Optimizing Communication Architectures in Heritage Buildings: A Decision Model for Transactional Kiosk Systems under Network Constraints

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Abstract. This paper proposes a heritage-aware decision model for selecting communication architectures for transactional kiosk systems under infrastructure constraints. Using an AHP–TOPSIS framework and empirical evaluation, it compares protocols across LAN and hybrid KNX–IP environments, showing that hybrid solutions can ensure reliability with acceptable latency.

Keywords: Cultural Heritage, Communication Architectures, Transactional Systems, AHP–TOPSIS, KNX–IP.

1 Introduction

The digital transformation of cultural heritage institutions is leading to the increasing use of transactional systems such as ticket machines and access control terminals. Unlike in standard environments, their implementation in protected buildings is limited by strict conservation requirements, which often do not allow the construction of new network infrastructure. However, in culturally significant sites, building automation systems (e.g. KNX) often remain the only possible communication infrastructure.

This poses an engineering challenge related to the need to ensure the reliability, consistency and security of transactions, including guarantees of correct processing order, idempotence and guaranteed delivery (Raynal, 2018), while at the same time aiming to comply with infrastructure and conservation constraints. However, existing studies do not explicitly incorporate infrastructure constraints into the selection of communication architectures in heritage environments.

This paper proposes a multi-criteria model for the selection of a communication architecture for transactional kiosk systems in environments with constraints specific to cultural heritage (Iliev, 2026). The model combines the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods (Iliev, 2025) to evaluate different communication protocols, systems and infrastructures against functional and non-functional requirements.

The approach is validated through experiments comparing HTTP/1.1, HTTP/2, RabbitMQ and Apache Kafka in two scenarios: a standard LAN environment and a hybrid KNX–IP architecture. The results show that while LAN-based solutions achieve the best performance, hybrid architectures can provide the necessary reliability and guarantees for transaction consistency at acceptable latency levels.

The main contribution of this paper is a heritage-aware decision model that integrates infrastructure constraints into the selection of communication architectures, validated through empirical evaluation.

2 Context and Problem Statement in Heritage Environments

The digital transformation of cultural heritage institutions has increased the adoption of transactional kiosk systems for ticketing, access control, and visitor management, where strict guarantees for reliability, ordering, and data integrity are essential due to their direct financial and operational impact (Luchev et al., 2021; Paneva-Marinova et al., 2017). However, installing such systems in historic buildings introduces constraints rarely addressed in traditional communication architecture research, as infrastructure upgrades are often costly or restricted. In many cases, existing building automation systems, such as KNX, remain the only viable communication medium (Aizam et al., 2024), creating a fundamental trade-off between communication performance and compliance with cultural heritage preservation requirements (Vyas et al., 2021).

3 Decision Model for Communication Architecture Optimization

3.1 Multi-Criteria Decision-Making Framework

To manage this complexity, the study uses an integrated approach combining the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods, which is presented by Iliev in another paper, in the form of a model for evaluating the combination of network infrastructure, communication protocols, communication systems, and often the use of a hybrid solution, in order to select the most appropriate solution for the available situation, but also in harmony with the functional and non-functional requirements (Iliev, 2025).

The AHP method is used to hierarchically structure the decision-making problem, incorporate expert judgment into the process, determine the relative weights of the different criteria, reflect the specific priorities of transactional systems in environments with infrastructure constraints. Then, the TOPSIS method is applied, which allows normalize the collected empirical performance data, build a weighted decision matrix, determine an ideal and anti-ideal solution, rank communication architectures according to their proximity to the optimal configuration (Khan et al., 2024).

Combining AHP and TOPSIS provides both a well-structured way to interpret the results, using an objective determination of the weights of the criteria important for a given domain, as well as sufficient analytical rigor through the mathematical ranking mechanism (Iliev, 2026).

3.2 Criteria Definition for Heritage-Constrained Transaction Systems

The evaluation criteria are structured into three categories: functional, non-functional, and infrastructure-related criteria (Iliev, 2026). The evaluation criteria are grouped into functional and performance categories.

Functional Criteria.

- Message Reliability ($Loss$) – Percentage of lost transactional messages.
- Ordering Guarantee ($Ordering\%$) – Percentage of transactions processed in correct sequential order.

