phase to confirm that the implemented system satisfied all documented functional and non-functional requirements [18].

The second phase, system design, translates these ideas into practical outputs such as circuit diagrams, system architecture, data flow analysis, and user interface (UI) design to ensure usability and efficiency. After the requirements analysis was completed, the design phase began. During this stage, system specifications were translated into detailed design diagrams, including algorithmic flowcharts and architectural schematics that guided subsequent implementation [19]. Based on the materials and electronic components gathered, the developer (1) created the circuit diagram, (2) drafted the machine structure, (3) designed the user interface (UI), and (4) prepared the system flowchart. The circuit diagram used images of actual components for clarity, though a detailed version was withheld to protect intellectual property. Two main circuits were developed: one for the water dispensing system and another for the water supply and sales tracking system. The water dispensing circuit included components such as the water dispenser, coin slot, timers, water pumps, and a modified power supply. The electrical power source (220V) was connected to a switch and then to a 4-gang outlet, which powered the hot and cold water dispenser as well as the modified power supply. This supply distributed electricity to the coin slot, timers, pumps, sensors, and modules, ensuring both dispensing operations and tracking functions worked properly. The tracking circuit incorporated NodeMCU ESP32, ultrasonic sensors, an IR sensor, an I2C LCD display, and LED indicators (green, yellow, red). The NodeMCU ESP32, powered by the modified power supply, connected to (5 pcs) ultrasonic sensors for water level detection and (4 pcs) IR sensors for coin detection. Additionally, (1pc) I2C LCD and LED indicators displayed real-time monitoring data on water levels and sales activity, providing immediate feedback for operators. Alongside circuit development, the design phase also produced prototype drawings that served as the blueprint for constructing the machine casing and the UI layout for the mobile application. The casing drawings depicted the physical structure and component placement, presented in multiple views for clarity. Meanwhile, the UI design illustrated the environment for tracking water levels and sales, emphasizing functionality and user accessibility. The system flowchart was initiated to visualize how the system processes inputs into outputs. This

included diagrams for the overall system mechanism, water level tracking, and sales tracking, providing a clear representation of how each subsystem integrates into the complete solution.

The flowchart on the system illustrates the operational sequence of a coin-operated water vending machine with IoT-enabled monitoring, providing a foundation for developing mobile integration with a revenue-centric focus. The process begins when a customer inserts a coin, which undergoes validation. If the coin is invalid, no water is dispensed; if valid, the system activates a timer, and the pump begins transferring water from one of the storage gallons (1,2,3, or 4) into the dispenser. The dispenser then pumps the water into the customer's bottle, while the IoT system simultaneously records and transmits transaction and operational data. By extending this IoT functionality to mobile integration, stakeholders can remotely track real-time revenue, water supply monitoring, and machine performance. This enables optimized revenue generation through insights such as peak usage times, refill scheduling, and location-based profitability. Additionally, predictive maintenance alerts can minimize downtime and ensure consistent service availability. Likewise, the flowchart on water level tracking, the process starts when a customer inserts a coin, which the system detects. If a coin is accepted, the total coin count is updated and displayed in the mobile app, enabling real-time revenue tracking. Instantaneously, the system monitors the water level across multiple gallons (1,2,3,4). In the machine, if the gallons are full of water, the LCD displays "FULL", a green LED indicator lights up, and in the mobile app shows 100% capacity. Then, if the gallons are half of water, the LCD shows "HALF", the yellow LED turns on, and the mobile app displays 50%. If the water level drops too low, the LCD shows "LOW", the red LED activates, and the app displays 25% means low. This integration ensures that vending operators not only collect accurate revenue data from coins in real time but also gain instant insights into water availability and system status through mobile access. From a revenue-centric optimization perspective, this system minimizes downtime by issuing alerts for refilling, maximizes sales by ensuring water availability, and provides operators with accounting on usage and earnings.

The third phase, implementation, involved the actual development and integration of the system components. This included assembling the hardware, programming the mobile application, and integrating sensors, actuators, and IoT modules responsible for water level monitoring and coin tracking. During implementation, developers translated the design artifacts into executable code modules and performed unit testing to verify compliance with the specified requirements [20]. The initial step involved constructing the casing, installing AC wiring, and designing a modified power supply to provide stable input/output regulation and AC-DC voltage conversion. Once the structural and electrical foundations were in place, the major components, including the water dispenser, boards with wires, and pipes, were mounted. The next stage focused on circuit simulation with programming, carried out on a breadboard to validate the functionality of the microcontroller and peripherals. Arduino IDE was used to program and test the components to ensure accurate operation based on their intended functions. Following hardware integration, development shifted to the mobile application, which serves as the monitoring interface for sales and water supply levels. The application was built in Android Studio, while Firebase was implemented as the real-time database to enable data storage, synchronization, and remote access. . It connects to a Firebase Real-time Database, where data from the ESP32 microcontroller is continuously uploaded. This includes the water level percentages of each gallon and the total number of IR detection events (usage activity). Within the mobile app interface, users can view the current water levels displayed as percentages for each gallon, allowing them to remotely assess which containers are full, partially filled, or nearly empty. The app also displays the total usage count based on IR sensor detections, giving insight into how frequently the machine is accessed. This promotes better maintenance scheduling and refill timing. Firebase acts as the central cloud database that stores and syncs data in real-time between the ESP32 hardware and the mobile app. The app retrieves the most recent sensor data from Firebase using listeners or API

calls, ensuring that users always see up-to-date information. The system also allows the possibility of sending notifications in future improvements, such as alerts when water levels are low or when the coin container is full. This phased approach ensured that both the hardware and software elements were properly integrated into a functional prototype of the water vending monitoring system. Most importantly, the water level sensors were designed not to come into direct contact with the water. Instead, they were mounted on the gallon cap and enclosed in a food-grade plastic wrapper to ensure the water remained clean and safe for consumption. The whole results from prototyping, showcasing real-time monitoring of the four gallons in a single vending machine. The interface displays both percentage and text indicators of water supply levels, along with the amount of cash accumulated in the coin box. These features transform a traditional water vending unit into a smart, revenue-optimized system by combining operational visibility with financial tracking.

