

Mitigating Administrative Latency through Edge-Computed Optical Decoding and Real-Time State Synchronization in Educational Environments

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Abstract

Administrative attendance routines can erode active teaching time, congest institutional networks, and produce fragile records when they depend on either manual logbooks or centralized server-side image processing. This study designed, implemented, and evaluated an edge-computed attendance framework that transfers QR-code decoding from the server to the client browser while preserving centralized validation and storage through an asynchronous FastAPI backend and PostgreSQL database. Using a developmental research design that integrated Agile SDLC with the Context, Input, Process, Product evaluation model, the study was deployed at Zamboanga del Sur Provincial Government College and assessed through time-motion observation, Apache JMeter stress testing, and an ISO/IEC 9126-based questionnaire completed by 47 respondents (42 students, 3 educators, and 2 IT administrators). Results showed that the legacy attendance workflow was characterized by recurring administrative delay ($M = 3.43$), bandwidth strain ($M = 3.39$), and record-management difficulty ($M = 3.37$). The deployed backend sustained strong benchmark performance from 50 to 500 concurrent users, with mean response times of 22-97 ms, peak CPU utilization of 21.6%, peak memory consumption of 209 MB, and zero failed requests. Post-implementation evaluation indicated positive system quality across functionality, reliability, usability, efficiency, portability, and security (overall $M = 3.97$, $p < .001$). Attendance-processing time decreased from 4.62 minutes under the manual procedure to 0.83 minutes with the proposed framework, recovering 3.79 minutes of pedagogical engagement per class session. The findings demonstrate that edge-computed optical decoding offers a scalable, hardware-agnostic, and instruction-preserving approach to attendance management in resource-constrained educational environments, though future iterations must balance this decentralized efficiency with advanced cryptographic safeguards and broader, multi-departmental validation.

Keywords: edge computing; attendance management; QR decoding; FastAPI; educational technology; administrative latency

INTRODUCTION

Administrative efficiency in higher education is often discussed as a peripheral operational concern, yet its cumulative effect on teaching and learning is substantial. In routine classroom practice, attendance

checking, late verification, and attendance-report preparation consume minutes that would otherwise be devoted to content delivery, formative assessment, or discussion. This condition may be described as administrative latency: the recurring loss of active instructional time caused by repetitive record-keeping tasks. In institutions that still rely on roll call or paper logbooks, the problem is visible in the classroom itself. In institutions that have attempted partial digitalization, the problem may simply migrate from paper to overloaded web portals and delayed synchronization. In either case, the instructional period is fragmented by procedures that are necessary for compliance but inefficient in execution.

The pedagogical relevance of this problem is clear. Attendance is not merely a clerical requirement but a variable associated with academic participation, continuity of learning, and classroom engagement. Recent work has continued to show that regular attendance and effective time management remain linked to better learning outcomes and stronger academic performance (Masnan et al., 2025; Soni & Banwet, 2025). Likewise, reductions in active instruction time can weaken motivation and achievement, especially in tightly scheduled higher-education settings (Niki, 2024). When several minutes of every class meeting are consumed by attendance administration, the cumulative loss across a semester becomes educationally consequential.

In many campuses, the administrative act of confirming attendance appears deceptively simple, but it triggers a chain of additional tasks: verification of late arrivals, consolidation of make-up or corrected entries, preparation of summaries for department monitoring, and eventual reproduction of records in printable or spreadsheet formats. These micro-processes are often invisible when institutions discuss digital transformation at the policy level, yet they determine whether a technology genuinely improves classroom operations. A system that merely digitizes the final record without changing how attendance is captured may preserve most of the original inefficiency. The more relevant question, therefore, is not whether attendance becomes digital, but whether the transaction architecture minimizes disruption during the moment of classroom use.

Many institutions have responded by adopting automated attendance technologies, but prevailing solutions are frequently more suitable to resource-constrained academic environments. Hardware-dependent approaches such as biometric scanners, RFID devices, and proprietary terminals require substantial acquisition sufficient and maintenance costs. Software-based alternatives that depend on centralized server-side computer vision introduce a different burden. Rather than merely validating small attendance submissions, the central server must process or decode visual data streamed from user devices. Under class-shifting conditions where many students attempt to check in simultaneously, such architectures can congest bandwidth, increase latency, and create server contention. Analytical models of overloaded web systems and network congestion show that centralized handling of burst traffic can degrade goodput and invite excessive overhead processing (Mathur & Apte, 2009; Wang et al., 2014).

The present study addresses that architectural bottleneck by shifting optical decoding from the cloud to the edge. Through browser-based access to the device camera and localized execution of the jsQR library, the proposed framework extracts the QR matrix on the client device itself. The server therefore receives only a lightweight deterministic payload rather than continuous image or video data. Validation, authentication, session rules, and persistent storage remain centralized through an asynchronous FastAPI backend and PostgreSQL database. In operational terms, the design aims to preserve the strengths of centralized record integrity while removing the most bandwidth-intensive and processor-intensive element of attendance capture.

The study is also grounded in a socio-technical perspective. From the standpoint of distributed computing, edge processing reduces unnecessary network traversal and places computation closer to the point of data generation. This approach is consistent with contemporary research on multi-access edge computing, which emphasizes lower latency, improved responsiveness, and more efficient network behavior when workloads are distributed toward end devices or access-layer nodes (Kamyszek-Mały et al., 2026; Viswanathan et al., 2026). In the viewpoint of technology acceptance, the system must also be easy to use and visibly useful if educators and students are to adopt it in everyday classroom practice. Browser-based access, device agnosticism, and immediate state feedback were therefore treated not as superficial interface choices but as design requirements tied to perceived usefulness and perceived ease of use.

A further dimension of the problem concerns sustainability and institutional modernization. Manual attendance systems produce fragile paper trails, require repetitive transcription, and complicate the

export into administrative reports. A digital attendance system that can produce accurate, chronologically organized, and interoperable outputs contributes to institutional data quality while reducing paper dependency. Such an intervention supports not only Quality Education through recovered instructional time but also more resilient educational infrastructure and more sustainable operational routines. In this sense, attendance management becomes a practical site where educational technology, organizational efficiency, and sustainable development intersect.

The institutional significance of the problem is particularly strong in settings where classes begin in rapid succession and multiple sections rely on the same network infrastructure. In such environments, even technically modest delays can scale into visible operational friction. Students wait for confirmation, faculty lose the rhythm of lesson opening, and administrators later inherit records that still require manual normalization. An architecture that prevents these delays at the point of entry can therefore create benefits that extend beyond the classroom moment itself and into the reporting, auditing, and planning functions of the institution.

