

An IoT-LoRaWAN Architecture for Cold-Chain Compliance Monitoring in Commercial Refrigeration

Luis Fernando Ramírez Ramos

Department of Electronics, Systems and Informatics, ITESO – Universidad Jesuita de Guadalajara, Tlaquepaque, Jalisco, México

Abstract

Cold-chain abuse in small and medium food-and-beverage venues remains a leading vector of foodborne illness, with prior surveys reporting that perishable products spend between 30 % and 50 % of their commercial life outside their target temperature window [9], [10]. Continuous, automated compliance monitoring is rare in this segment because conventional industrial telemetry is cost-prohibitive and manual point-in-time logs systematically miss time-temperature abuse events. This paper presents SensorGrid, a four-layer Internet-of-Things architecture aligned with ISO/IEC 30141 [6] that combines LoRaWAN 915 MHz perception nodes, a Cloudflare Workers serverless processing layer, a Neon Postgres time-series database with TimescaleDB, and a React 19 dashboard, together with a two-tier alert engine providing 30-min escalation, 30-min cooldown, energy-spike detection, sustained door-open detection, and a cron-driven stale-data watchdog. The system was validated through a three-phase field experiment at a food-and-beverage establishment within a university campus, comprising a domestic control refrigerator (F1, $n = 179$), an in-the-wild commercial unit denoted Refrigerator 1 (F2, $n = 214$), and its post-intervention replacement Refrigerator 2 (F3, $n = 41$). Sixteen formal test cases yielded 13 APPROVED, 2 OBSERVED, and 1 NOT APPROVED verdicts. SensorGrid detected a critical door-seal failure in Refrigerator 1 — 63.6 % of readings exceeded the NOM-251-SSA1-2009 [1] 7 °C ceiling, peaking at 15.8 °C — and the alerts directly motivated equipment replacement, after which the critical fraction fell to 12.2 %. Mean Tier-1 alert dispatch latency was 0.38 s. The longest sustained event covered 39.9 h continuously above 4 °C across a weekend, exposing a sociotechnical gap that complements the technical contribution.

Index Terms — *Internet of Things, LoRaWAN, cold chain, food safety, NOM-251-SSA1-2009, serverless computing, time-series database, ISO/IEC 30141, cloud computing.*

I. INTRODUCTION

The integrity of the cold chain is a cornerstone of modern food safety. The World Health Organization estimates that foodborne hazards caused 600 million illnesses and 420,000 deaths globally in 2010, with non-typhoidal *Salmonella enterica* and diarrhoeal pathogens dominating the burden [26]. Time-temperature abuse — the accumulated time during which a perishable product remains above its target storage temperature — is a principal driver of microbial proliferation and is repeatedly identified as the highest-impact failure mode in the postharvest cold chain. Recent reviews report that perishable products spend between 30 % and 50 % of their post-production lifetime outside the recommended temperature window, with the retail and final-storage stages accounting for the largest share of the deviation [9], [10]. Microbiological evidence supports the criticality of even modest temperature excursions: *Listeria monocytogenes* doubles within hours at 7 °C and grows measurably at temperatures as low as 4 °C [25], [27], aligning with the thresholds adopted by international regulators [2], [3] and by the Mexican standard NOM-251-SSA1-2009 [1]. While large logistics operators routinely instrument trucks and warehouses with industrial telemetry, the final stage of the cold chain — the commercial refrigerators of small and medium food-and-beverage venues — is largely uninstrumented. In these venues, compliance is typically verified by manual point-in-time temperature logs filled in two or three times per shift. Such logs are blind to nocturnal failures, weekend events, gradual seal degradation, and to the brief excursions that nonetheless accumulate into significant abuse time. The result is that the venues most

exposed to retail-stage abuse are also those least likely to detect it. The gap is not primarily one of sensing technology but of integrated end-to-end systems: low-cost LoRaWAN sensors and serverless cloud platforms have matured to the point where continuous compliance monitoring is technically and economically feasible, yet most published work either stops at the data-acquisition layer [12], [14], [29] or targets supply-chain logistics rather than venue-level refrigeration [11], [13], [15]. This paper addresses that gap by presenting SensorGrid, an end-to-end cold-chain compliance monitoring platform validated through field deployment at a food-and-beverage establishment within a university campus. The contributions are threefold. First, the system implements a complete four-layer architecture aligned with ISO/IEC 30141 [6], integrating Milesight AM307 and CT101 LoRaWAN sensors, a Milesight UG63 gateway, The Things Network v3, a Cloudflare Workers ingestion and rule engine, a Neon Postgres database with TimescaleDB hypertables, and a React 19 dashboard. Second, the platform contributes a two-tier alert engine with formal Tier-1/Tier-2 escalation, 30-min cooldown, an energy-spike rule keyed to a 24-h rolling baseline, a sustained door-open rule that requires two of three readings within ten minutes to exceed the threshold, and a cron-driven stale-data watchdog. Third, SensorGrid is validated through a structured three-phase experiment that contrasts a domestic control unit, a failing commercial unit (Refrigerator 1), and its post-intervention replacement (Refrigerator 2), supported by 16 formal test cases. The remainder of this paper is organised as follows. Section II reviews related work on cold-chain wireless sensor networks, LoRaWAN-based monitoring, IoT-

supported food spoilage detection, and smart-campus IoT infrastructures, and identifies the specific gap that SensorGrid fills. Section III presents the four-layer architecture, the alert engine, and the data model. Section IV describes the three-phase experimental methodology and the test-case battery. Section V reports the temperature-compliance results, the alert-engine performance, the critical events, and the limitations of the experiment. Section VI discusses the operational and sociotechnical implications. Section VII concludes and outlines future work.

II. RELATED WORK

Wireless sensor networks for cold-chain monitoring have been investigated for over a decade. Carullo et al. [12] presented one of the earliest ZigBee-based deployments for refrigerated transport and demonstrated that low-power radio nodes could provide multi-hour continuous coverage in metallic enclosures. More recent work continues this line: Sarkar et al. [14] proposed a low-cost cold supply-chain monitoring system based on commodity microcontrollers and cloud dashboards, while Wisessing and Vichaidis [15] integrated a blockchain layer to provide auditability of temperature records during transport. Awasthi et al. [11] expanded the alerting layer with real-time SMS notifications for perishable goods, and the recent systematic review by Müller et al. [13] catalogued more than seventy IoT and AI-based cold-chain studies and concluded that the literature is dominated by transport-stage solutions, with venue-level retail refrigeration substantially underrepresented. LoRaWAN has emerged as the radio of choice for low-power wide-area sensing in cold-chain settings due to its sub-GHz penetration and multi-year battery life. Codeluppi et al. [18] demonstrated the suitability of LoRaWAN for agricultural monitoring through their LoRaFarM platform, including coverage characterisation in obstructed rural environments. Manzano et al. [19] showed that LoRaWAN can operate reliably even inside RF-shielded radiation-monitoring facilities, supporting its applicability to enclosed commercial refrigerators. The comparative LPWAN study by Mekki et al. [20] establishes LoRaWAN as the preferred trade-off between cost, range, and energy when compared with Sigfox and NB-IoT for low-rate periodic telemetry. Adelantado et al. [21] formalised the throughput and duty-cycle limits of LoRaWAN, providing the theoretical envelope within which any deployment must remain. SensorGrid operates well inside this envelope: each AM307 transmits roughly every 5 min and each CT101 every 2 min, both at the lowest US915 spreading factors compatible with the gateway link budget [7], [8]. Beyond temperature, IoT-supported food spoilage assessment has explored chemical signals. Damdam et al. [16] demonstrated an electronic-nose system for beef spoilage detection based on volatile organic compounds, complementing temperature monitoring with direct chemical evidence of degradation. Postharvest physiology provides the rationale for many auxiliary measurements: Fonseca et al. [17] modelled the respiration

rates of fresh fruits and vegetables and showed that CO₂ and humidity inside a closed refrigerator are dominated by produce metabolism rather than by occupant respiration, which has direct implications for the reframing of indoor-air-quality thresholds when those thresholds are repurposed inside refrigeration enclosures. Smart-campus IoT precedents inform both the architecture and the deployment context of SensorGrid. Domínguez-Bolaño et al. [22] documented an end-to-end university-campus IoT platform spanning environmental, occupancy, and energy use cases, identifying interoperability and gateway management as recurring bottlenecks. Gilman et al. [23] reported a multi-year campus deployment focused on smart spaces and confirmed that LoRaWAN-based perception layers scale gracefully when paired with cloud-native back-ends. Verma et al. [24] reviewed sensing and IoT infrastructure in smart buildings and explicitly framed such systems against the ISO/IEC 30141 [6] reference architecture, motivating the four-layer decomposition adopted in this work. Adjacent LoRaWAN platform work [28], [29], [30] further illustrates that MQTT-based or webhook-based ingestion plus a time-series database is now an established baseline, with parallel evidence from MQTT-driven building monitoring [31] and from real-time IoT indoor-air-quality networks [32]; SensorGrid adopts this baseline and refines it with a serverless processing layer, a TimescaleDB hypertable, and a formal two-tier alert engine. The microbiological foundation of the temperature thresholds is well established. Tarrant et al. [25] and Cole et al. [27] characterised *L. monocytogenes* growth at refrigeration temperatures and showed that operational targets at or below 4 °C strongly suppress growth, whereas excursions above 7 °C lead to rapid proliferation in potentially hazardous foods. These thresholds anchor both the FDA Food Code 2022 [2] and the USDA FSIS Danger Zone framing [3], and align with NOM-251-SSA1-2009 [1]. Table I summarises the gap that SensorGrid fills relative to representative prior systems.