The fourth phase, testing, verifies system reliability and performance, ensuring that all features work as intended to support business operations. After the implementation and prototyping stage, the project proceeded to the testing phase, where the system was evaluated to verify the proper operation of its components and ensure reliable communication between the machine and the mobile application. During this phase, the system underwent rigorous testing to ensure compliance with the specified requirements [21]. Functional testing was conducted to assess the performance of sensors, the LCD display, LED indicators, and data transmission processes. A test case analysis approach was applied, using various scenarios to determine how each function responded under specific conditions compared to the expected results. The testing process specifically focused on the following: (1) verifying the stability of the power supply, (2) inspecting circuits and wiring to ensure that no electronic component overheated, (3) checking hoses and calibrating the timer module to confirm accurate water distribution from the gallon containers to the dispenser tank avoiding to much water comes to the tank causing water overflow, (4) measuring the volume of dispensed water to ensure adequacy, and (5) confirming that the mobile application correctly received and displayed data related to sales and water supply levels.

Table 1(a). Testing components functionality of EMWVM

Component Tested	Description	Number of Trials	Expected Output	Actual Result	Remark
Gallon Refilling System	Validate ease and accuracy of gallon refilling across 4 compartments	64 cycles (16 per gallon)	No spillage, smooth loading, no leaks	All compartments refilled smoothly; 0 leaks; ergonomic and efficient	PASSED
Pipe Connection Integrity	Check system pressure, flow consistency, and leakage points	16 tests	No leakage or pipe disconnection	No leakage after reinforcement; stable flow maintained	PASSED
1-Peso Coin Detection Module	Validate accuracy of coin counting for revenue tracking	48 trials	100% accurate coin detection	100% detection accuracy; 0 false counts	PASSED

Table 2(b). Continuation of testing components functionality of EMWVM

Component Tested	Description	Number of Trials	Expected Output	Actual Result	Remark
Ultrasonic Water Level Sensor	Verify real-time detection of Full/Half/Near Empty levels	48 trials	Accurate water level readings within ±5%	±2% accuracy; fast response time (0.8s)	PASSED
Timer Functions (5 Timers)	Validate pump activation timing and cycle consistency	240 total triggers	Correct activation per assigned pump	All timers triggered pumps accurately; no delays	PASSED
Water Pump Operations	Validate pump performance in refilling and dispensing	144 cycles (46 per pump)	Stable flow rate; no overheating	All pumps performed reliably after minor wiring correction	PASSED
LED Indicator System	Verify color-coded water level indicators	48 trials	Correct LED color for each water level	Accurate signal for all levels (Green/Yellow /Red)	PASSED
LCD Display Module	Display water level percentage and status	48 trials	Clear real-time display	Accurate display, no flickering or delay	PASSED
Mobile Application Communication	Verify real-time data synchronization (water levels & sales)	48 connectivity tests	1-2 sec delay; accurate real-time monitoring	Succesful sync; all data accurate after debugging	PASSED
Sales Tracking (Coin Count Sync)	Validate mobile tracking of total coins inserted	48 trials	Real-time accurate coin count display	Accurate coin total displayed in app	PASSED

The testing phase confirmed that the water vending system's design meets all functional and operational requirements, demonstrating reliable performance across core components such as gallon refilling, coin detection, pipe connections, timers, pumps, and the integrated monitoring interface. Results revealed that the refilling mechanism for four-gallon compartments is efficient and user-friendly, while 48 successful trials of the 1-peso coin detector ensured accurate revenue collection, and 16 times pipe-connection tests verified leak-free operation, collectively improving uptime and profitability. Similarly, all five timers and four pumps performed consistently across 48 cycles, ensuring precise dispensing, reduced waste, and dependable water delivery essential for sustaining customer satisfaction and minimizing downtime. The successful operation of LEDs, LCD displays, and the mobile application after resolving initial wiring and logic issues validated the system's capability to provide real-time water-level visibility and sales tracking, enabling data-driven decision-making.

The fifth phase, deployment, introduces the water vending machine prototype to actual customers for feedback as well as the operator. After the testing phase, the project proceeded to

the deployment phase, where the machine was installed in the target environment for actual use and for monitoring and evaluation. To support proper operation, a user manual was developed and provided to the beneficiaries, ensuring that deployment and maintenance procedures were clear and easy to follow. The manual outlined essential safety precautions, detailed the key features of the machine, and provided step-by-step instructions for system setup. It also included guidelines for establishing communication between the machine and the mobile application, along with procedures for routine maintenance and basic troubleshooting. During deployment, the validated system was installed on the production environment, configuration settings were finalized, and end-users were transitioned to operational use [22].

Finally, the sixth, maintenance and improvement phase, emphasized continuous monitoring and enhancement based on operational performance and user feedback. This improvement process ensured the long-term reliability, usability, and sustainability of the developed prototype. Thus, part 2 evaluation method of the prototype using Garvin's 8 quality dimensions is conducted.