Guided by these concerns, the study aimed to design, implement, and evaluate a decentralized architectural framework for attendance management at Zamboanga del Sur Provincial Government College. Specifically, it sought to: (1) determine the baseline condition of attendance management and classroom logistics in terms of administrative latency, infrastructure load, and record reliability; (2) evaluate the computational performance of the client-side jsQR and asynchronous FastAPI architecture; (3) assess post-implementation system quality and user adoption through the ISO/IEC 9126 dimensions of functionality, reliability, usability, efficiency, portability, and security; and (4) test whether the proposed framework significantly reduced attendance-processing time relative to the conventional method. The working assumption of the study was that decentralizing optical decoding would lower server pressure, preserve request integrity, and reclaim measurable teaching time without imposing proprietary hardware costs.

Theoretical foundation.

The study is anchored in three complementary lenses that explain why the proposed framework is both technically viable and practically adoptable in educational settings. First, distributed computing and edge-computing theory justify relocating QR extraction from the central server to the client device so that only compact attendance payloads traverse the network. Second, the Technology Acceptance Model explains institutional adoption in terms of perceived usefulness and perceived ease of use, both of which

are addressed through browser-based access, minimal setup friction, and immediate attendance confirmation. Third, behavioral reinforcement and light gamification explain why deterministic feedback on attendance status can strengthen punctuality, compliance, and routine engagement among students.

LITERATURE REVIEW

The literature on digital attendance management converges around a central tension: institutions seek automation to reduce clerical burden, yet many attendance technologies create new infrastructural, financial, or ethical constraints. A thematic review of the literature presents a comprehensive discussion on the research gap to clarify why an edge-computed, browser-based architecture is a promising alternative.

Administrative latency and the instructional value of time. The educational case for attendance innovation begins with the value of classroom time itself. Research in higher education consistently indicates that attendance, time management, and classroom engagement are entangled determinants of academic outcomes (Masnan et al., 2025; Soni & Banwet, 2025). Studies on instructional time have likewise shown that reductions in contact time can negatively affect motivation and achievement (Niki, 2024). These findings imply that attendance systems should not be assessed solely by whether they produce a record; they should also be assessed by how much of the scheduled period they preserve for teaching. In this regard, administrative latency is not simply an inconvenience but an educational inefficiency with measurable pedagogical implications.

Traditional attendance technologies and their limitations. A major body of work on attendance automation centers on biometric recognition, facial recognition, and institutionally managed access devices. Design science studies and computer-vision implementations have demonstrated that such systems can automate identity capture, yet they also remain sensitive to environmental factors, privacy concerns, and infrastructure cost (Nguyen-Tat et al., 2024; Bah & Ming, 2020). Facial-recognition pipelines typically require image pre-processing and centralized inference workloads that can become computationally expensive under real-world conditions such as variable illumination, pose, and background noise. Hardware-bound solutions may reduce some classroom friction but often impose acquisition and maintenance burdens that resource-conscious colleges cannot easily sustain. The literature therefore suggests that the problem is not automation per se, but the choice of automation architecture.

Recent investigations into attendance automation indicate that institutional adoption is directly contingent upon the seamless integration of new systems into established operational workflows. Regardless of technological sophistication, implementations frequently fail in pedagogical settings if they necessitate extensive user retraining, continuous technical troubleshooting, or proprietary hardware configurations. This distinction is critical, as contemporary discourse surrounding educational technology frequently prioritizes functional novelty over practical utility.

When contrasted with alternative digital attendance modalities, the edge-computed jsQR approach offers a distinct infrastructural compromise. Recent computer vision pipelines employing facial recognition successfully achieve passive identity capture but demand continuous, high-bandwidth image streaming and centralized inference. This architecture frequently scales poorly under the sudden, high-density traffic bursts characteristic of rapid class transitions. Conversely, hardware-bound solutions effectively localize the authentication process but introduce rigid acquisition, maintenance, and proprietary constraints. The proposed asynchronous FastAPI architecture bridges this gap by co-opting

the computational capacity already present in users' mobile devices. This effectively mirrors the decentralized processing efficiency of hardware systems without the associated costs, while simultaneously bypassing the severe network latency inherent in centralized image pipelines.

Network strain, centralization, and overloaded service behavior. Centralized attendance architectures exhibit critical vulnerabilities during periods of peak operational demand, specifically the high-concurrency intervals preceding instructional shifts or simultaneous class transitions. As demonstrated by analytical models of web server congestion, system throughput under such burst traffic can precipitously decline despite sustained, high-level CPU utilization. This paradoxical degradation occurs because the centralized server exhausts critical computational capacity on non-productive tasks, namely the management of TCP connection overhead, the processing of redundant request retries, and the handling of abandoned user sessions (Mathur & Apte, 2009). Work on overload control in session-oriented networks similarly demonstrates that edge-side control and load estimation are preferable to exclusive reliance on core server processing during traffic spikes (Wang et al., 2014). Translated to an educational setting, these insights support architectures that minimize central workload during attendance capture rather than expanding the amount of visual or transactional data delivered to the server.

Edge computing as a response to institutional constraints. Contemporary studies on multi-access edge computing describe a broader migration away from cloud-only logic toward distributed execution models that place computation near the data source (Kamyszek-Mały et al., 2026). This shift is especially relevant in environments where connectivity is limited, latency matters, or privacy is enhanced by local processing. Within educational attendance architectures, the integration of edge computing effectively mitigates backhaul network traffic by localizing the most computationally intensive procedure—specifically, the optical decoding of QR matrices—to the client device prior to network transmission. Research on optimization in dense communication environments also indicates that system performance improves when traffic is balanced and unnecessary communication overhead is avoided (Manganaris et al., 2025). The present study adopts that principle by allowing the mobile device to perform matrix extraction locally and sending only compact attendance data to the server.

QR technology and browser-based optical decoding. Compared with facial recognition and similar image-intensive modalities, QR-based attendance systems offer determinism, low computational complexity, and clear state transitions. Reviews of QR and barcode applications have noted their practicality for rapid information access and site-based workflows where reliable identification is needed without heavy processing overhead (Lopez & Rose, 2025). Emerging OCR and optical-identification studies likewise suggest that when recognition tasks are simplified and targeted, response times can remain fast even in lightweight deployments (Wu & Chang, 2025). Browser-based optical decoding extends these advantages by removing the need for native mobile applications. Through standard web APIs and client-side libraries, institutions can deploy attendance capture across heterogeneous devices with minimal installation friction.

Technology acceptance and behavioral reinforcement. Technical efficiency alone does not guarantee adoption. Studies examining technology use in educational environments repeatedly show that perceptions of usefulness and ease of use shape whether a system becomes part of everyday practice (Açıkgül & Şad, 2026; Schittko et al., 2026). Automated attendance systems are particularly susceptible to these adoption dynamics, as they require high-frequency utilization under strict temporal constraints by user cohorts exhibiting heterogeneous levels of technological proficiency. A browser-based, camera-

enabled interface reduces training demands, while immediate confirmation of attendance status addresses user assurance. The study also draws on the logic of behavioral reinforcement: when users receive immediate and unambiguous system feedback, compliance and routine adherence tend to improve. Gamification research in educational environments has shown that immediate feedback can enhance participation and engagement when used judiciously (Romero-Rodríguez et al., 2024; Wang et al., 2025).