Reference	Focus	Radio	Backend	Alert engine	Field validation
Carullo 2009 [12]	Cold-chain WSN, transport	ZigBee	Custom	Threshold	Lab + transport
Sarkar 2020 [14]	Supply-chain monitoring	Wi-Fi/GSM	Cloud dashboard	Threshold	Prototype
Wisessing 2021 [15]	Cold-chain + blockchain	LoRa	Blockchain ledger	Threshold	Prototype
Awasthi 2025 [11]	Perishable goods, SMS alerts	GSM	Cloud	SMS threshold	Prototype
Codeluppi 2020 [18]	Smart farming (LoRaFarM)	LoRaWAN	InfluxDB / Grafana	None	Multi-month field
Manzano 2021 [19]	Radiation monitoring	LoRaWAN	Custom	None	Field, RF-shielded
Domínguez-Bolaño 2024 [22]	Smart-campus IoT	Mixed	Multi-tier	Use-case specific	Multi-year campus
Müller 2026 [13]	Cold-chain IoT/AI review	—	—	—	Systematic review
SensorGrid (this work)	Venue-level cold-chain compliance	LoRaWAN 915 MHz	Serverless + TimescaleDB	Two-tier with cooldown, escalation, stale-data, energy-spike, door-open	Three-phase field (F1/F2/F3) + 16 test cases

TABLE I. RELATED-WORKS COMPARISON

No prior work in the surveyed literature combines venue-level commercial refrigeration, a serverless ISO/IEC 30141-aligned stack, a formal two-tier alert engine, and a structured field validation that contrasts a control unit, a failing unit, and a post-intervention replacement.

III. SYSTEM ARCHITECTURE

III-A. Four-Layer ISO/IEC 30141 Decomposition

SensorGrid is organised as four loosely coupled layers consistent with the ISO/IEC 30141:2024 IoT reference

architecture [6]: a perception layer that senses the physical environment, a network layer that transports the resulting payloads, a processing layer that ingests, persists, and reasons over the data, and an application layer that exposes the data and the alert lifecycle to operators. The decomposition is deliberate: each layer can evolve independently, and the contracts between layers — TTN webhooks, the Worker REST API, and the database schema — are stable enough to permit replacement of any single layer without rewriting the others. The four-layer decomposition is illustrated in Fig. 1.

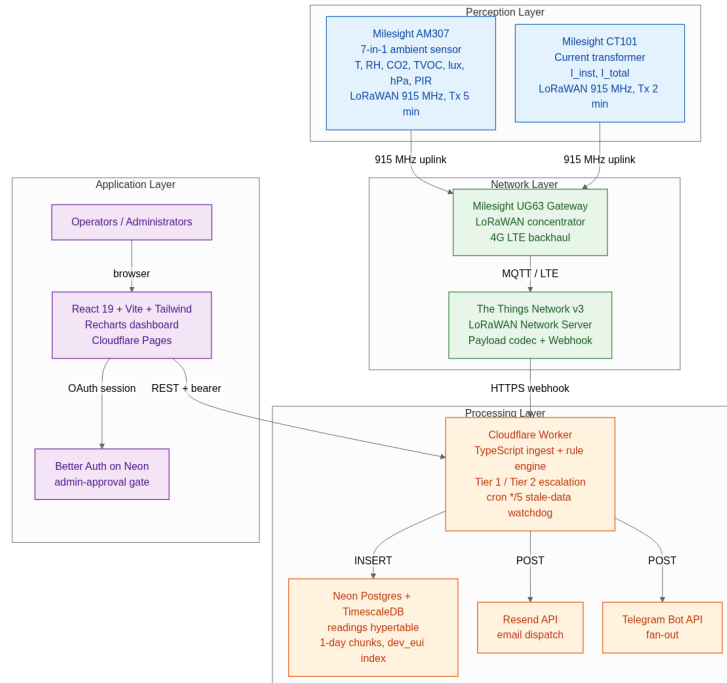


Fig. 1. Four-layer ISO/IEC 30141 architecture of SensorGrid. The perception layer integrates the Milesight AM307 7-in-1 ambient sensor and CT101 current transformer over LoRaWAN 915 MHz; the network layer terminates at a Milesight gateway and The Things Network v3; the processing layer runs on Cloudflare Workers with Neon Postgres + TimescaleDB; the application layer is a React 19 dashboard on Cloudflare Pages with Better Auth.

III-B. Perception Layer

The perception layer integrates two off-the-shelf Milesight LoRaWAN devices that transmit on the US915 sub-band. The Milesight AM307 7-in-1 ambient sensor is mounted on the inner wall of each refrigerator and reports temperature, relative humidity, CO₂ from a non-dispersive infrared cell, total volatile organic compounds via the Sensirion SGP40 [33], illuminance, barometric pressure, and passive infrared motion. Its transmission interval is approximately 5 min. The Milesight CT101 current transformer, intended to monitor the compressor circuit of the refrigerator, transmits instantaneous and accumulated current values approximately every 2 min [34]. Both devices comply with the LoRaWAN 1.1 specification [7] and operate within the duty-cycle envelope described by Semtech AN1200.22 [8].

III-C. Network Layer

A single Milesight UG63 gateway acts as the local LoRaWAN concentrator. It is configured as a packet forwarder against The Things Network v3 (TTN), which terminates the LoRaWAN MAC and runs the Milesight payload formatters that decode each uplink into JSON. Because the deployment site offers no fixed Ethernet port, the gateway uses a 4G LTE backhaul to reach TTN. TTN forwards each decoded uplink to the SensorGrid processing layer through an HTTPS webhook, isolating the cloud back-end from any direct exposure to the LoRaWAN MAC.

III-D. Processing Layer

The processing layer is implemented as a single 967-line TypeScript module deployed to Cloudflare Workers and built against the @neondatabase/serverless v1.0.2 driver. Every TTN webhook is delivered to POST /ingest, which authenticates the request through a constant-time bearer-token comparison performed via crypto.subtle.timingSafeEqual against a Worker secret. The decoded payload is then persisted into a Neon Postgres instance whose readings table is a TimescaleDB hypertable partitioned by time in 1-day chunks, with a secondary B-tree index on (dev_eui, time DESC). The schema retains the AM307 fields (temperature, humidity, CO₂, TVOC, illuminance, pressure, PIR) and the CT101 fields (instantaneous and total current). Bucketed aggregation queries served to the dashboard rely on TimescaleDB's time_bucket() over a fixed allowlist of intervals (5 min, 15 min, 1 h, 4 h, 1 day), which preserves predictable latency under heavy time-range queries while resisting bucket-injection misuse. The Worker exposes a small REST surface to the dashboard — bucketed time-series, latest readings, device list, alert rules, and alert events — and a reverse proxy under /auth/* that connects to the Neon-hosted Better Auth instance. Notifications are delivered through the Resend HTTP API from the address alertas@sensorgrid.site and through a Telegram bot, with per-rule fan-out arrays for Tier-1 and Tier-2 recipients. A Cloudflare Workers cron trigger (* /5 * * * *) executes the stale-data watchdog described below. The end-to-end uplink-to-notification path is summarised in Fig. 2.