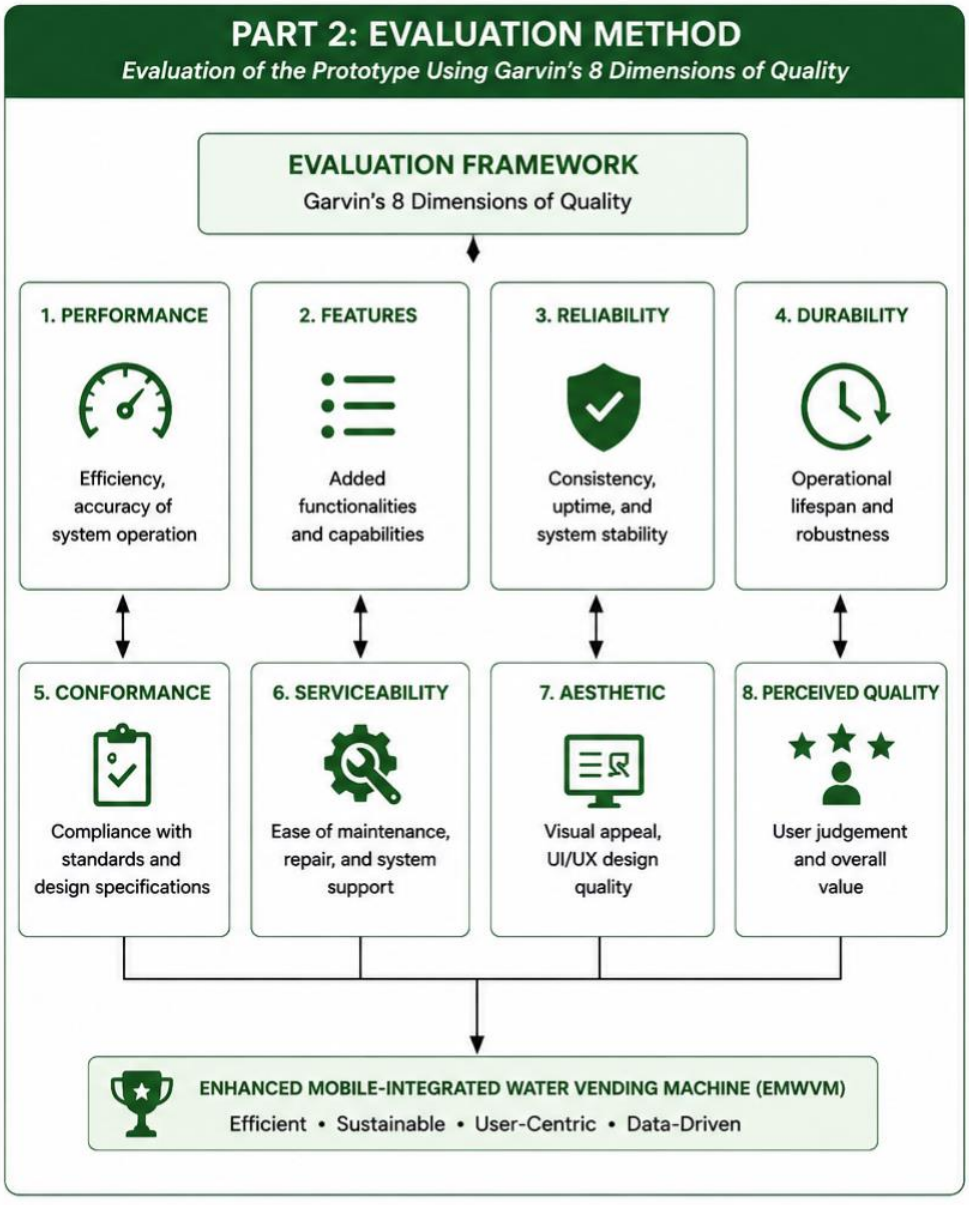


Figure 4. Part 2 System Evaluation Framework based on Garvin's Eight Dimensions of Product Quality, with visualization assistance from OpenAI ChatGPT

Furthermore, this figure illustrates the evaluation framework used to assess the EMWVM based on Garvin's Eight Dimensions of Product Quality. The framework evaluates the prototype in terms of performance, features, reliability, durability, conformance, serviceability, aesthetics, and perceived quality. These dimensions collectively measure the system's operational efficiency, added functionalities, stability, compliance with standards, ease of maintenance, visual appeal, and overall user satisfaction. Through this multidimensional evaluation, the study determines the effectiveness and quality of the developed prototype. The framework highlights that integrating real-time monitoring, mobile connectivity, and automated coin tracking contributes to an efficient, sustainable, user-centered, and data-driven water vending system. This demonstrates a clear causal logic; technically sound development directly contributes to sustainable business value and operational viability.

Statistical treatment of data

The collected data were analysed using descriptive and inferential statistical techniques to evaluate the quality and business performance of the Enhanced Mobile-Integrated Water Vending Machine (EMWVM). The target respondents of the study included customers/users, water vending machine operators, and IT experts. These respondents consisted of students and residents living near the water vending stations, as well as water vending business owners and IT professionals, since they represent the primary users, stakeholders, and direct beneficiaries of the developed system. Descriptive statistics, including mean and standard deviation, were employed to summarize respondents' evaluations of the system's quality dimensions and operational performance. Standard deviation values were used to determine the variability and consistency of responses across indicators.

Reliability analysis was conducted to assess the internal consistency and stability of the measurement instrument. Cronbach's Alpha (α) and Composite Reliability (CR) were utilized, with threshold values of 0.70 or higher considered acceptable for construct reliability. Convergent validity was evaluated through factor loadings and Average Variance Extracted (AVE), where factor loadings of at least 0.50 and AVE values of 0.50 or above indicated adequate construct validity.

Moreover, Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM) using AMOS were applied to test the hypothesized relationships among Garvin's eight product quality dimensions, overall product quality, and business outcomes. SEM enabled the simultaneous assessment of both measurement and structural models. Model fitness was evaluated using several goodness-of-fit indices, including Chi-square/degrees of freedom ratio (CMIN/DF $\leq$ 5.0), Comparative Fit Index (CFI $\geq$ 0.90), Tucker-Lewis Index (TLI $\geq$ 0.90), and Root Mean Square Error of Approximation (RMSEA $\leq$ 0.08). These statistical procedures ensured the validity, reliability, and predictive capability of the proposed model.

Overall, the study hypothesized that Garvin's Eight Dimensions of Product Quality significantly influence Product Quality, which subsequently affects Product Standards and Overall Product Quality. Furthermore, Overall Product Quality was hypothesized to positively influence Business Outcomes. These relationships were examined using Structural Equation Modeling (SEM) through AMOS to determine the direct and indirect effects among the constructs.

