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Research on Design Challenges and Optimization Paths of Smart Temperature-Controlled Food Delivery Cabinets for College Students

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ABSTRACT
With the rapid development of the food delivery economy, smart temperature-controlled food delivery cabinets have become an important tool for addressing food storage issues among college students. However, there remain significant design challenges in technology, user experience, and environmental adaptability. This paper systematically explores the current design status and issues of smart temperature-controlled food delivery cabinets through a literature review and case analysis, and proposes optimization paths. The study finds that the main design challenges include temperature zoning management, energy consumption optimization, privacy protection, and congestion during peak pickup times. By introducing the Theory of Planned Behavior (TPB) and a "globalization-localization" dual-dimensional framework, this paper puts forward solutions such as optimizing dynamic temperature control algorithms, improving user experience processes, and designing for cross-cultural adaptability. These solutions provide theoretical support and practical guidance for the promotion and industry optimization of smart temperature-controlled food delivery cabinets.

KEYWORDS
College Student; Food Delivery; Smart Food Delivery Cabinets

1 Background

With the ubiquitous application of internet technology and the rapid expansion of the food delivery economy, college students have emerged as a pivotal segment within the food delivery consumer market. Studies indicate that over 70% of college students place food delivery orders on a weekly basis, with approximately 50% of these students ordering food via delivery platforms three or more times per week. The convenience and diverse options offered by food delivery services have made them an essential means of meeting the dietary needs of college students, especially when campus food services fall short in catering to the personalized and varied demands of this demographic. In such scenarios, food delivery has become an indispensable part of the daily lives of college students. However, as food delivery consumption becomes increasingly widespread, traditional food storage methods (such as dormitory access controls and temporary storage points in cafeterias) have gradually revealed numerous issues. For instance, during the storage process, food delivery items are prone to quality deterioration or spoilage due to temperature fluctuations, a problem that is particularly pronounced in the high temperatures of summer or the cold conditions of winter. Additionally, the security of food storage and privacy protection have become significant concerns among students. To address these challenges, smart temperature-controlled food delivery cabinets have been developed. Through technological means, these cabinets regulate the temperature of stored food, provide real-time monitoring, and safeguard privacy, thus presenting an effective solution to the problems associated with food delivery storage.

Despite the significant advantages in functional design offered by smart temperature-controlled food delivery cabinets, numerous design challenges persist in their actual promotion and application. For example, achieving efficient temperature zoning management within limited space, optimizing user experience through intelligent technologies, and reducing energy consumption while ensuring food safety are all pressing issues. These challenges not only affect the usage effectiveness of smart temperature-controlled food delivery cabinets but also limit their popular in institutions of higher education. Therefore, an in-depth exploration of the design challenges faced by smart temperature-controlled food delivery cabinets and the identification of optimization pathways are of paramount importance. Such research can enhance the food delivery experience for college students, promote the construction of smart campuses, and foster the sustainable development of the food delivery industry.

2 Literature Review

In recent years, with the rapid development of the food delivery economy, smart temperature-controlled food delivery cabinets have emerged as a novel solution and have gradually become a research hotspot. Scholars both domestically and internationally have conducted extensive research on the design and application of smart temperature-controlled food delivery cabinets from multiple dimensions, including technology, user experience, and environmental adaptability. However, there are still research gaps and design challenges that need to be addressed.

2.1 Current Research Status in Terms of Technology

At the technological level, one of the core functions of smart temperature-controlled food delivery cabinets is temperature regulation. Research indicates that this function is crucial for maintaining the taste and safety of delivered food. For instance, Pratiwi et al. (2023) noted that smart cabinets must achieve bidirectional temperature control, including both heating and cooling, to cater to various types of meals, such as beverages, hot food, and cold dishes. Additionally, empirical analysis by Tus et al. (2022) revealed that college students in the Philippines have significant demands for temperature zoning management, especially in high-temperature environments.

However, current research still has shortcomings in temperature zoning management and energy consumption optimization.

For example, achieving efficient temperature zoning management within limited space while reducing energy consumption remains a technical challenge. Furthermore, there is a pressing need to optimize intelligent sorting functions. Students have suggested incorporating AI recognition technology to automatically allocate storage space based on the type of delivered food (e.g., liquids, fragile items, fresh produce), thereby minimizing manual sorting errors and enhancing retrieval efficiency.