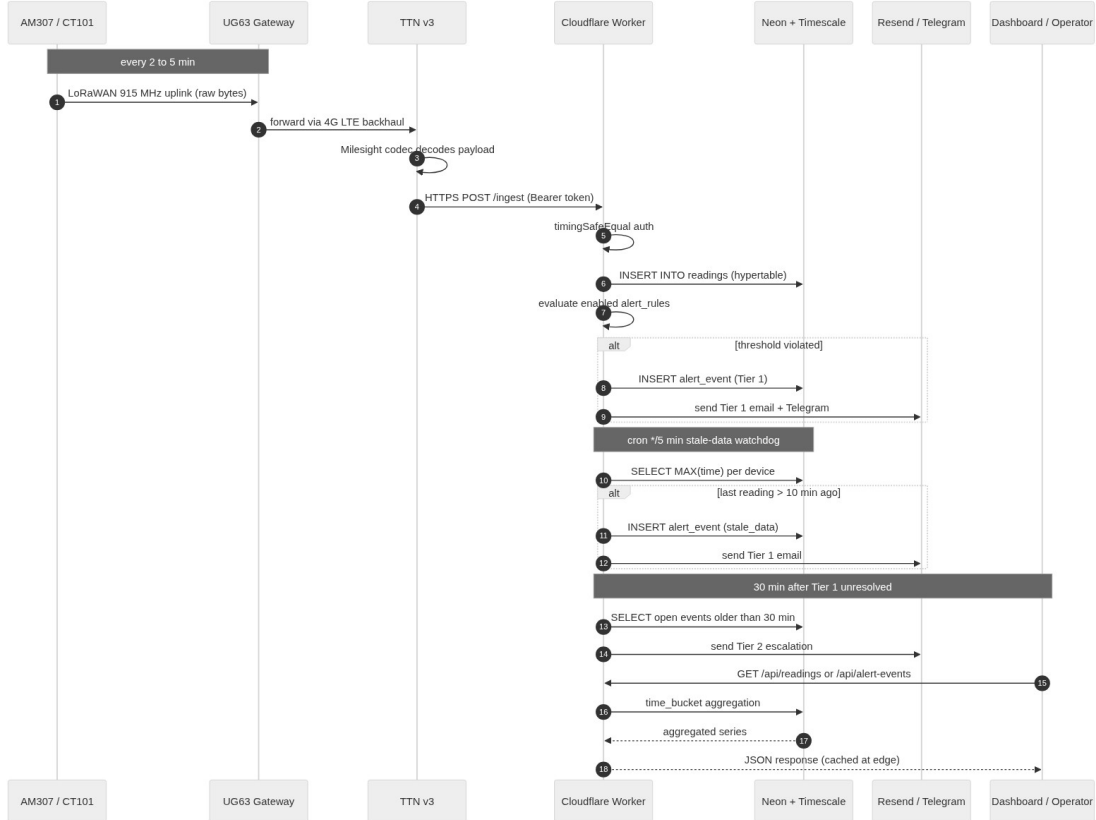


Fig. 2. End-to-end sequence diagram from sensor uplink to operator notification, including the cron-driven stale-data watchdog and the Tier-1/Tier-2 escalation path.

III-E. Application Layer

The application layer is a React 19 single-page application built with Vite 6 and Tailwind CSS v4, visualised through Recharts, and deployed to Cloudflare Pages. Authentication uses Better Auth running on Neon Auth, with cookies kept same-origin via a two-stage reverse proxy through a Cloudflare Pages Function and the Worker's `/auth/*` route — a design specifically introduced to bypass mobile Safari's third-party-cookie blocking. Access is gated by an explicit administrator-approval workflow backed by the `user_approvals` table, with approval and rejection notifications dispatched through Resend. The dashboard offers four pages: a per-fridge overview (Resumen) with bucketed time-series and threshold zones, a device list (Sensores) with battery and last-seen indicators, an alert-management page (Alertas) split into active-alerts, rule-configuration, and alert-history tabs, and a configuration page (Config) for profile and administrator user management.

III-F. Alert Engine

The alert engine is the operational heart of SensorGrid. It is evaluated synchronously on every `/ingest` write, so the latency from sensor uplink to operator notification is bounded by the Worker request lifetime rather than by any separate scheduler. Each enabled rule in the `alert_rules` table couples a metric (e.g. temperature, humidity, `co2`, `light_level`, `energy_spike`, `stale_data`), an operator (gt, lt, or eq), and a numeric threshold.

Three rules require special evaluation logic. The `energy_spike` rule compares each incoming `total_current` value against the device's 24-h rolling average and fires when the ratio exceeds the configured threshold, providing a baseline-aware compressor-cycle anomaly detector. The `door-open` rule built on the AM307 illuminance channel requires at least two of the three most recent `light_level` readings within the previous ten minutes to exceed the threshold, which eliminates momentary openings while remaining responsive to sustained ones. The `stale_data` rule is delegated to the cron-driven watchdog described below. Alerts follow a formal state machine. When a rule first triggers, an `alert_events` row is created and a Tier-1 notification is dispatched. Repeated triggers on the same (rule_id, dev_eui) pair while the event is still unresolved are suppressed by a database-level uniqueness check, eliminating notification storms. After a configurable delay — defaulting to 30 min via the rule-level `email_tier2_delay_min` field — an unresolved event escalates to Tier 2, at which point a second notification is dispatched to the escalation recipients and `tier2_sent_at` is stamped to prevent re-sending. As soon as the next reading no longer satisfies the trigger condition, the event auto-resolves by setting `resolved_at` to `NOW()`. A 30-min cooldown then applies to that rule-and-device combination, suppressing immediate re-triggering and absorbing measurement jitter around the threshold. The complete state machine is depicted in Fig. 3.

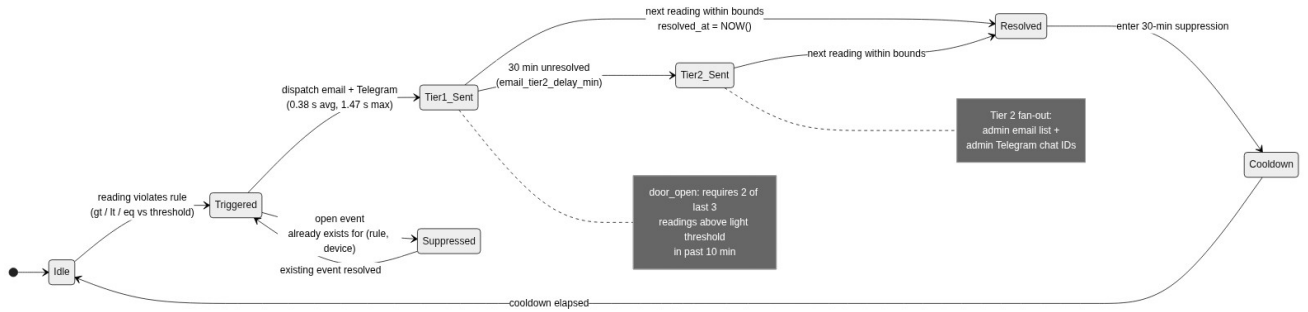


Fig. 3. Alert state machine. Each rule transitions through Triggered → Tier1_Sent → Tier2_Sent → Resolved → Cooldown, with a Suppressed state for duplicate triggers on an open event.

The `stale-data` watchdog runs on a `* /5 * * * *` cron schedule. For every device, it compares the maximum reading time against `NOW() - INTERVAL '10 minutes'`; if the device is silent beyond that window and no unresolved metric=`'stale_data'` event already exists for it, a new event is opened. A one-hour anti-flapping cooldown prevents repeated openings during gateway intermittency, and a single bulk UPDATE resolves all stale events for any device whose latest reading has caught up. This rule was the most frequent contributor to alert volume during the field experiment, reflecting the LTE-backhaul intermittency of the on-site UG63 gateway rather than sensor failure.

III-G. Data Model

The persisted schema is intentionally compact. The `devices` table stores `dev_eui`, human-readable `name`, `fridge_label`, `location`, and `type`. The `readings` hypertable stores the AM307

and CT101 fields together with a foreign key to `devices`. The `alert_rules` table couples a metric, operator, threshold, enabled flag, and four notification arrays (`email_tier1`, `email_tier2`, `telegram_tier1`, `telegram_tier2`) plus the per-rule escalation delay. The `alert_events` table records the trigger time, resolution time, and four send-time stamps for the four notification channels. The `user_approvals` table captures the administrator-approval workflow, and `neon_auth.user/neon_auth.session` are provisioned by Better Auth. All time-series queries served to the dashboard are expressed as `time_bucket()` aggregations over readings, which keeps the API contract narrow and the database layer cleanly separable.