The proposed integrated Garvin-based product quality structural equation model (IGPQ-SEM) for the EMWVM

The study employed a quantitative, non-experimental research design using a descriptive-correlational and causal-predictive approach, assessing the intricate relationships

between mobile integration features and user engagement [23]. Structural Equation Modeling (SEM) via AMOS was used to evaluate the measurement and structural relationships among the adopted Garvin's 8 product quality dimensions, overall product quality, and business outcomes by facilitating the evaluation of complex models with reflective measurements and accommodating non-normally distributed data [24]. Using purposive sampling, a total of 264 responses of targeted respondents were gathered, consisting of IT experts/water vending operators (11.37%) and customers/users (88.63%). Additionally, the statistical treatment used in this study includes descriptive statistics, reliability analysis (Cronbach's Alpha, Composite Reliability), validity testing (convergent and discriminant validity), Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM) using AMOS to test the hypothesized relationships among constructs. Model fit indices were also employed to evaluate the goodness-of-fit of the measurement and structural models.

Figure 5 presents the Integrated Garvin-Based Product Quality Structural Equation Model (IGPQ-SEM), which links Garvin's Eight Dimensions of Product Quality as exogenous constructs to Product Quality (ProdQ), Product Standards (ProdS), and Overall Product Quality (OvQ), ultimately influencing Business Outcomes (Bus).

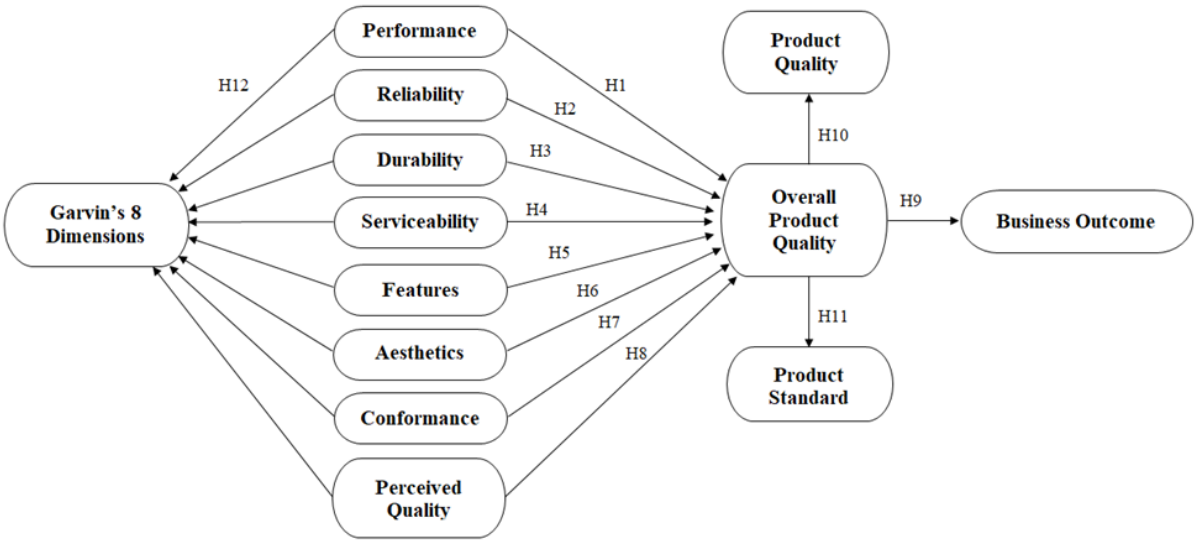


Figure 5. Integrated Garvin-Based Product Quality Structural Equation Model (IGPQ-SEM)

As shown in Figure 5, the left side of the model illustrates the first eight-order quality constructs, which collectively represent Garvin's 8 dimensions of product excellence. Each dimension is theorized to contribute uniquely to shaping quality, conceptualized as part of the broader construct of overall product quality (OvQ). These were represented through hypothesized paths H1-H8, indicating the influence of each dimension on overall product quality. The model then shows that OvQ serves as a central mediating construct. Through path H9, OvQ is hypothesized to exert a direct positive effect on business outcome (Buss), representing benefits such as customer satisfaction, operational efficiency, adoption likelihood, and market viability. In addition, the model includes two supplementary constructs, product quality (ProdQ) and product standard (ProdS), which link to OvQ through hypothesized paths H10 and H11. These represent the technical evaluation results of the developed prototype, including compliance with functional requirements, performance benchmarks, and relevant standards for water-vending systems. Their inclusion strengthens the assessments of OvQ by incorporating both subjective perception

(user-based quality) and objective technical outcomes. Moreover, this study also utilized a researcher-made survey instrument, as shown in the Appendices.

RESULTS AND DISCUSSION

This section presents the empirical findings derived from the applied methodologies, offering a comprehensive analysis of the collected data. The results delineate the extent to which products adhere to established quality standards, identifying key performance indicators and highlighting any significant deviation or areas for improvement. These results were measured through rigorous descriptive statistical analysis and structural equation modeling (SEM), and fit of the model. The descriptive analyses provide the primary dataset, providing a foundational understanding of the responses [25]. Subsequently, reliability analysis utilized Cronbach's alpha, average variance extracted, and composite reliability to ensure consistency and stability of the measurement instrument [26] as well as the structural equation modeling to assess complex relationships between latent variables and observed indicators [27], while model fit indices evaluate overall suitability and validity of the proposed models [28]. Table 3 presents the measurement metrics for the correlations between constructs, revealing a significant positive relationship between key indicators of Garvin's product quality dimensions and overall product quality evaluation.

Results of descriptive evaluation of the EMWVM constructs used in the structural equation model

This section presents the mean evaluation results of the Enhanced Mobile-Integrated Water Vending Machine (EMWVM) based on Garvin's Eight Dimensions of Product Quality, including Performance, Reliability, Durability, Serviceability, Aesthetic, Feature, Conformance, and Perceived Quality. The table also includes respondents' assessments of Product Quality (ProdQ), Product Standards (ProdS), Overall Product Quality (OvQ), and Business Outcomes (Bus). These evaluation constructs were utilized to determine the operational effectiveness, usability, compliance, overall quality performance, and potential business viability of the developed system. The results provide descriptive evidence supporting the Structural Equation Model (SEM) analysis conducted in the study.

Table 2 results indicate that the Enhanced Mobile-Integrated Water Vending Machine (EMWVM) obtained generally high evaluations across Garvin's Eight Dimensions of Product Quality, suggesting that respondents perceived the system as functional, reliable, and beneficial for operational use. Among the dimensions, Conformance obtained the highest mean score (M=4.70), indicating that respondents strongly agreed that the system met its intended design specifications and operational standards. This implies that the prototype was successfully developed according to the planned requirements and technical expectations, strengthening the credibility and acceptability of the system for practical deployment.