2.2 Current Research Status in Terms of User Experience

User experience is a critical consideration in the design of smart temperature-controlled food delivery cabinets. Studies have shown that college students have high demands for the operational convenience and privacy protection of these cabinets.

For example, Yun et al. (2023) found through multi-city case studies that students in the UK, South Korea, and China have significant needs for real-time monitoring systems, dynamic pickup reminders (such as SMS or mini-program notifications), and regular maintenance mechanisms.

Moreover, in terms of data security, users have emphasized the importance of privacy protection and have recommended strengthening the security of personal information storage and transmission through end-to-end encryption technology.

Despite these findings, current research still lacks in-depth exploration of user experience. For instance, further research is needed on how to optimize user operation processes through intelligent technologies and how to alleviate pickup congestion during peak hours.

2.3 Current Research Status in Terms of Environmental Adaptability

Environmental adaptability is an indispensable factor in the design of smart temperature-controlled food delivery cabinets. Research has demonstrated that the performance requirements for these cabinets vary depending on the climatic conditions of different regions. For example, in the hot and humid regions of Southeast Asia, the equipment needs stronger heat dissipation and moisture-proof functions, while in cold regions, greater insulation capabilities are required. Additionally, scholars in Germany have pointed out that restrictions on campus dining during the pandemic indirectly increased the demand for food delivery cabinets. In contrast, the UK has designated "food delivery management zones" around schools to limit the supply of high-salt and high-fat foods, reflecting a policy design logic oriented towards public health. Nevertheless, current research still has weaknesses in cross-cultural comparisons and the optimization of environmental adaptability. For instance, most domestic and international research focuses on quantitative comparisons in single regions, neglecting comprehensive considerations of local cultural, geographical, and other factors.

2.4 Research Gaps and Future Directions

In summary, although existing research has achieved certain results in the technology, user experience, and environmental adaptability of smart temperature-controlled food delivery cabinets, the following gaps still exist:

Technology: Insufficient research on temperature zoning management and energy consumption optimization.

User Experience: Inadequate research on privacy protection and pickup congestion during peak hours.

Environmental Adaptability: Limited research on cross-cultural comparisons and adaptability under extreme climate conditions.

2.5 Future Research Directions

Future research can be conducted in the following directions:

Technological Optimization: Explore algorithmic optimizations for dynamic temperature control and energy consumption balance to enhance the intelligence level of the equipment.

Enhancing User Experience: Further uncover user needs through in-depth interviews and user behavior analysis, and optimize operational processes.

Enhancing Environmental Adaptability: Design smart temperature-controlled food delivery cabinets with greater adaptability by considering the climatic conditions and policy environments of different regions.

Cross-Cultural Research: Compare cases from countries such as China, the UK, and Indonesia to analyze the moderating effects of cultural differences on design requirements.

3 Temperature Control System Schematic - Challenges in Basic Function Verification

3.1 Core Hardware Challenges

Multi-Sensor Real-Time Control (DHT22 Temperature and Humidity Sensor + Peltier Cooler)

The precision of temperature control is highly susceptible to environmental conditions (e. g., high summer temperatures causing delayed response of the Peltier cooler). Additionally, unstable power supply from lithium batteries may lead to temperature fluctuations exceeding food safety standards (e. g., temperatures in refrigerated cabinets exceeding 8°C).

Conflict Between Touchscreen (1.8-inch TFT) and Input Module

Simultaneous operation of the touchscreen (for meal storage) and RFID card swiping (for meal collection) may cause the STM32 microcontroller to crash due to interrupt priority conflicts.

3.2 Meal Storage Coordination (Order Input - Slot Allocation)

Non-Uniform Order Formats from Multiple Platforms (Meituan/Ele.me)

Inconsistent order formats from different platforms can lead to parsing failures in the STM32 microcontroller (e.g., OCR recognition errors in fields like "Mom's Order").

Slot Allocation Conflicts During Peak Hours

Conflicts may arise when two orders compete for the same available slot during peak usage times.

3.3 Meal Collection Process (Card Swiping → Cabinet Opening)

Vulnerability of RFID Cards to Duplication

RFID cards are susceptible to duplication, posing security risks in campus settings.