IV. EXPERIMENTAL METHODOLOGY

The validation strategy was designed around a three-phase experiment that progressively introduced ecological complexity while preserving instrumentation continuity. Phase 1 (F1) instrumented a domestic refrigerator outside the establishment to act as a control: it characterised the noise floor, confirmed the calibration of the AM307 and the CT101, and produced a reference NOM-251 distribution against which the commercial deployments could be compared. Phase 2 (F2)

deployed the same instrumentation inside Refrigerator 1, the unit nominated by the establishment for monitoring, to capture in-the-wild operating behaviour without any intervention. Phase 3 (F3) was triggered by the SensorGrid alerts themselves: after F2 revealed sustained NOM-251 violations, the establishment replaced the unit and SensorGrid migrated to Refrigerator 2 to characterise the post-intervention regime. The three phases together span 2026-03-16 to 2026-03-27 in Central Standard Time. Fig. 4 summarises the experimental design.

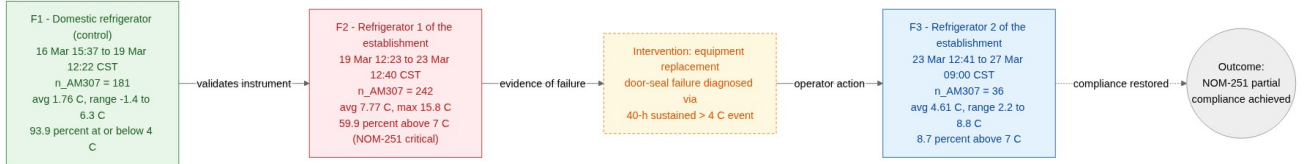


Fig. 4. Three-phase experimental design: domestic control (F1), in-the-wild observation of Refrigerator 1 (F2), and post-intervention monitoring of Refrigerator 2 (F3).

In parallel with the longitudinal experiment, sixteen formal test cases were defined and executed against the deployed system. The cases are partitioned into ten functional, four integration, and two performance categories, and each case carries an explicit acceptance criterion and a binary verdict drawn from APPROVED, OBSERVED, or NOT APPROVED. The functional cases exercise the end-to-end ingestion path, user authentication, the administrator-approval workflow, and each path of the alert engine (Tier-1 dispatch, Tier-2 escalation, stale-data detection, and email delivery). The integration cases probe sensor-data validity, temporal continuity, cross-phase coherence of variables, and the relationship between current readings and compressor cycles. The performance cases measure dashboard load time and API latency for representative seven-day queries. The statistical comparators come from four normative sources. NOM-251-SSA1-2009 [1] provides the only Mexican legal ceiling for potentially hazardous foods, fixing the 7 °C maximum and recommending 4 °C or below; the 4 °C operational threshold itself is anchored in the FDA Food Code 2022 [2] and the USDA FSIS Danger Zone framing [3], which is reflected in this paper's choice of 4 °C as the warning threshold and 7 °C as the critical threshold. ASHRAE Handbook Refrigeration Chapter 21 [4] provides the humidity bands for mixed perishable storage. Three additional standards were investigated and explicitly judged non-applicable inside a refrigerator: NOM-010-STPS-2014 [5], which fixes a TWA-8h CO₂ limit of 5,000 ppm for occupational atmospheres; ASHRAE 62.1-2022, which targets habitable spaces; and the WHO Indoor Air Quality Guidelines, which target indoor environments with human occupancy. The methodological contribution is to recognise that interior-refrigerator CO₂ and humidity are dominated by produce respiration [17] rather than by occupant load, and therefore demand a postharvest-aware reframing rather than the direct re-use of occupational-IAQ thresholds.

V. RESULTS

V-A. Test-Case Outcomes

The 16 test cases produced a final tally of 13 APPROVED, 2 OBSERVED, and 1 NOT APPROVED. The single NOT APPROVED verdict arises from the CT101 toroid mis-installation discussed in Section V-F, and the two OBSERVED verdicts arise from the LTE-backhaul intermittency of the UG63 gateway, which manifests as both temporal gaps in the readings stream and a high volume of stale-data alerts. All functional cases connected with the alert engine itself were APPROVED, including the Tier-1 dispatch latency, the Tier-2 escalation, and the email-delivery cases. Both performance cases passed comfortably, with dashboard largest-contentful-paint at approximately 2 s and seven-day API queries returning in 200–350 ms. The full battery and verdicts are listed in Table II.

ID	Description	Type	Acceptance criterion	Result	Verdict
FUN-END2END-001	End-to-end flow sensor → gateway → TTN → Worker → DB → dashboard	Functional	Visible in dashboard < 5 min	Visible in 2–3 min	APPROVED
FUN-END2END-002	End-to-end flow with Refrigerator 1 → Refrigerator 2 transition	Functional	Time-series captures relocation	Drop 7.9 °C → 0.5 °C captured	APPROVED
FUN-INGEST-001	TTN webhook ingestion and DB persistence	Functional	100 % valid payloads stored	100 % stored (459 AM307 + 3,360 CT101)	APPROVED
FUN-AUTH-001	User registration via email/password	Functional	Successful registration	Registration completed	APPROVED
FUN-AUTH-002	Login with valid credentials	Functional	Dashboard access after login	Successful login, session active	APPROVED
FUN-AUTH-003	Administrator approval for new users	Functional	User pending until approved	Approval flow functional	APPROVED
FUN-ALERT-001	Tier-1 alert: temperature > 4 °C	Functional	Alert generated < 1 s	0.38 s mean dispatch	APPROVED
FUN-ALERT-002	Tier-2 escalation after 30 min unresolved	Functional	Email to administrators	10 alerts correctly escalated	APPROVED
FUN-ALERT-003	Stale-data alert when sensor exceeds expected interval	Functional	Alert when no Tx beyond expected interval	83 stale-data alerts (77.6 % of total)	OBSERVED
FUN-ALERT-004	Email notification from alertas@sensorgrid.site	Functional	Email received with detail	Emails received correctly	APPROVED
INT-DATA-001	AM307 readings within sensor range −20...60 °C	Integration	All readings within range	100 % within range (−1.4 °C to 15.8 °C)	APPROVED
INT-DATA-002	CT101 current matches compressor cycles	Integration	Variable current reflecting cycles	Constant 0.00 A inst., 0.84 A acc., no variation	NOT APPROVED
INT-DATA-003	Temporal consistency, no prolonged gaps	Integration	Gaps < 30 min between AM307 readings	Gaps > 30 min frequent at the establishment	OBSERVED
INT-DATA-004	Cross-phase coherence of variables	Integration	Pressure σ < 5 hPa across phases	Consistent 836–842 hPa in all phases	APPROVED
PERF-WEB-001	Dashboard load time < 3 s	Performance	LCP < 3 s	~2 s (LCP)	APPROVED
PERF-API-001	REST API latency < 500 ms (7-day query)	Performance	< 500 ms	200–350 ms	APPROVED

TABLE II. SIXTEEN FORMAL TEST CASES

V-B. Temperature Compliance Across Phases

The temperature record is the principal compliance signal. Fig. 5 shows the time-series for the three phases against the 4 °C and 7 °C reference lines, and Fig. 6 summarises the resulting NOM-251 zone distribution. In Phase 1, the domestic control refrigerator produced $n = 179$ valid AM307 readings with a mean of 1.76 °C, a standard deviation of 1.50 °C, and a range from −1.4 °C to 6.3 °C; 95.0 % of readings sat at or below 4 °C, and none exceeded the 7 °C NOM-251 ceiling. This regime defines the achievable behaviour of a well-functioning unit and provides the baseline against which the

commercial deployments are assessed. Phase 2 produced $n = 214$ AM307 readings inside Refrigerator 1, with a mean of 8.16 °C, a standard deviation of 2.73 °C, and a range from 1.8 °C to 15.8 °C. Only 11.2 % of the readings sat at or below 4 °C, 25.2 % fell within the 4–7 °C operational margin, and 63.6 % exceeded the NOM-251 7 °C ceiling. This is the headline finding of the deployment: under normal operation, almost two-thirds of the time, Refrigerator 1 was above the legal limit for potentially hazardous foods. The hourly profile (Fig. 7) localises the failure: the thermal stress concentrates between 16:00 and 18:00 CST, coinciding with end-of-service activity and ambient kitchen heat load. Phase 3, after equipment

replacement, produced $n = 41$ AM307 readings inside Refrigerator 2, with a mean of 3.94 °C, a standard deviation of 2.75 °C, and a range from 0.5 °C to 11.3 °C; 58.5 % of readings sat at or below 4 °C, 29.3 % fell within 4–7 °C, and

12.2 % exceeded 7 °C. The replacement therefore reduced the NOM-251 critical fraction from 63.6 % to 12.2 % — an 81 % relative reduction in non-compliant time — and shifted the bulk of the distribution back into the green zone.