Similarly, Serviceability received a high mean score (M=4.53), indicating that respondents found the system easy to maintain, troubleshoot, and refill during operation. This finding suggests that the machine promotes operational convenience and minimizes maintenance difficulties, which may contribute to reduced downtime and improved sustainability of vending operations. Performance also obtained a very high rating (M=4.48), reflecting the effectiveness of the real-time monitoring, sales tracking, and water dispensing functions. This implies that the integration of mobile monitoring and sensor-based automation successfully enhanced operational efficiency and system responsiveness.

Moreover, Reliability (M = 4.39) and Perceived Quality (M = 4.26) demonstrated positive evaluations, indicating that the system consistently functioned without interruptions and provided satisfactory overall quality and value. These findings imply that the developed system can support dependable long-term operation while increasing user confidence and acceptance. Likewise,

Durability (M = 4.20) and Feature (M = 4.17) received favorable responses, suggesting that the machine can sustain repeated usage and that its integrated functionalities, such as mobile monitoring and coin tracking, are practical and useful for both operators and customers.

However, Aesthetic received the lowest rating among the quality dimensions (M = 3.92), although it still falls within the "Agree" category. This indicates that while the respondents considered the system visually acceptable and user-friendly, improvements in physical appearance, interface layout, and design presentation may further enhance user satisfaction and product appeal. The implication is that improving the external design and user interface may increase customer attraction and market competitiveness.

Table 2. Mean evaluation results of the EMWMV based on Garvin's product quality dimensions

A. Garvin's Eight Dimensions of Product Quality		
Key Indicators	Statement	Mean
Performance	The system performs real-time monitoring of water level, sales tracking, and water dispensing efficiently during operation.	4.48
Reliability	The system operates consistently without interruptions or errors during repeated use.	4.39
Durability	The system can withstand continuous operation and repeated dispensing cycles without failure.	4.20
Serviceability	The system is easy to maintain, troubleshoot, and refill during operation.	4.53
Aesthetic	The system has a visually appealing and user-friendly design.	3.92
Feature	The integrated features, such as mobile monitoring and coin tracking, are useful and functional.	4.17
Conformance	The system meets the intended design specifications and operational standards.	4.70
Perceived Quality	The system provides overall quality, reliability, and value based on its actual performance.	4.26
B. Product Quality (ProdQ)		
The system performs its intended functions correctly.		4.30
The system operates without crashes or unexpected errors.		4.48
The system is easy to learn and use.		4.41
C. Product Standards (ProdS)		
The system meets applicable quality and safety standards.		3.95
The system adheres to documented operational specifications.		3.56
D. Overall Product Quality (OvQ)		
The system consistently performs reliably during operation.		4.27
The machine satisfies expected quality and performance standards.		3.97
The system is easy to use and meets operational expectations.		3.80
E. Business Outcomes (Bus)		
The system reduces manual effort and operational time.		3.82
The system has the potential to increase sales and customer satisfaction.		3.92
The system provides good return on investment (ROI).		3.89

For Product Quality (ProdQ), all indicators received high mean scores, particularly the statement that the system operates without crashes or unexpected errors (M = 4.48). This finding implies that the EMWVM achieved stable operational performance and dependable system functionality. The ease of learning and using the system (M = 4.41) further suggests that the

prototype promotes accessibility and usability among intended users, which is essential for customer acceptance and practical implementation.

In contrast, the Product Standards (ProdS) construct obtained comparatively lower mean scores, particularly in adherence to documented operational specifications (M = 3.56). This result suggests that respondents perceived limitations in the system's compliance with formalized standards and documentation requirements. The implication is that while the system functions effectively, further refinement, validation, and standardization may still be necessary to strengthen regulatory compliance, technical documentation, and product certification for broader commercialization.

Regarding Overall Product Quality (OvQ), the system consistently performed reliably during operation (M = 4.27), indicating strong operational effectiveness. However, slightly lower ratings for meeting expected standards (M = 3.97) and usability expectations (M = 3.80) suggest that certain aspects of the system may still require enhancement to fully satisfy user expectations. These findings imply that continuous system refinement and interface improvements could further strengthen overall product acceptance and user experience.

Lastly, the Business Outcomes (Bus) indicators showed positive evaluations, with respondents agreeing that the system has the potential to increase sales and customer satisfaction (M = 3.92) and provide good return on investment (ROI) (M = 3.89). Although the ratings are relatively lower compared to technical quality dimensions, the findings still indicate promising economic and operational benefits. This suggests that the EMWVM has the potential to reduce manual effort, improve operational efficiency, and support sustainable business opportunities. However, further implementation in real operational environments may be necessary to fully validate its long-term profitability, scalability, and commercial viability.

Results of Integrated Garvin-Based Product Quality Structural Equation Model (IGPQ-SEM) for the EMWVM

This section presents a structural equation model (SEM) examining the relationships among Garvin's eight product quality dimensions towards overall product quality, which is dependent on the product quality and standards of the product, and potentially to become a business output-oriented. The model integrates both measurement and structural components, with standardized factor loadings and path coefficients displayed.

Figure 6 illustrates the Structural Equation Model (SEM), showing the relationships among the latent constructs and their observed indicators. The model evaluates how Garvin's product quality dimensions influence the overall product quality and business outcomes of the developed system.

At the left side of the model are latent constructs, which include Performance (Perf), Reliability (Rel), Durability (Dur), Serviceability (Serv), Aesthetic (Aes), Features (Feat), Conformance (Conf), and Perceived Quality (PerQ). These observed variables are connected to the latent construct with standardized factor loadings ranging from moderate to high values. Among the indicators, Aesthetics (.78) and Reliability (.72) exhibit relatively strong contributions to the Dimensions construct, indicating that users highly value the visual appeal and dependability of the vending machine system. Meanwhile, Serviceability shows the lowest loading, suggesting that maintenance-related aspects contributed less strongly compared to the other dimensions.