Infrastructure modernization and educational sustainability. The literature also frames digital educational infrastructure as part of wider institutional modernization. Research on the concentration of higher-education resources and the role of digital systems in regional innovation suggests that institutions gain organizational value when operational processes are streamlined and digital records become more reliable and interoperable (Chen et al., 2026; Li & Gao, 2026). Attendance systems that can export structured outputs into CSV, Excel, or PDF formats reduce clerical duplication and strengthen administrative continuity. In institutions where paper logbooks remain common, a shift to structured digital reporting simultaneously improves record quality and supports paperless processes.

Across these themes, three ideas recur. First, attendance management should be evaluated as a pedagogical and organizational process rather than a purely clerical task. Second, centralized systems can become weakest when user concurrency is highest, which makes architectural choices central to performance. Third, user acceptance depends on whether a system is simple, trustworthy, and compatible with ordinary device conditions. These themes collectively justify the present study's focus on edge-decoded QR attendance as a context-appropriate balance of speed, affordability, interoperability, and everyday usability.

Synthesis. The literature identifies a clear gap between the promise of attendance automation and the operational realities of many colleges. Existing systems either depend too heavily on proprietary hardware, demand central image-processing workloads, or inadequately address user adoption and record interoperability. The literature therefore supports the hypothesis that an edge-computed, QR-based, browser-accessible attendance framework can offer a more context-appropriate balance of efficiency, affordability, usability, and data quality.

METHODS

Research design. This study utilized a developmental research methodology that synergized the Agile Software Development Life Cycle (SDLC) with the Context, Input, Process, and Product (CIPP) evaluation framework. The Agile SDLC was adopted to facilitate the continuous, iterative refinement of the system's interface architecture, localized decoding algorithms, backend validation protocols, and data reporting modules. Concurrently, the CIPP model served as the macro-evaluative structure, enabling a systematic assessment of the initial institutional constraints, the mobilized technical resources, the deployment execution, and the final system outcomes. This hybrid methodological approach was deliberately selected; the primary objective extended beyond the mere construction of a software artifact, seeking to empirically validate its efficacy in resolving targeted pedagogical and infrastructural bottlenecks.

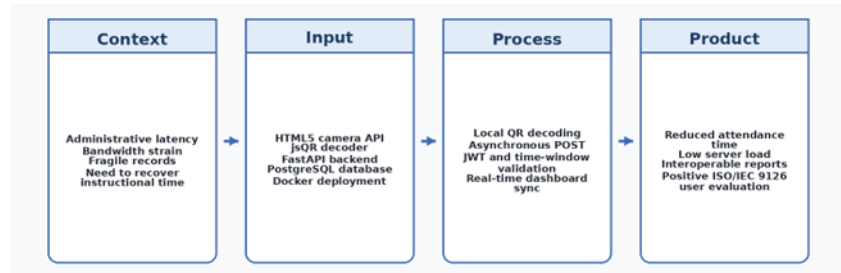


Figure 1. *CIPP-based conceptual framework used to evaluate the institutional need, technical inputs, implementation process, and resulting product quality.*

Research setting and respondents. The study was conducted at Zamboanga del Sur Provincial Government College, an academic environment characterized by ordinary classroom schedules, institutional Wi-Fi dependency, and mixed user-device conditions. The post-implementation evaluation involved 47 respondents, composed of 42 students, 3 educators or faculty members, and 2 IT administrators. The respondent profile was intentionally stratified to capture the perspectives of direct users, classroom process owners, and technical evaluators. Students evaluated actual use conditions, educators assessed classroom utility and time recovery, and IT administrators assessed deployment readiness, portability, security, and infrastructure behavior.

The research setting was purposively selected to embody authentic academic constraints rather than optimized laboratory conditions. The deployment context encompassed heterogeneous client devices with disparate optical capabilities and operating systems, rigorous temporal constraints typical of instructional shifts, and the inherent bandwidth limitations of existing institutional infrastructure. Evaluating the framework under these naturalistic conditions was critical for establishing ecological validity, ensuring that the empirical findings reflect the system's operational viability for routine pedagogical deployment rather than its theoretical efficacy in an idealized state.

Table 1. *Distribution of respondents*

Respondent group	n	%
Student	42	89.4
Educator/Faculty	3	6.4
IT Administrator	2	4.3
Total	47	100.0

System architecture and implementation. The framework followed a decentralized edge-to-cloud architecture appropriate to Information Technology and Computer Science deployment contexts. On the client side, the browser accessed the camera through the HTML5 mediaDevices API and executed the jsQR library to decode the QR matrix locally. Once decoding succeeded, the application paused the capture loop and transmitted only the deterministic text payload needed for attendance validation. On the server side, an asynchronous FastAPI application received the request, validated the tokenized session state, matched the payload against the active attendance window, and persisted the record to PostgreSQL. A real-time dashboard updated the attendance state through lightweight polling rather than full-page

refreshes. Docker containerization was used to stabilize deployment across environments and to reduce dependency drift during testing and rollout.

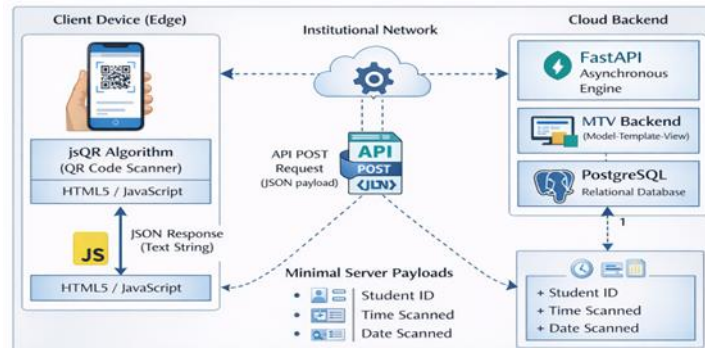


Figure 2. System architectural design of the edge-computed attendance framework.

Figure 2 presents the system architectural design adopted in the implementation. Its principal design decision is the transfer of QR extraction from the cloud to the client device. This reduces network traffic from continuous image streaming to a compact JSON payload and constrains the backend to validation, persistence, and state synchronization tasks.

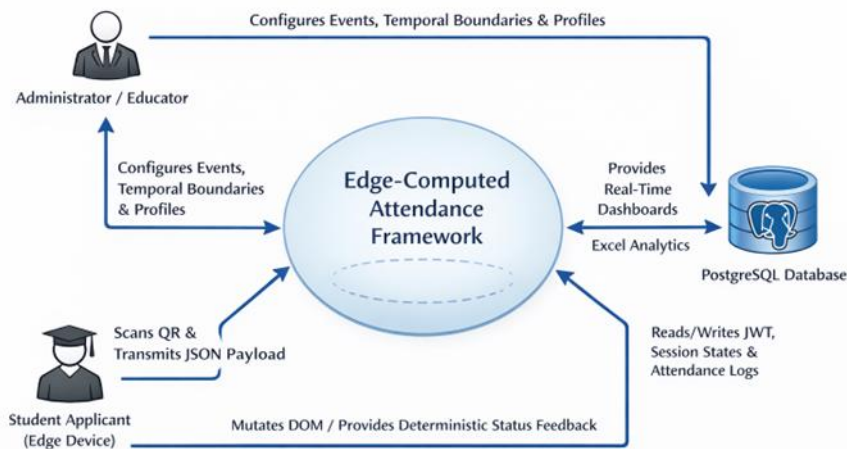


Figure 3. High-level interaction diagram for configuration, scanning, validation, and record generation.