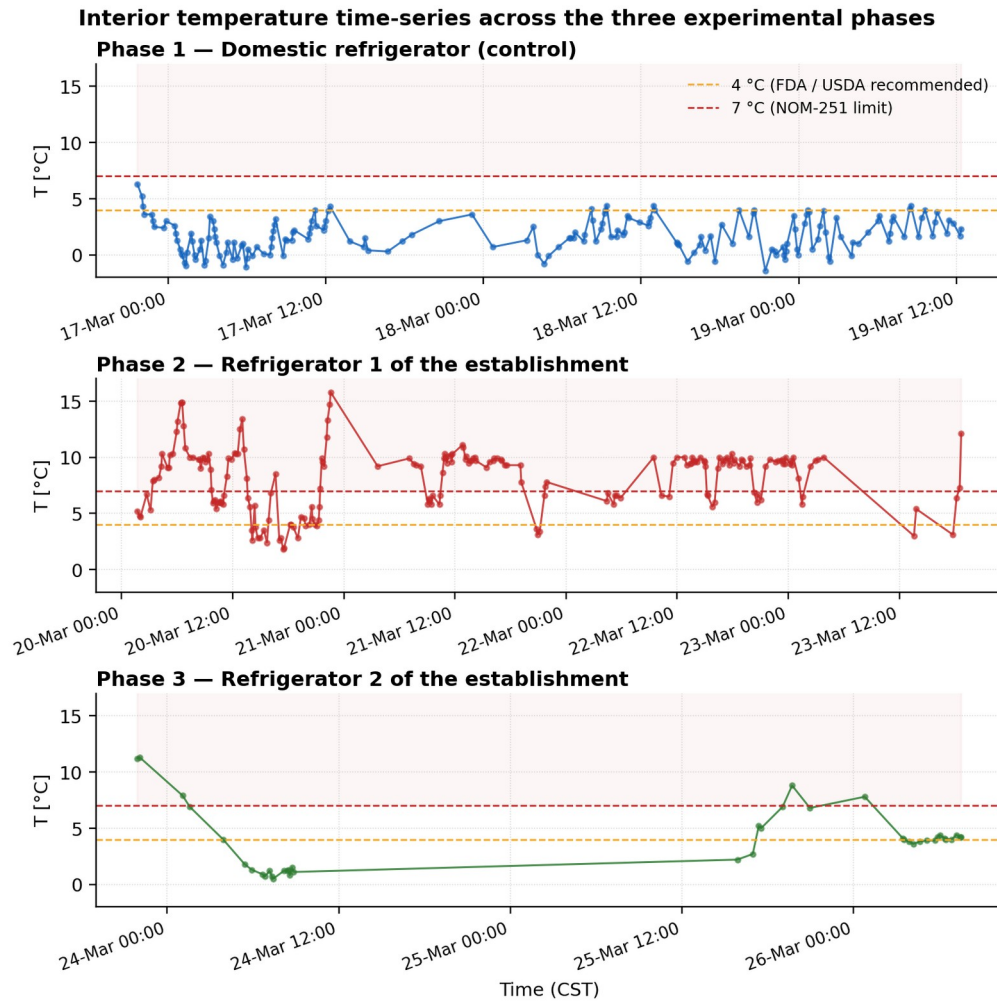


Fig. 5. Interior temperature time-series across the three experimental phases. The 4 °C and 7 °C reference lines correspond to FDA / USDA recommended and NOM-251 maximum limits, respectively.

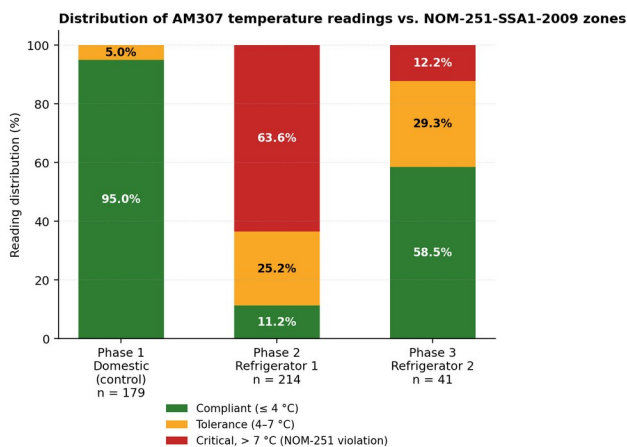


Fig. 6. Distribution of AM307 temperature readings vs. NOM-251-SSA1-2009 zones. Refrigerator 1 (F2) concentrates 63.6 % of readings in the > 7 °C critical zone; the post-intervention Refrigerator 2 (F3) reduces the critical fraction to 12.2 %.

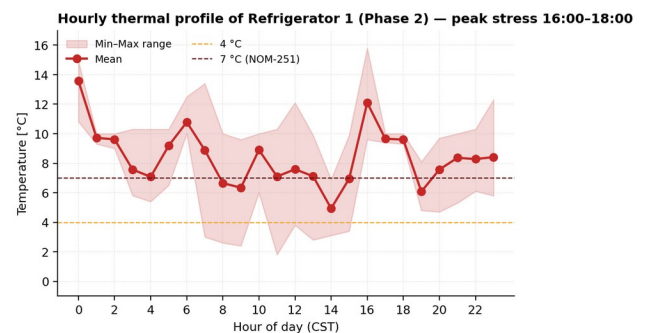


Fig. 7. Hourly thermal profile of Refrigerator 1 (Phase 2). Peak thermal stress concentrates between 16:00 and 18:00 CST, coinciding with end-of-service activity and ambient kitchen heat load.

V-C. Alert Engine Performance

Table III summarises the alert-engine activity across the F2 + F3 windows. Across these windows the alert engine produced 107 alert events. Of these, 24 were temperature alerts and 83 were stale-data alerts. The high stale-data fraction (77.6 % of all events) is a direct manifestation of the LTE-backhaul intermittency of the UG63 gateway and accounts for the OBSERVED verdict on the corresponding test case. Tier-2

Metric	Value
Total alert events	107
Temperature alerts	24 (10 warning + 14 critical)
Stale-data alerts	83 (77.6 %)
Tier-2 escalations	10
Tier-1 dispatch latency, mean	0.38 s
Tier-1 dispatch latency, min	0.22 s
Tier-1 dispatch latency, max	1.47 s
Longest sustained event (alert #137)	39.9 h continuous > 4 °C
Absolute peak temperature	15.8 °C (20-Mar 16:00–18:00 CST)
Cooldown after resolution	30 min
Tier-2 escalation delay	30 min (default)

TABLE III. ALERT-ENGINE SUMMARY (F2 + F3 WINDOW)

V-D. Critical Events

The most consequential alert of the deployment was alert #137, a 39.9 h continuous event above 4 °C that began on Friday 21 March at 15:39 CST and resolved on Sunday 23 March at 07:33 CST. The event spanned the entire weekend and reached an internal peak of 10.0 °C. Both Tier-1 and Tier-2 notifications were dispatched within their respective service-level windows, but no operator intervention occurred until staff returned on Monday morning. Under the USDA FSIS Danger Zone framing [3], food held in this regime can support bacterial doubling on the order of every 20 min, and *Listeria monocytogenes* growth at these temperatures is well documented [25], [27]. The event is therefore a cold-chain failure of practical significance and not merely a metric excursion. Fig. 8 shows the full window.

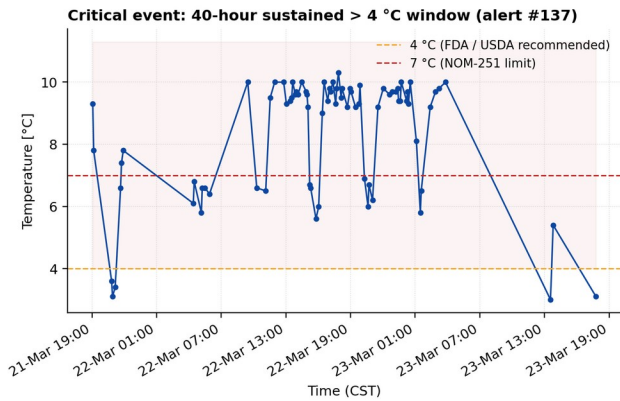


Fig. 8. Critical event window: 40-hour sustained temperature above 4 °C (alert #137, 21–23 March). Despite Tier-1 and Tier-2 dispatches, the event spanned the weekend without operator intervention. A separate alert (#119) recorded an 11.6 h continuous excursion above the NOM-251 7 °C ceiling, beginning Friday 20 March at 15:27 CST, resolving early Saturday 21 March at 03:04 CST, and peaking at 9.2 °C. The absolute peak temperature of the deployment, 15.8 °C, was recorded during the

escalation triggered ten times during the deployment, reflecting events that remained unresolved 30 min after their initial Tier-1 dispatch. The mean Tier-1 dispatch latency from the moment a triggering reading was persisted to the moment the Resend API accepted the email was 0.38 s, with a minimum of 0.22 s and a maximum of 1.47 s. Tier-1 latency therefore meets the FUN-ALERT-001 criterion of below one second by a comfortable margin.

evening of Thursday 20 March between 16:00 and 18:00 CST, again coincident with the daily end-of-service window identified in Fig. 7. The peak window is reproduced in Fig. 9.