The model further shows that Overall Product Quality positively affects several outcome variables. The strongest relationship is observed between Overall Product Quality and Business Outcomes (.87), indicating that higher perceived product quality contributes significantly to improved business-related outcomes such as operational efficiency, customer satisfaction, and usability. The indicators of Business Outcome Bus1, Bus2, and Bus3 demonstrate acceptable factor loadings, with Bus3 (.87) having the strongest contribution.

Additionally, Overall Product Quality strongly influences Product Quality (.93), suggesting that users perceive the developed vending machine as highly capable in meeting expected quality standards. The indicators ProdQ1, ProdQ2, and ProdQ3 all show strong loadings, particularly ProdQ3 (.82), indicating consistency in respondents' evaluations of the product's quality attributes.

The model also reveals a moderate positive relationship between Overall Product Quality and Product Standard (.67). Although weaker than the other structural paths, this relationship still indicates that overall product quality contributes positively to compliance with product standards and system requirements. The indicators ProdS1 and ProdS2 demonstrate moderate factor loadings, implying acceptable but comparatively lower contributions to the construct.

Furthermore, the circles labelled e1-e31 represent error terms or residual variances associated with each observed and latent variable, accounting for unexplained variances within the model. The presence of acceptable factor loadings and strong structural relationships indicates that the proposed SEM model adequately explains the interrelationship among product quality dimensions, overall system quality, and business outcomes.

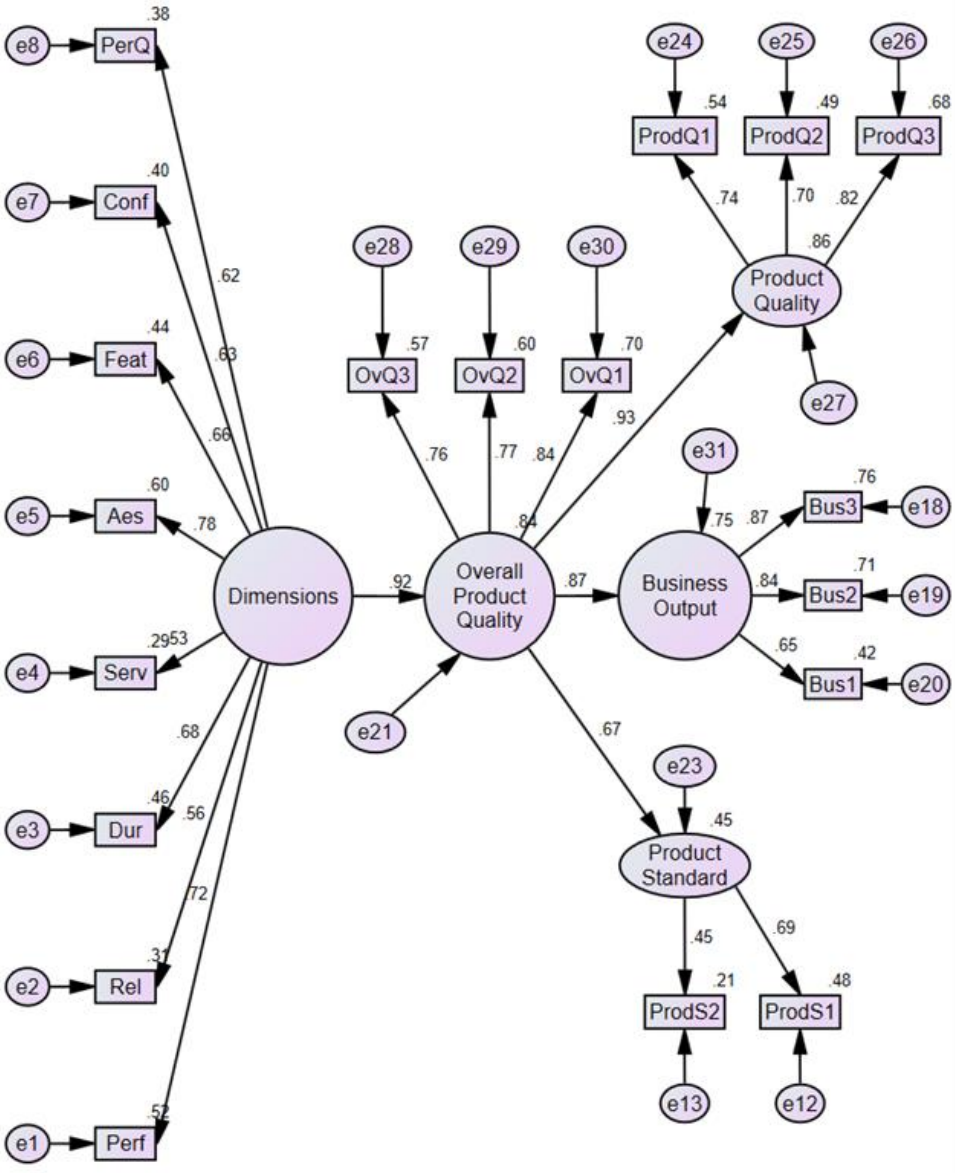


Figure 6. This model integrates both measurement and structural components

Generally, Figure 6 demonstrates that Garvin's product quality dimensions significantly influence the perceived overall quality of the EMWVM system, which in turn positively affects product quality, product standards, and business outputs. The findings support the effectiveness of the developed system in achieving quality-oriented and business-oriented objectives.