The operational interaction design clarifies how administrative actors configure sessions and profiles, how student devices initiate localized QR scanning, and how the framework produces deterministic feedback and synchronized records.

Algorithm 1 summarizes the client-side scan routine and the server-side validation sequence that jointly produce deterministic attendance capture and synchronization.

Input: video stream V, QR decoder D, authenticated session token T

Output: persisted attendance state R and updated client status S

```
1: initialize browser camera and bind stream V
2: while V is active do
3:   frame <- capture current video frame
4:   payload <- D.decode(frame)
5:   if payload is valid then
6:     pause local scanning loop
7:     request <- {student_id: payload, token: T, timestamp: now()}
8:     send asynchronous POST request to /attendance/scan
9:     if backend validates token, time window, and session rules then
10:       persist attendance record R in PostgreSQL
11:       return success response and status metadata
12:       trigger client dashboard refresh to obtain state S
13:     else
14:       return deterministic rejection message
15:     end if
16:   break
17: end if
18: end while
```

Algorithm 1. *Pseudocode of the edge-computed scan, validation, and synchronization workflow.*

Figures 4 through 6 delineate the graphical user interfaces deployed during the live implementation phase, specifically encompassing the administrative scanning module, the centralized administrative dashboard, and the student access portal. The study evaluates an applied computing artifact, parameters such as heuristic usability, deterministic feedback latency, and interface lucidity constitute core variables of the research design rather than mere post hoc visual supplements.

Figure 4. Administrative scanner workflow: secure activation, camera initialization, live QR detection, and success feedback.

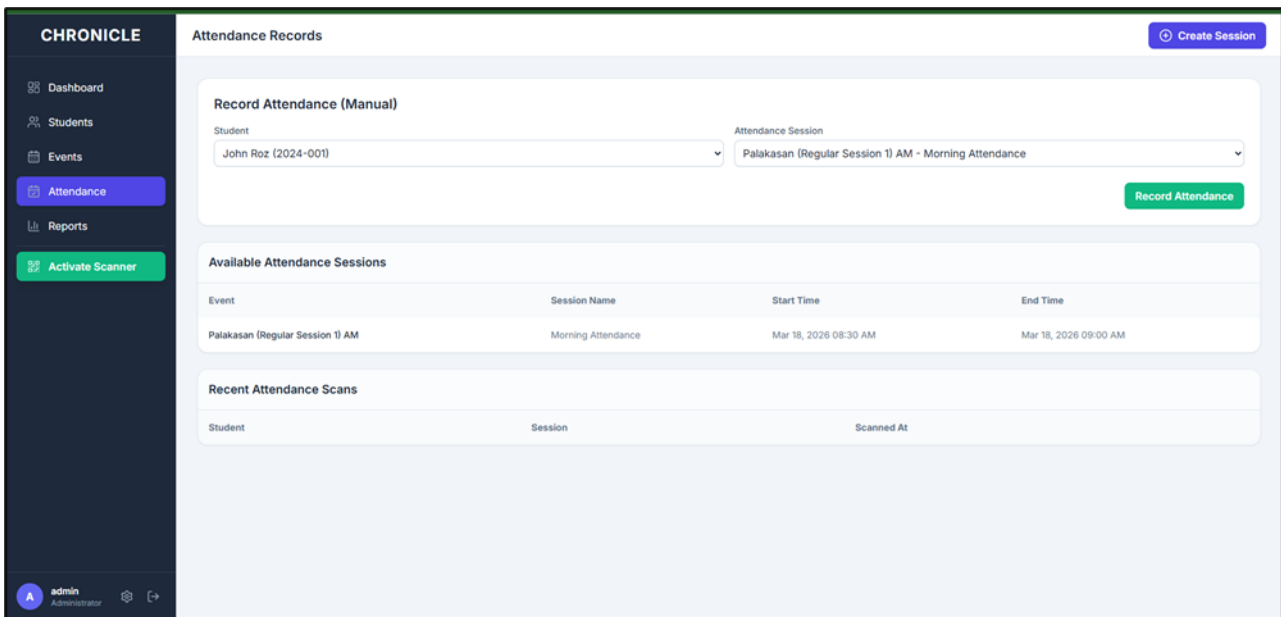
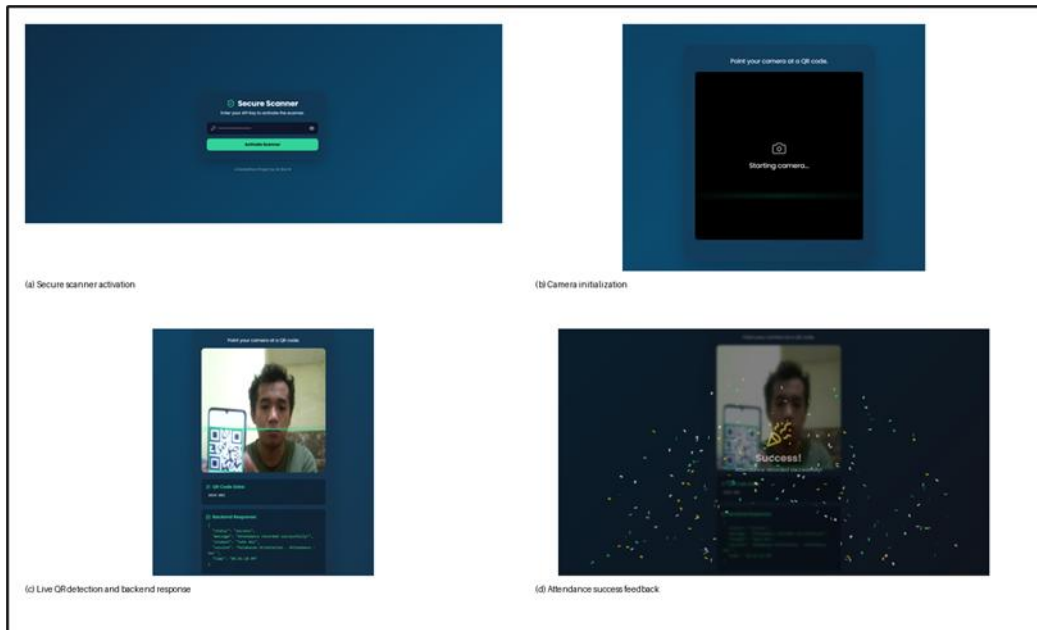


Figure 5. Administrator dashboard showing session selection, manual attendance fallback, recent scans, and session-level monitoring.