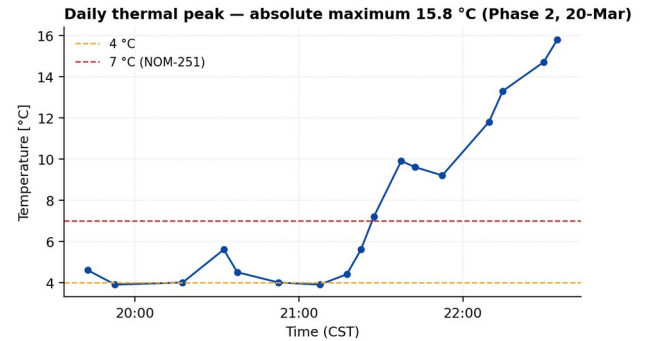


Fig. 9. Daily thermal-peak window. Absolute maximum 15.8 °C reached on 20 March between 16:00 and 18:00 CST. The Refrigerator-1-to-Refrigerator-2 transition itself is shown in Fig. 10. The handover occurred at approximately 12:40 CST on 23 March, after which the AM307 recorded a continuous cool-down from 7.9 °C at 19:04 on 23 March to 0.5 °C at 01:24 on 24 March. The transition is visible as a clean exponential settle to the new operating point and is the strongest single piece of evidence that the F2 anomaly was an equipment failure rather than an operational pattern: identical sensors, identical ambient kitchen, identical contents, and a step change of nearly 8 °C in the steady-state interior temperature. The most parsimonious explanation, consistent with the elevated humidity record and the sustained thermal load, is a deteriorated door seal in Refrigerator 1.

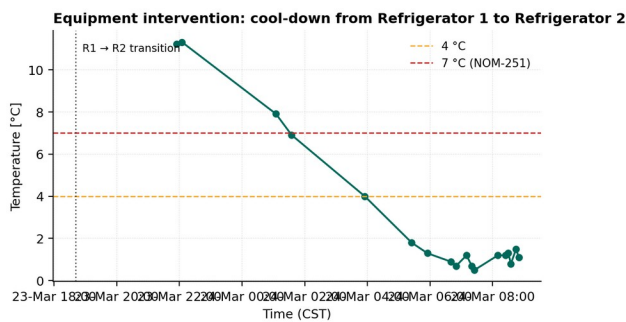


Fig. 10. Refrigerator-1-to-Refrigerator-2 transition: cool-down from 7.9 °C to 0.5 °C following equipment replacement (intervention motivated by SensorGrid alerts).

V-E. Auxiliary Variables

Relative humidity remained within the ASHRAE Chapter 21 [4] band for mixed perishable storage across both commercial phases. In Phase 2 the AM307 reported a mean of 71.91 % with a range of 45.5 % to 89.5 %, consistent with the elevated water-vapour load expected when warm humid air infiltrates through a degraded seal and condenses on the cold evaporator. In Phase 3 humidity centred around 59.6 %, in the middle of the recommended commercial-walk-in range. The CO₂ record stayed well within bounds: Phase 2 mean 531 ppm and Phase 3 mean 617 ppm, both an order of magnitude below the NOM-010-STPS-2014 [5] occupational TWA-8h limit of 5,000 ppm, and well within the postharvest-respiration regime modelled by Fonseca et al. [17]. The barometric pressure record was used as a calibration validator: AM307 reports were consistent at 836–842 hPa across all three phases — a span well within the cross-phase coherence test (INT-DATA-004), and consistent with the high-altitude character of the deployment region under the ISO 2533 standard atmosphere. The TVOC channel reported a constant SGP40 VOC Index of 1 across all phases: the SGP40 [33] uses a 24-h adaptive baseline, and inside a closed refrigerator with limited VOC variability the index saturates at the scale floor.

V-F. Limitations and Inconclusive Findings

Two methodological limitations must be reported alongside the headline results, because each constrains the scope of claims that SensorGrid can support in its current configuration. The first limitation concerns the energy-consumption analysis, which was inconclusive. The CT101 reported a constant `total_current` = 0.84 A and `current` = 0.00 A for all 2,056 readings of its operating window, and then ceased transmitting on 23 March at 16:54 CST. The flat record is shown in Fig. 11. The root cause is not a failure of the sensor itself but a deployment-time installation error: the toroid was clamped around the entire multi-conductor power cable of the refrigerator (live, neutral, and ground), rather than around a single conductor. As stated in the Milesight CT10x User Guide §3.2 [34], a toroid that encloses the full cable measures zero net magnetic flux because the inbound and outbound currents cancel; the measured value therefore reflects only sensor offset and self-noise. The verdict for INT-DATA-002 is consequently NOT APPROVED. The compressor-cycle

analysis, the energy-spike rule, and any predictive-maintenance reasoning that depends on current draw are therefore not validated by the present deployment. Rectifying the wiring is a one-shot intervention; the analysis itself was deferred to a follow-up campaign. The second limitation concerns the door-open detection rule built on the AM307 illuminance channel. The originally intended door-open/closed experiment was not viable at the establishment because both Refrigerator 1 and Refrigerator 2 have transparent glass doors with permanent internal lighting that remains on regardless of door position. Under such conditions the AM307 illuminance reading is dominated by the always-on internal lamp rather than by the door state, and any threshold-based door-open inference becomes uninformative — the lux signal is essentially decoupled from operator behaviour. The light-level rule was nonetheless retained in the codebase because it remains valid, and useful, for opaque-door equipment, where the signal-to-state relationship is restored. In the present deployment, however, no quantitative claim is made about door-opening behaviour. This limitation is intrinsic to the venue and is not a SensorGrid design defect; it is reported here so that future deployments at glass-door establishments can plan for an alternative proxy (for example, a magnetic reed switch on the door frame).

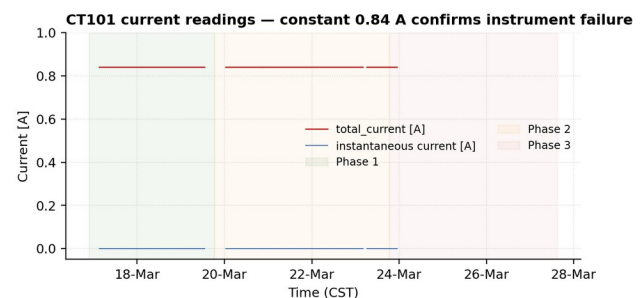


Fig. 11. CT101 current readings — constant 0.84 A across all 2,056 samples, evidencing toroid mis-installation per Milesight CT10x User Guide §3.2 and the inconclusiveness of the energy-consumption analysis.

VI. DISCUSSION

The most consequential operational finding of the deployment is that Refrigerator 1 was not merely warm — it was systematically out of compliance, with 63.6 % of readings above the NOM-251 7 °C ceiling and a peak of 15.8 °C. The natural diagnostic question is whether this regime reflects a duty-cycle problem (the compressor was undersized or under-cooled), an operational problem (doors held open during service), or an equipment problem (a degraded seal). Three converging pieces of evidence point to the third hypothesis. First, the relative humidity record was elevated and stable around 72 % during F2, which is consistent with continuous warm-humid air infiltration that condenses on the evaporator rather than with intermittent door openings, which would manifest as humidity spikes rather than a sustained shift. Second, the hourly temperature profile shows a clean diurnal cycle with the peak concentrated in the late-afternoon kitchen-load window, consistent with an envelope that fails to hold