Non-Functional Performance Criteria.

- Average End-to-End Latency (L_{avg}) – Mean time from transaction initiation to confirmation.
- 99th Percentile Latency (L_{p99}) – Tail latency reflecting worst-case user experience.
- Throughput ($Tput_{txn}$) – Number of successfully processed transactions per second.

Infrastructure and Deployment Criteria.

- Compatibility with existing automation infrastructure – The ability to operate over existing systems such as KNX.
- Need for new physical cabling – Installing it requires structural intervention.
- Gateway conversion overhead – Additional latency introduced by protocol translation (e.g., KNX↔IP encoding/decoding).

These criteria capture the feasibility dimension of the architecture, reflecting conservation regulations and physical immutability constraints.

Although the full decision model includes functional and infrastructure-related criteria, the experimental validation in this study focuses on a subset of measurable performance criteria (latency, loss, ordering, throughput), which can be empirically evaluated.

The remaining criteria (e.g. compatibility, cabling requirements, gateway overhead) are considered as contextual constraints and are discussed qualitatively in the decision interpretation rather than included in the quantitative TOPSIS ranking.

3.3 Weight Adaptation for Heritage Context

The weighting process is conducted following the AHP pairwise comparisons, led by domain-specific priorities selected for heritage transactional systems.

Unlike information systems or those for collecting some kind of sensor data, which mainly provide content and a single message loss is not critical, here duplication or incorrect order can lead to incorrect payment, an invalid transaction, unauthorized access or a loss of trust on the part of visitors. In other words, the heritage transactional domain emphasizes ordering guarantees, reliability and loss minimization, transactional consistency. As a result, higher weights are assigned to reliability, ordering, and loss-related criteria, while throughput and average latency receive comparatively lower but still significant weights.

The AHP weighting process was conducted using expert judgment from a panel of domain experts with experience in distributed systems and transactional architectures.

Pairwise comparisons were performed using the Saaty scale (1–9). The resulting consistency ratio (CR) was below 0.1, indicating acceptable consistency. For example, reliability-related criteria (loss and ordering) were considered significantly more important than throughput, while latency was considered moderately important relative to reliability.

These judgments were then aggregated using the geometric mean method and normalized to derive the final weight vector. The final normalized weight vector is:

$$W = \{w_{L_{avg}} = 0.25,\ w_{L_{p99}} = 0.20,\ w_{Loss} = 0.20,\ w_{Ordering} = 0.20,\ w_{Tput} = 0.15\}$$

This weight configuration reflects an approach to optimization that is tailored to the requirements of cultural heritage conservation. The preferred communication architecture should not only demonstrate high performance under ideal network conditions but also be robust and applicable in cultural heritage environments where infrastructure capabilities are limited.

4 Experimental Architecture in Heritage-constrained Scenarios

The experimental setup consists of Raspberry Pi 4 Model B devices (4GB RAM), used as kiosk clients and KNX↔IP converters (with KNX HAT), and a central transaction server.

Each transaction message includes trace_id, sequence_id, and event_ts, allowing end-to-end latency, ordering, and loss detection.

Message payload size is fixed to approximately 200 bytes. The experiments were executed for 10 minutes per scenario, including a short warm-up phase. Each scenario was repeated three times, and the reported values represent the average results, with low variance (<5%) observed across runs.

Message loss was detected by comparing sent and acknowledged transaction IDs, while ordering violations were identified through sequence_id mismatches.

Idempotent processing logic was applied at the server side.

All nodes were time-synchronized using NTP (chrony), and metrics were collected via InfluxDB and visualized in Grafana.

4.1 Transactional Kiosk System Model

Given the financial and operational sensitivity of ticketing systems, the architecture must guarantee end-to-end message integrity, deterministic ordering of transaction events, idempotent processing in case of retries, confirmed acknowledgment of successful operations.

Two variants of the experimental architecture are designed. In both variants, the application layer logic is the same; only the transport protocols are changed. In both cases, InfluxDB collects metrics from both nodes (kiosk/server), and Grafana is used for analysis.