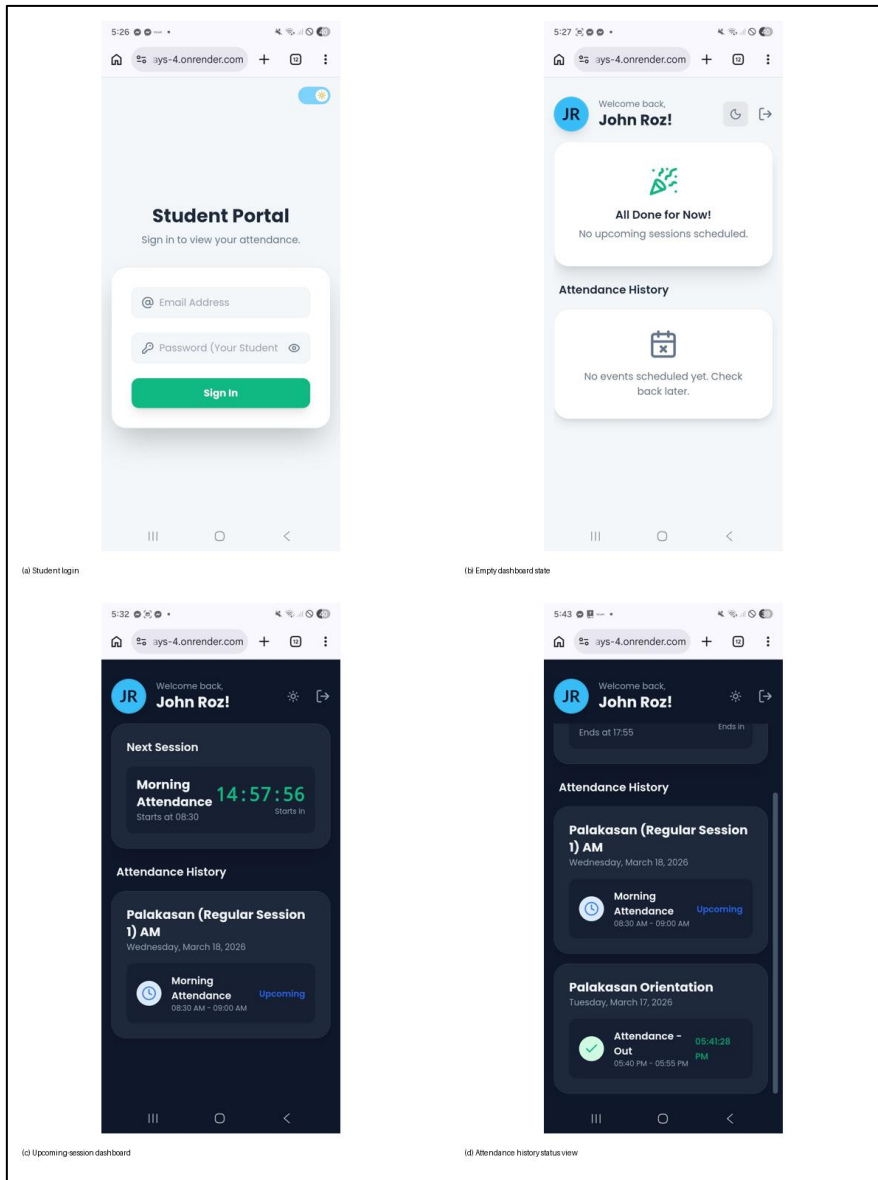


Figure 6. Student portal interfaces showing login, empty dashboard, upcoming-session state, and attendance-history state.

Research instruments. Three principal instruments were used. First, a time-motion observation log measured the duration of attendance-taking under both the conventional manual procedure and the deployed framework during live sessions. Second, Apache JMeter simulated escalating concurrent traffic to the attendance endpoint, producing metrics for throughput, mean response time, 95th-percentile response time, CPU usage, memory usage, and request integrity. Third, a structured questionnaire based on ISO/IEC 9126 measured functionality, reliability, usability, efficiency, portability, and security. A separate baseline section asked respondents to rate the existing attendance process in terms of administrative latency, infrastructure strain, and record reliability.

Instrument validation and reliability. The questionnaire was reviewed by subject-matter experts in information technology and educational research to establish content validity. After revision, the instrument was pilot tested and subjected to internal-consistency analysis through Cronbach's alpha. The

final study retained scales with acceptable-to-excellent internal consistency, allowing the questionnaire to support both descriptive and inferential analysis.

The use of multiple instruments served a methodological purpose. The questionnaire captured perception, the JMeter benchmark captured infrastructure behavior, and the time-motion log captured a direct educational outcome. Together, these measures reduced the risk of evaluating the framework through a single lens only. A system may be liked by users while still performing poorly under concurrency, or it may benchmark well while failing to save time in actual classes. The triangulated design was intended to avoid those interpretive blind spots.

Table 2. Internal consistency estimates of the questionnaire scales

Scale	Items	Cronbach's α	Interpretation
Administrative Latency and Loss of Instructional Time	5	0.832	Good
Infrastructure Load and Network Bandwidth	5	0.920	Excellent
Data Interoperability and Record Reliability	5	0.780	Acceptable
Functionality	5	0.876	Good
Reliability	5	0.923	Excellent
Usability	5	0.914	Excellent
Efficiency	5	0.932	Excellent
Portability	5	0.891	Good
Security	5	0.906	Excellent
Part I overall scale	15	0.923	Excellent
Part II overall scale	30	0.972	Excellent

Scoring and statistical treatment. The baseline questionnaire used a five-point frequency scale ranging from 1 (Never) to 5 (Always), while the post-implementation system-quality section used a five-point agreement scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). Weighted means and standard deviations summarized the distribution of responses, confidence intervals were computed at the 95% level, and one-sample t-tests were used to test whether post-implementation scores exceeded the neutral midpoint. The time comparison between manual attendance and the proposed framework was analyzed with a paired-samples t-test.

To preserve transparency in the statistical procedure, the following formulas guided analysis:

$$\bar{X} = \Sigma(fx) / N$$

$$\alpha = K / (K - 1) \cdot (1 - \Sigma\sigma_i^2 / \sigma_t^2)$$

$$t = \bar{d} / (s_d / \sqrt{n})$$

where \bar{X} is the weighted mean, f is the frequency of responses, x is the numerical scale value, and N is the number of responses; α denotes Cronbach's alpha; K is the number of items in the scale; and the paired-samples t -statistic compares the mean difference in attendance-processing time against the variability of those differences.

Data-gathering procedure. Data collection proceeded in three phases. During the pre-implementation phase, respondents assessed the baseline attendance workflow. During implementation, live sessions were observed and benchmark tests were executed. During post-implementation evaluation, respondents completed the ISO/IEC 9126 questionnaire after using the system in an operational context. All responses were checked for completeness, anonymized, and prepared for statistical analysis.