against ambient stress rather than with discrete operator events. Third, and most decisively, replacing the unit with Refrigerator 2 — an otherwise comparable commercial refrigerator at the same site, exposed to the same ambient kitchen, and holding similar product — restored the 4 °C regime within hours and reduced the NOM-251 critical fraction by a factor of more than five. The simplest explanation that fits all three observations is a deteriorated door seal allowing continuous infiltration, and SensorGrid's alerts were the proximate cause of the establishment's decision to replace the unit. Beyond the technical diagnosis, the deployment exposes a sociotechnical pattern that is, if anything, more important for cold-chain practice. The alert engine performed exactly as designed — Tier-1 within 0.38 s, ten correct Tier-2 escalations, no spurious deduplication — yet alert #137 ran continuously for 39.9 h above 4 °C across a weekend without operator intervention. The engine succeeded technically and failed culturally: Tier-2 emails arrived in inboxes that were not monitored outside business hours, and there was no out-of-band channel (such as a phone call or an on-call rotation) to convert the digital escalation into a physical one. The implication for future deployments is that low-latency dispatch is necessary but not sufficient; the alert pathway must terminate in a recipient whose presence is contractually or operationally guaranteed during the windows in which excursions occur. This is a research direction in itself, and it suggests integrating SensorGrid alerts into the establishment's existing incident-response or maintenance workflows rather than treating email and Telegram as the ultimate sinks. A second discussion point concerns the indoor-air-quality variables. NOM-010-STPS-2014 [5], ASHRAE 62.1-2022, and the WHO IAQ Guidelines all target habitable spaces with human occupants, and their thresholds — most notably the 5,000 ppm CO₂ TWA-8h ceiling — were never intended to apply inside a refrigerator. The dominant CO₂ source inside a closed cold-storage volume is produce respiration [17], not occupant breath, and the appropriate benchmark is therefore the postharvest physiology of the stored commodity rather than an occupational exposure limit. Using the wrong benchmark would have made every reading look benign; reframing the threshold in terms of expected respiration rates allows CO₂ to function instead as a slow-moving indicator of product physiology. SensorGrid retains the rule with a configurable threshold so that operators can set it according to the dominant product mix, and we recommend that subsequent venue-level deployments adopt the same reframing rather than copying habitable-space limits unmodified. The architecture's generalisability rests on the cleanliness of its layer contracts. Replacing the AM307 and CT101 with any LoRaWAN device whose payload formatter produces the same JSON keys requires no change in the Worker. Replacing TTN with a different LoRaWAN network server requires only a webhook reconfiguration. Replacing the React dashboard with another front-end is a matter of consuming the same REST endpoints. The processing layer's serverless deployment also keeps the marginal cost of additional venues close to zero up to

substantial uplink volumes, which is the dimension along which venue-level cold-chain monitoring has historically failed economically. SensorGrid is therefore positioned to scale to multi-tenant deployments with per-tenant rule sets and dashboards, which is the natural next step beyond the single-establishment validation reported here.

VII. CONCLUSION

This paper has presented SensorGrid, a four-layer ISO/IEC 30141-aligned IoT platform for cold-chain compliance monitoring in commercial refrigeration. The technical contribution is an end-to-end stack — Milesight LoRaWAN sensors, a Milesight UG63 gateway, The Things Network v3, a Cloudflare Workers ingestion and rule engine, a Neon Postgres TimescaleDB hypertable, and a React 19 dashboard on Cloudflare Pages — backed by a two-tier alert engine with formal Tier-1/Tier-2 escalation, 30-min cooldown, an energy-spike rule, a sustained door-open rule, and a cron-driven stale-data watchdog. The empirical contribution is a structured three-phase field validation at a food-and-beverage establishment within a university campus, complemented by sixteen formal test cases. Across these: Phase 1 (domestic control, $n = 179$) recorded a mean of 1.76 °C with 95.0 % of readings at or below 4 °C; Phase 2 (Refrigerator 1, $n = 214$) recorded a mean of 8.16 °C with 63.6 % of readings above the NOM-251 7 °C ceiling and a peak of 15.8 °C; Phase 3 (Refrigerator 2, $n = 41$) recorded a mean of 3.94 °C with the NOM-251 critical fraction reduced to 12.2 %, motivated by a SensorGrid-driven equipment replacement. The alert engine produced 107 events with a mean Tier-1 dispatch latency of 0.38 s and ten correct Tier-2 escalations; the longest sustained event lasted 39.9 h above 4 °C. The test-case battery returned 13 APPROVED, 2 OBSERVED, and 1 NOT APPROVED verdicts. Two limitations are reported transparently. The energy-consumption analysis was inconclusive due to a CT101 toroid mis-installation that produced a constant 0.84 A reading and is documented in the Milesight CT10x User Guide §3.2 [34]. The intended door-open/closed experiment was not viable because the establishment's transparent glass doors with always-on internal lighting decouple the AM307 illuminance signal from door state. Future work falls along five axes. First, the platform will be scaled to a multi-tenant deployment with per-tenant rule sets, dashboards, and SLA reporting. Second, a root-cause-inference layer will be added on top of the alert engine to combine temperature, humidity, CO₂, and current signatures into hypothesis-ranked diagnoses. Third, once the CT101 wiring is corrected, compressor-cycle machine learning will be revisited as a predictive-maintenance signal. Fourth, formal HACCP integration will turn alert events into auditable critical-control-point records suitable for regulatory inspection. Fifth, the sociotechnical gap exposed by alert #137 motivates an on-call escalation layer that converts digital notifications into physical interventions during nights and weekends.

ACKNOWLEDGMENTS

The authors thank Mtro. Jorge Higinio Ochoa de León and Dr. Carlos Manuel Hernández Mejía, professors of the Laboratorio de Desarrollo de Soluciones Tecnológicas course at ITESO, for their guidance and support throughout the development and validation of this work. We are also grateful to the participating establishment for granting access to its refrigeration infrastructure and for collaborating with the field experiments.