Table 3. Model fit data results from figure 6

Construct	Indicator	Standard Deviation (≤ 1.0)	Factor loading (≥ 0.50)	Average Variance Extracted (AVE) (≥ 0.50)	Cronbach's Alpha (α) (≥ 0.70)	Composite Reliability (CR) (≥ 0.70)
Dimensions	Perf	0.707	0.718	0.425	0.849	0.854
	Rel	0.630	0.559			
	Dur	0.706	0.681			
	Serv	0.613	0.535			
	Aes	0.847	0.777			
	Feat	0.834	0.664			
	Conf	0.525	0.630			
	PerQ	0.829	0.615			
Product Quality	ProdQ1	0.764	0.736	0.568	0.799	0.797
	ProdQ2	0.728	0.698			
	ProdQ3	0.784	0.822			
Product Standard	ProdS1	0.952	0.691	0.342	0.478	0.499
	ProdS2	0.963	0.454			
Overall Product Quality	OvQ1	0.795	0.755	0.623	0.827	0.832
	OvQ2	0.841	0.774			
	OvQ3	1.041	0.836			
Business Outcome	Bus1	0.910	0.875	0.631	0.817	0.835
	Bus2	0.847	0.843			
	Bus3	0.897	0.646			

Likewise, as shown in Table 3, all constructs had a standard deviation within the range of 0.51 -1.0, indicating moderate variability or a healthy spread of responses, which is interpreted as the most acceptable data distribution. Likewise, all factor loadings also ranged from 0.535 to 0.875, indicating a robust relationship between constructs. Specifically for the "Dimensions" construct, the composite reliability values of 0.854 for most constructs exceeded the commonly accepted threshold of 0.7, affirming consistency of the measurement scales used in this study [29]. Similarly, the Cronbach's alpha value of 0.849, above 0.70, confirms strong internal consistency across various product quality dimensions. However, the average variance extracted obtained value of 0.425 is closer to the 0.50 threshold.

Moreover, the reliability indices, including Cronbach's Alpha and Composite Reliability [30], for the Product Quality construct were also acceptable values of 0.799 and 0.797, thereby confirming the internal consistency and reliability of the scales used [31]. Thus, the average variance extracted was 0.568, indicating that more than 50% of the variance in the indicators is explained by the latent construct [32]. For the Product Standard, the Cronbach's alpha value of 0.478 and the composite reliability of 0.499 fall below the 0.70 threshold, suggesting that the

internal consistency of the items measuring this construct is suboptimal [33]. The weak reliability construct may be due to limited indicators, and respondents may have varying interpretations regarding compliance with operational, safety, and regulatory standards because these aspects are often technical and not directly observable during actual system use. This suggests a potential need for refinement or re-evaluation of the `Product Standard` construct's measurement items to improve its psychometric properties and ensure its validity in future studies [29]. Hence, the average extracted variance was 0.342, falling considerably below the 0.50 threshold, thereby raising concerns about the convergent validity of the Product Standard construct within this specific measurement model. Additionally, the EMWVM was developed with consideration for applicable water safety since the system design incorporated food-grade water containers and non-contact sensors to prevent contamination of potable water.

Furthermore, the Overall Product Quality and Business Outcome constructs demonstrated high reliability with Cronbach's alpha values of 0.827 and 0.817, respectively, and composite reliability values of 0.832 and 0.835, which exceed the generally accepted threshold of 0.70 [34]. These strong indicators of internal consistency and reliability suggest that the scales effectively measure the intended constructs [35]. The average variance extracted values for overall product quality (0.623) and business outcome (0.631) further confirm their convergent validity, as both exceed the 0.50 threshold, indicating a substantial proportion of variance is accounted for by their respective latent constructs.

However, the model fit indicates a mixed level of model adequacy. The chi-square to degrees of freedom ratio (CMIN/DF = 1.635) falls well below the recommended threshold of 5.0, suggesting a good overall fit between the proposed model and the observed data. Conversely, the incremental fit indices are close to meet the conventional cut-off values, with Comparative Fit Index (CFI = 0.852) and Tucker-Lewis Index (TLI = 0.811) both falling below but close to the recommended minimum of 0.90. The Root Mean Square Error of Approximation (RMSEA = 0.097) exceeds the minimum threshold of 0.08. The results suggest that the model demonstrates an acceptable absolute fit; however, model refinement may be necessary to improve overall goodness-of-fit. Nevertheless, the data results can't be changed.

Nonetheless, the overall results suggest that the enhanced mobile-integrated water vending machine exhibits robust product quality dimensions, high overall product quality, and promising business outcomes, despite some limitations in the "Product Standard" construct's measurement validity [36]. This highlights a critical area for refinement in future research, as a clearly defined and reliably measured "Product Standard" [37] is essential for comprehensive market potential assessment [18].

CONCLUSION(S) AND RECOMMENDATION(S)

This study successfully developed and evaluated EMWVM, designed to improve operational efficiency, water monitoring, and revenue management through mobile and sensor-based technologies. Using the Modified Waterfall Model, the system integrated real-time water level monitoring, automated coin tracking, mobile application support, and multi-container water storage to address the limitations of conventional water vending systems. The findings revealed that the prototype achieved satisfactory performance across Garvin's Eight Dimensions of Product Quality, particularly in terms of performance, reliability, serviceability, and conformance. Statistical analyses confirmed acceptable reliability and validity for most constructs, while Structural Equation Modeling (SEM) demonstrated a significant positive relationship between product quality dimensions, overall product quality, and business outcomes. These results indicate that the EMWVM can contribute to improved operational efficiency, reduced manual monitoring, enhanced customer satisfaction, and sustainable water resource utilization in urban and semi-urban communities.

Despite these promising results, future studies are recommended to further strengthen the Product Standard construct by incorporating additional indicators related to sanitation compliance, microbiological testing, electrical safety certification, and operational benchmarking. The integration of advanced IoT capabilities such as cloud-based analytics, predictive maintenance, digital payment systems, and renewable energy support also enhances the sustainability and scalability of the system. Moreover, large-scale and long-term implementation studies involving diverse operational settings are encouraged to further validate system effectiveness, user acceptance, and commercial viability. Overall, the EMWVM demonstrates strong potential as a sustainable and scalable technological solution for efficient water management, operational optimization, and improved accessibility to safe and affordable drinking water.