Ethical considerations. Participation in the questionnaire component was voluntary. Respondents were informed of the study objectives, and data were handled confidentially. The system itself was designed with bounded scope and authenticated access. JWT-based routines were used to control requests, and the framework was treated strictly as an attendance-state and reporting mechanism rather than as an autonomous disciplinary tool. Any academic judgment based on the generated records remained under the authority of the educator.

RESULTS

Results are presented in direct sequence with the research objectives. The section begins with the baseline status of attendance management, proceeds to the computational profile of the deployed architecture, then presents post-implementation system-quality outcomes, and finally reports the difference in attendance-processing time between the manual and edge-computed procedures.

Baseline condition of attendance management. Respondents described the pre-existing workflow as moderately to frequently problematic. Among the three baseline dimensions, administrative latency and loss of instructional time registered the highest mean, followed by infrastructure load and network bandwidth, and data interoperability and record reliability. The pattern suggests that the legacy process did not fail in a single dimension alone; rather, it produced a compound burden across time, connectivity, and documentation.

Table 3. *Summary of baseline attendance-management conditions*

Dimension	Mean	SD	95% CI	α	Rating
Administrative Latency and Loss of Instructional Time	3.43	0.69	3.23-3.64	0.832	Often
Infrastructure Load and Network Bandwidth	3.39	0.91	3.12-3.66	0.920	Sometimes
Data Interoperability and Record Reliability	3.37	0.60	3.19-3.54	0.780	Sometimes
Overall baseline condition	3.40	0.64	3.21-3.59	0.923	Sometimes

The administrative-latency mean of 3.43 indicates that respondents often experienced delays and disruption related to attendance administration. The significance of this finding is underscored by the

study's conceptualization of attendance efficiency as a pedagogical imperative rather than a purely administrative function. When routine record-keeping and the iterative verification of tardy students monopolize the initial minutes of a class, the instructional period inevitably commences under structurally fragmented conditions. In turn, the infrastructure dimension mean of 3.39 suggests that existing network-dependent approaches were vulnerable to slowdown during peak periods. Finally, the record-reliability mean of 3.37 indicates recurring difficulty in generating reports, exporting data, or maintaining dependable attendance records. The baseline therefore substantiates the need for a system that simultaneously reduces delay, minimizes network burden, and improves reporting structure.

The baseline data indicates that administrative inefficiencies manifest as cumulative, rather than isolated, phenomena. Institutions that incur instructional time loss during initial attendance capture are highly susceptible to compounding delays during subsequent record consolidation and error remediation. This trajectory is critical for comprehensive system evaluation; it dictates that the operational benefits of the proposed framework must not be quantified solely by the latency reduction at the immediate point of data entry, but must also encompass the downstream mitigation of clerical redundancies associated with record organization and verification.

Computational performance of the decentralized backend. Stress testing through JMeter demonstrated that the application sustained strong performance as simulated load increased from 50 to 500 concurrent users. Throughput increased proportionally, mean response time remained under 100 ms even at the highest test level, and no failed requests were recorded. CPU and RAM use also remained restrained, supporting the premise that localized decoding shields the backend from computationally heavy visual-processing work.

Table 4. Consolidated JMeter performance profile of the deployed backend

Concurrent users	Throughput (req/s)	Mean RT (ms)	P95 RT (ms)	Peak CPU (%)	Peak RAM (MB)	Error rate (%)
50	48.7	22	39	6.8	126	0.00
100	97.1	31	55	9.7	139	0.00
250	242.8	58	94	14.3	171	0.00
500	481.5	97	151	21.6	209	0.00

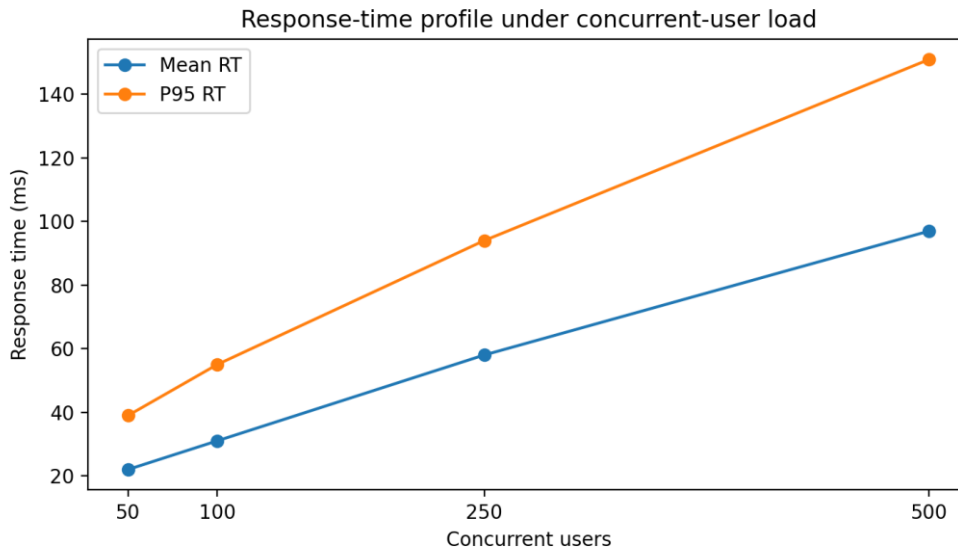


Figure 7. Mean and 95th-percentile response times across increasing concurrent-user loads.

The profile shown in Table 4 and Figure 7 indicates that the framework sustained low-latency transactional efficiency despite an order-of-magnitude escalation in concurrent user load. Furthermore, the proportional stability between the mean and 95th-percentile (P95) response times indicates an absence of pathological tail-latency degradation under high-stress conditions. System resource consumption was similarly bounded, with peak CPU utilization constrained to 21.6% and maximum memory allocation not exceeding 209 MB. The significance of these metrics is underscored by their attainment alongside a zero-percent request failure rate, establishing both robust throughput capacity and absolute transactional integrity. Operationally, the centralized backend preserved substantial computational reserves to seamlessly accommodate peak instructional traffic; this efficiency was realized because the most resource-intensive phase of the attendance protocol—specifically, the optical extraction of the QR matrix—was deliberately offloaded from the central server architecture.

From a systems architecture perspective, the empirical findings demonstrate that the backend infrastructure exhibited predictable scalability, effectively circumventing the abrupt performance degradation frequently associated with escalating concurrent user loads. This resilience is exceptionally critical in educational environments, where attendance-related network traffic is characterized by acute, high-concurrency bursts. Consequently, sustaining operational stability during these brief, high-intensity intervals of peak demand holds substantially greater practical significance for institutional deployment than merely optimizing average throughput across extended periods of low-volume traffic.

Post-implementation system quality and user adoption. After live use, respondents evaluated the framework using the six ISO/IEC 9126 domains. The overall post-implementation mean of 3.97 fell within the Agree range. Security and usability emerged as the strongest domains, followed closely by portability, functionality, efficiency, and reliability. All domains remained clearly above the neutral midpoint.