Incorrect Cabinet Opening Due to User Error

Users may mistakenly swipe another person's order card, leading to unauthorized cabinet access.

3.4 System-Level Risks

Lack of Self-Diagnostic Capability for Hardware Failures

The system lacks the ability to self-diagnose hardware issues (e. g., Peltier cooler failure), necessitating manual troubleshooting.

Reduced Lithium Battery Capacity in Low-Temperature Environments

Lithium battery capacity can significantly decrease in cold conditions, potentially causing temperature control to fail.

4 Temperature Control System Schematic - IoT Expansion Challenges

4.1 Communication Module (ESP8266 + MQTT)

Hardware Stability Issues

ESP8266 Prone to Crashes in Harsh Environments: The ESP8266 is susceptible to crashes in high-temperature and high-humidity conditions, such as during prolonged outdoor operation of food delivery cabinets in summer.

WiFi Signal Interference: Frequent disconnections occur due to WiFi signal interference, especially in environments with dense APs (e.g., campus settings).

MQTT Protocol Implementation Risks

Message Piling Up: Loss of unsent temperature and humidity data during network interruptions.

Improper QoS Level Selection: Critical status updates may be lost if the QoS level is set to 0.

4.2 Cloud Platform (Alibaba Cloud IoT Basic Edition)

Data Timeliness and Consistency

Upload Delays: Delays in uploading temperature and humidity data exceeding 5 seconds, which prevents real-time alerts (e.g., for cabinet doors not properly closed).

State Desynchronization: Discrepancies between cloud and device states (e.g., cloud shows "idle" but the cabinet door is actually occupied).

Alibaba Cloud IoT Integration Complexity

Device Authentication Management: The management of device authentication (ProductKey/DeviceSecret) is cumbersome and prone to leakage.

Rule Engine Misconfiguration: Errors in rule engine configuration can lead to failed data routing.

4.3 User Interaction Expansion (WeChat Mini Program)

QR Code Meal Collection Reliability

Compatibility Issues with QR Code Parsing: Compatibility issues when the mini program parses QR codes from Meituan/Ele.me (e.g., encrypted QR codes cannot be recognized).

API Response Lag During High Concurrency: Slow API responses during peak times (e. g., lunch rush scan delays exceeding 3 seconds).

Status Query Latency

Long Data Retrieval Path: When users query cabinet door status, data must be fetched from Alibaba Cloud IoT, resulting in a lengthy path (User → WeChat → Alibaba Cloud → ESP8266 → Alibaba Cloud → WeChat → User).

5 Temperature Control System Schematic - Optimization and Testing

5.1 System Testing Phase

Stress Testing

Task Deadlock in STM32: Potential for system deadlock when STM32 handles multiple tasks, such as conflicts between disinfection and temperature control tasks.

Disinfection Module Validation

UV Lamp Lifespan: Frequent starting and stopping of UV lamps may reduce their operational lifespan.

5.2 Temperature Control Optimization

PID Algorithm Tuning

Parameter Sensitivity: Fine-tuning the Kp (proportional), Ki (integral), and Kd (derivative) parameters can lead to system oscillation (e.g., temperature fluctuation within ±2°C of the target value).

Poor Environmental Adaptability: The same set of parameters may yield significantly different control effects in high-temperature (summer) and low-temperature (winter) environments.

Precision Verification (±0.5°C)

Sensor Error Accumulation: Low-cost sensors like the DHT22 may experience drift over long-term use (e.g., ±1°C error).

Spatial Temperature Differences: Difficulty in controlling temperature differences within the cabinet, with variations exceeding 1°C (e.g., higher temperatures near door seals).

5.3 Pain Points in UI Upgrade Phase

UI Beautification

Information Overload: Displaying multiple pieces of information simultaneously, such as order numbers, pickup codes, and countdowns, can lead to a cluttered interface.

Brand Inconsistency: Embedding brand colors from partners (Meituan/Ele.me) may disrupt overall UI consistency.

Touchscreen Interaction Optimization

Hardware Response Delay: Low sampling rates in low-end touchscreens (e.g., 50Hz) can cause lag during rapid sliding actions.