REFERENCES

- [1] Secretaría de Salud, "NOM-251-SSA1-2009: Prácticas de higiene para el proceso de alimentos, bebidas o suplementos alimenticios," Diario Oficial de la Federación, México, Mar. 2010. [Online]. Available: <https://dof.gob.mx/normasOficiales/3980/salud/salud.htm>
- [2] U.S. Food and Drug Administration, "Food Code 2022", U.S. Dept. of Health and Human Services, Washington, DC, 2022. [Online]. Available: <https://www.fda.gov/food/retail-food-protection/fda-food-code>
- [3] U.S. Department of Agriculture, Food Safety and Inspection Service, "Refrigeration and Food Safety," 2023. [Online]. Available: <https://www.fsis.usda.gov/food-safety/safe-food-handling-and-preparation/food-safety-basics/refrigeration>
- [4] ASHRAE, "ASHRAE Handbook — Refrigeration", Ch. 21: "Commodity Storage Requirements," Atlanta, GA, USA, 2018. [Online]. Available: <https://www.ashrae.org/technical-resources/ashrae-handbook>
- [5] Secretaría del Trabajo y Previsión Social, "NOM-010-STPS-2014: Agentes químicos contaminantes del ambiente laboral," Diario Oficial de la Federación, México, Apr. 2014. [Online]. Available: https://www.dof.gob.mx/nota_detalle.php?codigo=5342372
- [6] ISO/IEC, "ISO/IEC 30141:2024 — Internet of Things (IoT) Reference Architecture", 2nd ed., Geneva, Switzerland: International Organization for Standardization, 2024. [Online]. Available: <https://www.iso.org/standard/88800.html>
- [7] N. Sornin and A. Yegin (Eds.), "LoRaWAN 1.1 Specification", LoRa Alliance, Beaverton, OR, USA, Oct. 2017. [Online]. Available: <https://resources.lora-alliance.org/technical-specifications/lorawan-specification-v1-1>
- [8] Semtech Corporation, "AN1200.22: LoRa™ Modulation Basics," Application Note, Rev. 2, May 2015. [Online]. Available: <https://www.semtech.com/uploads/documents/an1200.22.pdf>
- [9] S. Mercier, S. Villeneuve, M. Mondor, and I. Uysal, "Time-Temperature Management Along the Food Cold Chain: A Review of Recent Developments," *Compr. Rev. Food Sci. Food Saf.*, vol. 16, no. 4, pp. 647-667, 2017. doi: 10.1111/1541-4337.12269. [Online]. Available: <https://doi.org/10.1111/1541-4337.12269>
- [10] N. Ndraha, H.-I. Hsiao, J. Vlajic, M.-F. Yang, and H.-T. V. Lin, "Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations," *Food Control*, vol. 89, pp. 12-21, Jul. 2018. doi: 10.1016/j.foodcont.2018.01.027. [Online]. Available: <https://doi.org/10.1016/j.foodcont.2018.01.027>
- [11] S. Awasthi, P. S. Pandey, and P. C. Vashisth, "IoT-Driven Cold Chain Management for Real-Time Monitoring and Alerts for Perishable Goods," in *Proc. 2025 Int. Conf. Power Commun. Technol. (ICPCT)*, Greater Noida, India, Feb. 2025, pp. 1008-1012. doi: 10.1109/ICPCT64145.2025.10940754. [Online]. Available: <https://doi.org/10.1109/ICPCT64145.2025.10940754>
- [12] A. Carullo, S. Corbellini, M. Parvis, and A. Vallan, "A Wireless Sensor Network for Cold-Chain Monitoring," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 5, pp. 1405-1411, May 2009. doi: 10.1109/TIM.2008.2009186. [Online]. Available: <https://doi.org/10.1109/TIM.2008.2009186>
- [13] T. Müller et al., "Enhancing Food Safety in the Cold Chain Through Internet of Things and Artificial Intelligence: A Systematic Literature Review," *J. Food Sci.*, 2026. doi: 10.1111/1750-3841.70871. [Online]. Available: <https://doi.org/10.1111/1750-3841.70871>
- [14] S. Sarkar, K. S. Akshatha, A. Saurabh, B. Samanvitha, and M. F. Sarwar, "IoT Enabled Cold Supply Chain Monitoring System," in *Proc. 2022 IEEE 3rd Global Conf. for Advancement in Technology (GCAT)*, Bangalore, India, 2022, pp. 1-6. doi: 10.1109/GCAT55367.2022.9972137. [Online]. Available: <https://doi.org/10.1109/GCAT55367.2022.9972137>
- [15] K. Wisessing and N. Vichaidis, "IoT Based Cold Chain Logistics with Blockchain for Food Monitoring Application," in *Proc. 2022 7th Int. Conf. on Business and Industrial Research (ICBIR)*, Bangkok, Thailand, 2022, pp. 188-192. doi: 10.1109/ICBIR54589.2022.9786493. [Online]. Available: <https://doi.org/10.1109/ICBIR54589.2022.9786493>
- [16] A. N. Damdam, R. Y. Alhalwani, et al., "IoT-Enabled Electronic Nose System for Beef Quality Monitoring and Spoilage Detection," *Foods*, vol. 12, no. 11, art. 2227, 2023. doi: 10.3390/foods12112227. [Online]. Available: <https://doi.org/10.3390/foods12112227>
- [17] S. C. Fonseca, F. A. R. Oliveira, and J. K. Brecht, "Modelling respiration rate of fresh fruits and vegetables for modified atmosphere packages: a review," *J. Food Eng.*, vol. 52, no. 2, pp. 99-119, Apr. 2002. doi: 10.1016/S0260-8774(01)00106-6. [Online]. Available: [https://doi.org/10.1016/S0260-8774\(01\)00106-6](https://doi.org/10.1016/S0260-8774(01)00106-6)
- [18] G. Codeluppi, A. Cilfone, L. Davoli, and G. Ferrari, "LoRaFarM: A LoRaWAN-Based Smart Farming Modular IoT Architecture," *Sensors*, vol. 20, no. 7, art. 2028, 2020. doi: 10.3390/s20072028. [Online]. Available: <https://doi.org/10.3390/s20072028>
- [19] L. G. Manzano, H. Boukabache, S. Danzeca, et al., "An IoT LoRaWAN Network for Environmental Radiation Monitoring," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1-12, 2021, Art. no. 6008512. doi: 10.1109/TIM.2021.3089776. [Online]. Available: <https://doi.org/10.1109/TIM.2021.3089776>
- [20] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," *ICT Express*, vol. 5, no. 1, pp. 1-7, Mar. 2019. doi: 10.1016/j.icte.2017.12.005. [Online]. Available: <https://doi.org/10.1016/j.icte.2017.12.005>
- [21] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, "Understanding the Limits of LoRaWAN," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 34-40, Sep. 2017. doi: 10.1109/MCOM.2017.1600613. [Online]. Available: <https://doi.org/10.1109/MCOM.2017.1600613>
- [22] T. Domínguez-Bolaño, V. Barral, C. J. Escudero, and J. A. García-Naya, "An IoT system for a smart campus: Challenges and solutions illustrated over several real-world use cases," *Internet of Things*, vol. 25, art. 101099, Apr. 2024. doi: 10.1016/j.iot.2024.101099. [Online]. Available: <https://doi.org/10.1016/j.iot.2024.101099>
- [23] E. Gilman, S. Tamminen, R. Yasmin, et al., "Internet of Things for Smart Spaces: A University Campus Case Study," *Sensors*, vol. 20, no. 13, art. 3716, 2020. doi: 10.3390/s20133716. [Online]. Available: <https://doi.org/10.3390/s20133716>
- [24] A. Verma, S. Prakash, V. Srivastava, A. Kumar, and S. C. Mukhopadhyay, "Sensing, Controlling, and IoT Infrastructure in Smart Building: A Review," *IEEE Sens. J.*, vol. 19, no. 20, pp. 9036-9046, Oct. 2019. doi: 10.1109/JSEN.2019.2922409. [Online]. Available: <https://doi.org/10.1109/JSEN.2019.2922409>

- [25] V. Pennone, U. Gonzales-Barron, K. Hunt, V. Cadavez, O. McAuliffe, and F. Butler, "Omnibus Modeling of *Listeria monocytogenes* Growth Rates at Low Temperatures," **Foods**, vol. 10, no. 5, art. 1099, 2021. doi: 10.3390/foods10051099. [Online]. Available: <https://doi.org/10.3390/foods10051099>
- [26] A. H. Havelaar, M. D. Kirk, P. R. Torgerson, et al., "World Health Organization Global Estimates and Regional Comparisons of the Burden of Foodborne Disease in 2010," **PLOS Med.**, vol. 12, no. 12, art. e1001923, Dec. 2015. doi: 10.1371/journal.pmed.1001923. [Online]. Available: <https://doi.org/10.1371/journal.pmed.1001923>
- [27] M. B. Cole, M. V. Jones, and C. Holyoak, "The effect of pH, salt concentration and temperature on the survival and growth of *Listeria monocytogenes*," **J. Appl. Bacteriol.**, vol. 69, no. 1, pp. 63-72, 1990. doi: 10.1111/j.1365-2672.1990.tb02912.x. [Online]. Available: <https://doi.org/10.1111/j.1365-2672.1990.tb02912.x>
- [28] E. R. Ramos Silvestre, R. I. Fuentes Tellería, and A. Otalora Rodriguez, "Desarrollo de una plataforma de monitoreo para una red de dispositivos IoT empleando tecnología LoRaWAN," **J. Boliv. Cienc.**, vol. 18, no. 53, pp. 6-25, 2022. doi: 10.52428/20758944.v18i53.371. [Online]. Available: <https://doi.org/10.52428/20758944.v18i53.371>
- [29] A. N. Rosli, R. Mohamad, Y. W. M. Yusof, S. Shahbudin, and F. Y. A. Rahman, "Implementation of MQTT and LoRaWAN System for Real-time Environmental Monitoring Application," in **Proc. 2020 IEEE 10th Symp. on Computer Applications & Industrial Electronics (ISCAIE)**, Penang, Malaysia, 2020, pp. 287-291. doi: 10.1109/ISCAIE47305.2020.9108808. [Online]. Available: <https://ieeexplore.ieee.org/document/9108808>
- [30] I. L. Nossa Ruiz and R. M. Arias Castañeda, "Implementación red de sensores inalámbricos de bajo costo utilizando protocolo LoRaWAN aplicada al monitoreo de material particulado, monóxido de carbono y dióxido de nitrógeno como indicadores de calidad de aire en exteriores," B.S. thesis, Facultad de Ingeniería, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia, 2020. [Online]. Available: <http://hdl.handle.net/11349/25644>
- [31] P. Pierleoni et al., "IoT Solution based on MQTT Protocol for Real-Time Building Monitoring," in **Proc. 2019 IEEE 23rd Int. Symp. on Consumer Technologies (ISCT)**, Ancona, Italy, 2019, pp. 57-62. doi: 10.1109/ISCT.2019.8901024. [Online]. Available: <https://ieeexplore.ieee.org/document/8901024>
- [32] A. A. Hapsari, A. I. Hajamydeen, et al., "Real Time Indoor Air Quality Monitoring System Based on IoT using MQTT and Wireless Sensor Network," in **Proc. 2019 6th IEEE Int. Conf. on Engineering Technologies and Applied Sciences (ICETAS)**, Kuala Lumpur, Malaysia, 2019. doi: 10.1109/ICETAS48360.2019.9117518. [Online]. Available: <https://doi.org/10.1109/ICETAS48360.2019.9117518>
- [33] Sensirion AG, "Sensirion SGP40 Datasheet — Indoor Air Quality Sensor for VOC Measurements," Document Version 1.2, Stäfa, Switzerland, 2021. [Online]. Available: https://sensirion.com/media/documents/296373BB/6203C5DF/Sensirion_Gas_Sensors_Datasheet_SGP40.pdf
- [34] Milesight IoT Co., Ltd., "CT10x LoRaWAN Current Transformer User Guide v1.3," Xiamen, China, 2022. [Online]. Available: <https://resource.milesight.com/milesight/iot/document/ct10x-user-guide-en.pdf>