Table 5. *Post-implementation evaluation of the Edge-Computed Attendance Framework*

Domain	Mean	SD	95% CI	α	Rating
Functionality	3.93	0.72	3.72-4.14	0.876	Agree
Reliability	3.88	0.80	3.64-4.11	0.923	Agree
Usability	4.06	0.75	3.84-4.28	0.914	Agree
Efficiency	3.89	0.70	3.68-4.09	0.932	Agree
Portability	3.94	0.67	3.74-4.13	0.891	Agree
Security	4.10	0.67	3.91-4.30	0.906	Agree
Overall system quality	3.97	0.62	3.78-4.15	0.972	Agree

Table 6. *One-sample t-tests of post-implementation domains against the neutral midpoint*

Domain	Mean	t	p	Decision
Functionality	3.93	8.84	< .001	Significant
Reliability	3.88	7.52	< .001	Significant
Usability	4.06	9.68	< .001	Significant
Efficiency	3.89	8.76	< .001	Significant
Portability	3.94	9.60	< .001	Significant
Security	4.10	11.26	< .001	Significant
Overall system quality	3.97	10.63	< .001	Significant

The one-sample tests confirm that the favorable post-implementation ratings were not incidental. All six domains and the overall system-quality score were significantly above the neutral midpoint (all $p < .001$). From the standpoint of technology acceptance, this finding is highly consequential; it demonstrates that the user cohort did not merely exhibit passive compliance, but rather provided a robust positive endorsement across the dimensions most critical to institutional software deployment. The comparatively high usability mean suggests that the browser-based interaction model reduced friction for end users, while the highest mean in security suggests that respondents recognized the importance of authenticated requests, controlled access, and record integrity.

To understand how evaluation varied by role, the overall post-implementation score was also summarized by respondent group. Students provided positive ratings, while educators and IT administrators rated the system even more favorably. This difference is analytically plausible: students, being the largest and most diverse user group, were more likely to register practical variation in device quality and use conditions, whereas educators and administrators evaluated the framework partly in terms of its operational benefits and architectural soundness.

Table 7. Overall post-implementation quality by respondent group

Respondent group	n	Mean	SD	Interpretation
Student	42	3.89	0.61	Agree
Educator/Faculty	3	4.63	0.20	Strongly Agree
IT Administrator	2	4.53	0.42	Strongly Agree

Difference in attendance-processing time. The direct institutional value of the framework is most visible in the time comparison. Manual attendance required an average of 4.62 minutes, whereas the edge-computed framework required 0.83 minutes. The mean recovered time per session was 3.79 minutes, and the paired-samples t-test indicated that the difference was statistically significant.

Table 8. Paired-samples comparison of attendance-processing time

Procedure	Mean time (minutes)	SD	Mean diff.	t	p	Decision
Manual attendance procedure	4.62	0.74				
Edge-computed framework	0.83	0.21	3.79	15.27	< .001	Reject H0

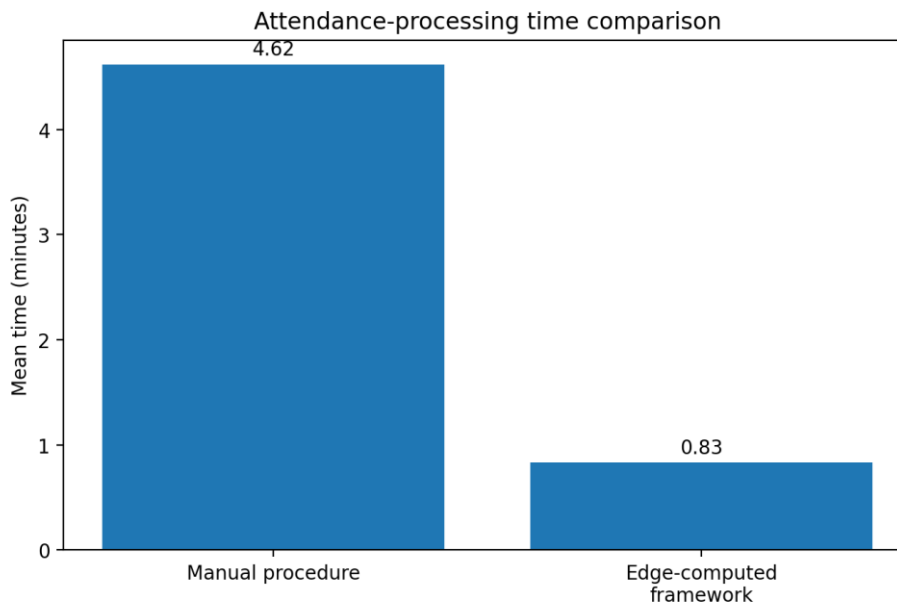


Figure 8. Mean attendance-processing time under the manual and edge-computed procedures.

The magnitude of this difference is educationally meaningful. Reclaiming 3.79 minutes in a single session may appear modest when viewed in isolation, but across repeated class meetings and multiple sections it accumulates into a substantial volume of pedagogical engagement time. The significance test

therefore complements the descriptive results: the baseline data showed that attendance administration was a recurring source of delay, and the time-motion data demonstrate that the deployed architecture materially reduced that delay.

In summary, the results answer all four research questions in a consistent direction. The pre-existing system generated recurring inefficiencies; the deployed backend demonstrated strong benchmark behavior under load; respondents positively evaluated the implemented framework across all quality dimensions; and attendance-processing time declined sharply after implementation. The next section interprets these results in relation to the literature and the broader aims of educational technology deployment.

DISCUSSION

The findings of the study support the central argument that administrative latency in educational environments is not simply a procedural inconvenience but an architectural problem. When attendance management depends on manual verification or centralized processing of visually rich data, it consumes teaching time and magnifies institutional dependence on stable, high-capacity networks. By contrast, the present results show that an edge-computed model can reduce the burden at its source. The baseline means for latency, infrastructure strain, and record fragility confirm that the old workflow imposed recurring operational costs. Those costs were then directly addressed by a design that removed image-decoding work from the server path.

The benchmark results reinforce the theoretical rationale for edge computing in educational web applications. Contemporary edge-computing literature argues that moving computation closer to the site of data generation improves responsiveness and protects the central system from unnecessary load (Kamyszek-Mały et al., 2026; Viswanathan et al., 2026). The present benchmark evidence is fully consistent with that claim. Even under 500 concurrent simulated users, the server preserved sub-100-millisecond mean response time, modest CPU use, moderate memory consumption, and zero request failure. That performance profile is precisely what would be expected when the backend receives compact transactional payloads rather than image streams or frame-processing workloads. The study therefore contributes practical evidence that edge-computed QR decoding is not only theoretically elegant but operationally effective in a real educational setting.