High Mis-Touch Rate: Button spacing less than 5mm can lead to accidental activation of adjacent functions, especially when operating with gloves

6 Challenges in Temperature Sensor Monitoring

6.1 Difficulties and Pain Points in Temperature Control

Temperature Monitoring Accuracy

Environmental Interference: Temperature sensors are prone to errors due to environmental factors such as frequent cabinet door openings, causing sudden local temperature changes and transient misjudgments.

Sensor Drift: Low-precision sensors (e.g., DHT22) may experience drift over long-term use, leading to errors exceeding ±0.5℃.

Response Efficiency of Cooling/Heating Systems

Slow Cooling by Thermoelectric Coolers: Thermoelectric coolers have a slow cooling rate (e. g., requiring over 15 minutes to cool from 30℃ to 5℃), making them unsuitable for high-frequency storage and retrieval scenarios.

Heating System Delays: Heating systems (e.g., PTC) may experience startup delays in low-temperature environments.

6.2 Challenges and Pain Points in Fault Detection and Disaster Recovery

False and Missed Fault Alarms

Transient Signal Interference: Sudden electromagnetic pulses or other transient signal interferences may trigger false fault alarms.

Sensor Failure Detection: The system cannot autonomously identify sensor failures and relies on manual inspection when sensors completely fail.

Reliability of Backup Component Switching

Performance Differences in Backup Components: Backup thermoelectric coolers may have performance discrepancies with the main equipment, leading to reduced temperature control stability after switching.

Temporary Temperature Loss of Control: There may be brief temperature fluctuations (e. g., ±2℃ within 3 minutes) during the switching process.

6.3 Challenges and Pain Points in User Notifications

Effectiveness of Fault Information Communication

User Oversight of Alarms: Users may ignore conventional alarm notifications (e.g., screen flashing).

Complex Multi-Platform Notifications: Managing notifications across multiple platforms (e. g., SMS, mini-programs, APPs) is complex and can lead to fragmented communication.

Efficiency of Repair Response Coordination

Remote Fault Verification: Maintenance personnel cannot remotely confirm the authenticity of faults, leading to unnecessary service dispatches.

7 Challenges and Pain Points in Fault Detection Diagram

7.1 Difficulties and Pain Points in Hardware Fault Detection

Temperature Sensor Failures (Disconnect/Drift)

Instantaneous Disconnection Misjudgment: Poor contact can lead the system to misjudge temporary disconnections as permanent failures (e.g., loose plugs due to vibration).

Conflicting Data from Multiple Sensors: When there is a significant difference in readings between primary and backup sensors, the system cannot quickly determine which one has failed.

Compressor Current Overload (Overload/Short Circuit)

Transient Current Interference: Grid fluctuations or startup currents may trigger false alarms.

Difficulty in Identifying Overload Causes: Current overload could stem from compressor aging, insufficient heat dissipation, or unstable voltage.

7.2 Challenges and Pain Points in Emergency Response Procedures

Reliability of Backup Component Switching

Switching Delay Causing Temperature Control Interruption: A 30-second delay in activating the backup compressor can lead to temperature exceeding standards during the switch.

Performance Discrepancies Between Primary and Backup Components: Backup sensors may have lower precision (e.g., ±1°C vs. the primary sensor's ±0.5°C).

Closed-Loop Management of Repair Notifications

Single Notification Channel: Relying solely on SMS notifications may result in user oversight, especially in campus settings where students may block marketing messages.

Desynchronization of Repair Status: If maintenance personnel fail to manually close the alarm after addressing the issue, the system may continue to send redundant notifications.

7.3 Potential Risks in Safe Mode Design

Overly Conservative Entry Conditions

Entering safe mode due to a single sensor disconnection can negatively impact user experience, such as when urgent meal retrieval is needed but cabinet doors are locked.

Complex Recovery Procedures

Manual reset is required to exit safe mode, making timely fault resolution difficult during nighttime.

8 Conclusion

This study examines the design challenges of smart temperature-controlled food delivery cabinets for college students, analyzing current issues across technology, user experience, and environmental adaptability. Key challenges include temperature zoning, energy consumption, privacy protection, and peak-hour congestion. By applying the Theory of Planned Behavior (TPB) and a "globalization-localization" framework, the research proposes optimization strategies such as dynamic temperature control algorithms, user experience process improvements, and cross-cultural design adaptations. The findings offer theoretical support for promoting smart temperature-controlled cabinets and inform industry optimization and policy-making.

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