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NOMENCLATURE

Symbols

v	volt

Greek letters

α	alpha

Subscripts and superscripts

ave	average
Aes	aesthetic
Buss	business outcome
Conf	conformance
Dur	durability
Feat	features
OvQ	overall quality
Perf	performance
PerQ	perceived quality
PQ	product quality
ProdS	product standard
Rel	reliability
Serv	serviceability

Abbreviations

AC/DC	Alternating Current/Direct Current
AMOS	Analysis of Moment Structures
API	Application Programming Interface
CFA	Confirmatory Factor Analysis

CFI	Comparative Fit Index
CMIN/DF	Chi-square to degrees of freedom ration
CR	Composite Reliability
EMWVM	Enhance Mobile-Integrated Water Vending Machine
IDE	Integrated Development Environment
IGPQ-SEM	Integrated Garvin-Based Product Quality Structural Equation Model
IR	Infrared
IoT	Internet of Things
I2C	Inter-Integrated Circuit
LCD	Greenhouse Gas
LED	Light Emitting Diode
RMSEA	Root Mean Square Error of Approximation
TLI	Tucker-Lewis Index
SEM	Structural Equation Model
UI	User Interface

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APPENDIX

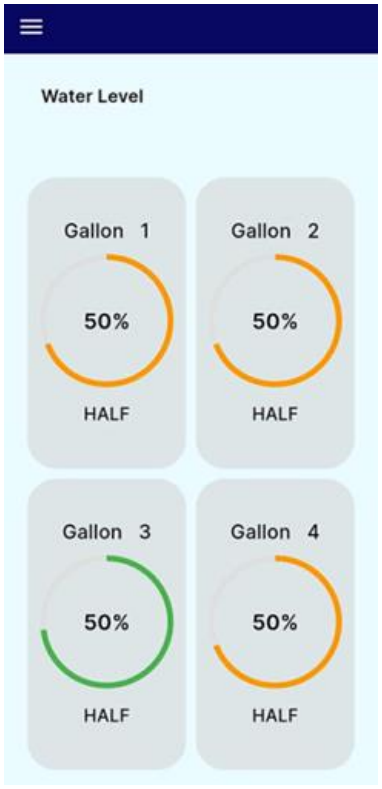


(a)

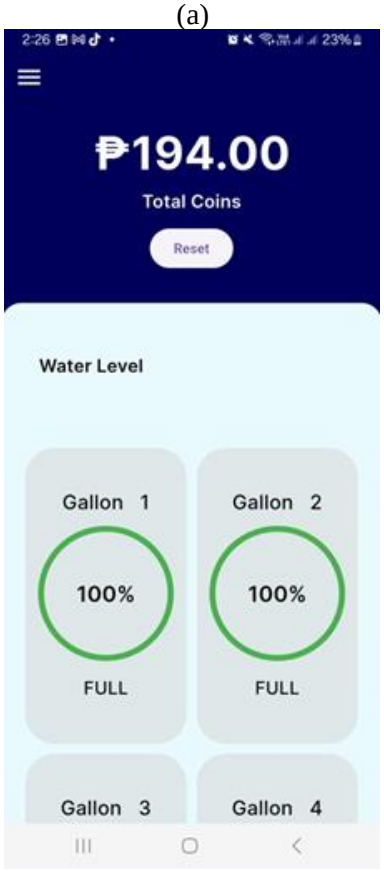


(b)

Figure 7. This prototype of EMWVM is depicted as: Figure 7a (a); and Figure 7b (b)



(a)



(b)

Figure 8. The user interface (UI) screenshot depicted as: Figure 8a (a); and Figure 8b (b)

Survey questionnaire

This section presents the researcher-made questionnaire utilized to evaluate the Enhanced Mobile-Integrated Water Vending Machine (EMWVM).

Part I. Respondent Profile

Please check or fill in the appropriate information.

1. Respondent Type
   - ☐ Customers/users
   - ☐ Water Vending Operator / IT experts
2. Age: _____
3. Sex
   - ☐ Male
   - ☐ Female
   - ☐ Prefer not to say
4. Frequency of Using Water Vending Machines
   - ☐ Daily
   - ☐ Weekly
   - ☐ Occasionally
   - ☐ Rarely

Part II. Prototype Evaluation Questionnaire

Direction:

Please rate the following statements based on your experience with the Enhanced Mobile-Integrated Water Vending Machine (EMWVM).

Rating Scale:

Scale	Description	Interpretation in the Study
5	Strongly Agree	The respondent perceived that the Enhanced Mobile-Integrated Water Vending Machine (EMWVM) fully satisfies the expected quality, functionality, efficiency, and usability requirements.
4	Agree	The respondent perceived that the EMWVM meets most of the expected operational and quality requirements with only minimal concerns.
3	Neutral	The respondent is undecided or has a moderate perception regarding the quality, performance, and effectiveness of the EMWVM.
2	Disagree	The respondent perceived that the EMWVM does not adequately meet several expected operational, usability, or quality requirements.
1	Strongly Disagree	The respondent perceived that the EMWVM fails to satisfy the expected standards for functionality, efficiency, reliability, and

		overall quality.

A. Garvin's Eight Dimensions of Product Quality

Key Indicators	Statement	1	2	3	4	5
Performance	The system performs real-time monitoring of water level, sales tracking, and water dispensing efficiently during operation.					
Reliability	The system operates consistently without interruptions or errors during repeated use.					
Durability	The system can withstand continuous operation and repeated dispensing cycles without failure.					
Serviceability	The system is easy to maintain, troubleshoot, and refill during operation.					
Aesthetic	The system has a visually appealing and user-friendly design.					
Feature	The integrated features, such as mobile monitoring and coin tracking, are useful and functional.					
Conformance	The system meets the intended design specifications and operational standards.					
Perceived Quality	The system provides overall quality, reliability, and value based on its actual performance.					

B. Product Quality

Statement	1	2	3	4	5
The system performs its intended functions correctly.					
The system operates without crashes or unexpected errors.					
The system is easy to learn and use.					

C. Product Standards

Statement	1	2	3	4	5
The system meets applicable quality and safety standards.					
The system adheres to documented operational specifications.					

D. Overall Product Quality

Statement	1	2	3	4	5
The system consistently performs reliably during operation.					
The machine satisfies expected quality and performance standards.					
The system is easy to use and meets operational expectations.					

E. Business Outcomes

Statement	1	2	3	4	5
The system reduces manual effort and operational time.					

The system has the potential to increase sales and customer satisfaction.					
The system provides good return on investment (ROI).					

Comments and Suggestions

_____
_____
_____
_____