A methodological implication of the findings is that educational software evaluation benefits from combining technical and classroom-centered metrics. An exclusive reliance on computational benchmarking would have merely validated backend efficiency without necessarily confirming any tangible enhancement to the pedagogical environment. Conversely, a singular dependence on heuristic user satisfaction risked obscuring critical insights regarding infrastructural resilience under high-concurrency stress. Ultimately, the convergence of optimal benchmark throughput, statistically significant instructional time recovery, and highly favorable system-quality evaluations fortifies the study's empirical validity, demonstrating that a singular architectural intervention yielded measurable optimizations across multiple independent evaluative domains

The post-implementation evaluation also highlights an important socio-technical point: usability and security are not competing priorities when the system is properly designed. The strongest means were observed in security and usability, indicating that respondents experienced the framework as both dependable and manageable. In many classroom technologies, security procedures become a source of friction. In this system, however, authenticated backend logic and bounded attendance windows were

implemented without requiring users to navigate complex interface steps. This balance is especially valuable in academic settings where frequent daily use punishes even small usability defects. The positive respondent ratings thus align with technology-acceptance research showing that usefulness and ease of use jointly shape adoption behavior (Açıkgül & Şad, 2026; Schittko et al., 2026).

Despite achieving high evaluations in the security domain ($M = 4.10$), edge-computed attendance architectures inherently expand the attack surface, notably introducing the risk of proxy attendance via QR code spoofing or replay attacks. For instance, a student might capture a screenshot of the active session QR code to forward to a remote peer. To mitigate this vulnerability without compromising the lightweight nature of the client-side execution, the framework's security posture currently relies on validated session states and bounded attendance windows. However, future developments should embed dynamic, cryptographic nonces or time-based one-time passwords (TOTP) within the QR payload to enforce rapid expiration. Furthermore, pairing the asynchronous FastAPI validation with strict IP address binding—restricting successful POST requests strictly to the institution's localized network—would effectively neutralize remote check-in attempts while preserving decentralized decoding efficiency.

Another important implication concerns the form of attendance data produced by the system. The baseline findings revealed moderate difficulty in exporting, consolidating, and preserving attendance records. In many schools, attendance records move through several stages: classroom capture, departmental consolidation, and institutional reporting. Successive administrative stages inherently introduce vulnerabilities to transcription errors and data degradation when records are relegated to analog formats or unstructured digital repositories. By generating centralized datasets natively formatted for automated reporting and structured data extraction, the proposed framework significantly mitigates redundant clerical effort and fortifies the integrity of institutional documentation. Although this operational efficiency may appear less salient than the direct reclamation of active instructional time, it constitutes a strategically critical optimization for institutional administration.

The paired time comparison provides the most direct evidence of pedagogical benefit. A mean reduction from 4.62 minutes to 0.83 minutes demonstrates that the architecture changed not only how attendance was recorded but how class time was experienced. In practical terms, nearly four additional minutes become available for the lesson proper. Across a semester, that recovery can amount to several hours of regained instructional opportunity. Such gains are especially valuable in courses with dense content coverage, laboratory or workshop structures, or frequent assessment activity. The system therefore advances the quality-education objective not through curriculum revision or additional staffing, but through the more efficient orchestration of existing class time.

Furthermore, these findings substantiate the premise that financial accessibility in educational innovation does not necessitate a compromise in operational rigor. Despite eschewing proprietary hardware dependencies, the deployed framework achieved robust security evaluations, sustained low-latency processing, and generated highly structured administrative outputs. This paradigm is particularly salient for resource-constrained academic institutions that frequently defer digital transformation due to the misconception that enterprise-grade reliability requires prohibitive capital expenditure. The present research demonstrates that strategic architectural engineering can yield substantial operational optimizations while remaining strictly within the parameters of existing institutional infrastructure.

While the post-implementation evaluation yielded statistically significant positive outcomes across all quality domains, the findings must be interpreted in light of certain methodological constraints.

Specifically, the respondent sample size ($n = 47$) was relatively modest and predominantly composed of student end-users (89.4%). Although this distribution accurately reflects the primary user demographic of the attendance framework, the comparatively small sub-samples of educators ($n = 3$) and IT administrators ($n = 2$) limit the generalizability of the findings regarding institutional portability and high-level administrative record reliability. Future evaluations would benefit from a broader, stratified deployment across multiple academic departments to capture a more comprehensive spectrum of faculty and administrative operational perspectives. Furthermore, the framework depends on the availability of camera-capable devices and adequate ambient conditions for QR scanning. Although these requirements are considerably lighter than the demands of server-side vision systems or proprietary hardware, they remain relevant constraints. Future studies may therefore extend the work by examining varied network environments and additional optimization strategies such as offline-tolerant synchronization or even WebAssembly-based decoder acceleration on legacy mobile processors.

Conclusion. Taken together, the evidence shows that the proposed framework is an effective and context-appropriate model for attendance management in resource-conscious educational environments. The legacy workflow was characterized by recurring inefficiency, the decentralized architecture displayed strong computational performance, users evaluated the system favorably across all measured quality domains, and attendance-processing time was significantly reduced. The study therefore concludes that edge-computed optical decoding, combined with asynchronous backend validation and real-time state synchronization, can mitigate administrative latency while preserving data integrity, scalability, and institutional usability.

Recommendation. For institutional practice, the framework may be adopted more broadly in programs where attendance-taking continues to reduce teaching time. Future implementations should preserve the architectural principle of client-side decoding and lightweight backend validation, as this principle appears central to the observed performance gains. Faculty should be oriented on consistent attendance-window configuration, and students should receive brief onboarding on QR presentation and dashboard verification to maximize transparency and compliance. Routine stress testing should accompany scaling, especially as the number of concurrent sections grows. To fortify the system against the proxy attendance risks identified during evaluation, future iterations must explore embedding time-based cryptographic nonces (TOTP) within the QR payloads and enforcing localized IP-address binding at the API level. Future research should also expand the evaluation sample to encompass a broader, stratified demographic of educators and administrators, compare different edge-decoding libraries, or integrate the framework into wider learning-management and analytics ecosystems.

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Author Contributions

John Bon Juvi D. Jumarito led the study conceptualization, system design, software development and implementation, data gathering, statistical analysis, and initial manuscript drafting.

Conflict of Interest

The authors declare no conflict of interest related to the conduct, analysis, or reporting of this study.

Funding Source

This research received no external grant funding.

Artificial Intelligence Use

Artificial-intelligence-assisted tools were used only to support language polishing and document preparation. All study design decisions, system implementation, statistical interpretation, and final manuscript approval remained under the direct responsibility of the authors.

Ethics Approval Statement

The study was conducted with voluntary participation, informed consent, and confidentiality safeguards. The questionnaire responses were anonymized, and the system was implemented as an attendance-recording and reporting mechanism rather than an autonomous disciplinary tool.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to institutional privacy considerations.

Acknowledgement

The authors acknowledge the respondents and institutional stakeholders of Zamboanga del Sur Provincial Government College for their participation and operational support during implementation and evaluation.