4.2 Scenario A: Standard LAN Deployment (Reference Model)

Scenario A (Fig. 1) represents a conventional deployment in which modern Ethernet infrastructure is available. This scenario serves as the performance reference baseline.

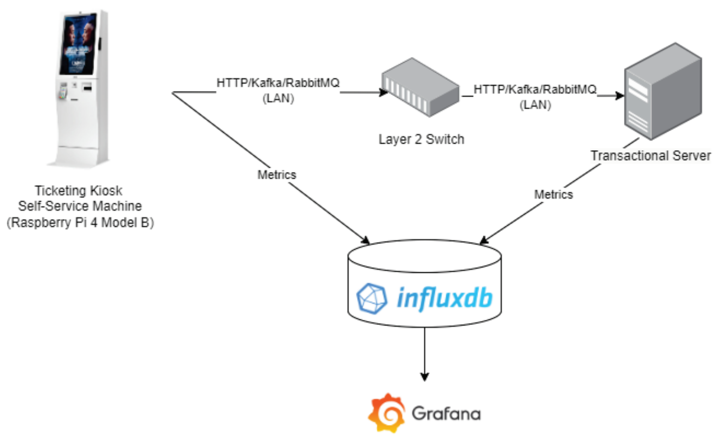

Fig. 1. Kiosk ↔ Transaction Server over LAN (HTTP/1.1, HTTP/2, AMQP, Kafka).

The architecture consists of a kiosk client, a transaction server, and a monitoring stack. Four communication approaches (HTTP/1.1, HTTP/2, RabbitMQ, Apache Kafka) are evaluated.

4.3 Scenario B: Hybrid KNX–IP Deployment (Heritage-Constrained Model)

Scenario B (Fig. 2) simulates a heritage-constrained deployment in which extending Ethernet infrastructure is not feasible due to conservation regulations or structural immutability. This experimental setup aims to simulate a hybrid environment where there is no built-in LAN infrastructure, but KNX automation is available (e.g. in a smart building or a ticket office with industrial cabling). Here, data is transferred over the KNX bus using KNX↔IP converters (Raspberry Pi + KNX HAT), which convert kiosk requests into KNX telegrams and back to the chosen IP protocol (HTTP/1.1/HTTP/2/RabbitMQ/Kafka). Additional times are considered in the conversion metrics to isolate the conversion contribution to the E2E latency.

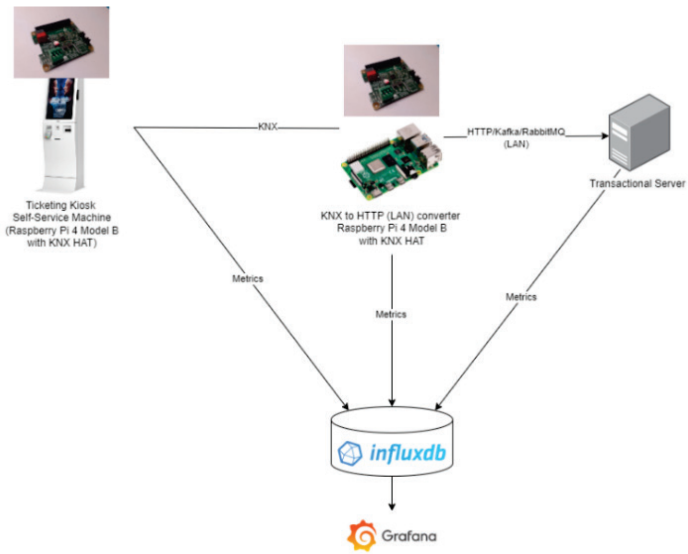

Fig. 2. Kiosk ↔ KNX ↔ IP ↔ Transaction Server (hybrid).

In this configuration, the kiosk communicates over a KNX-based building automation backbone, where KNX–IP converters perform bidirectional translation between KNX telegrams and IP protocols, while the central transaction server remains unchanged. The architecture reflects real-world heritage environments with restricted structural modifications and reliance on existing KNX infrastructure. Additional processing stages, including encoding, transmission over the KNX bus, and decoding back to IP, introduce measurable overhead, enabling the analysis of gateway-induced latency and highlighting the trade-off between communication performance and infrastructure preservation constraints.

4.4 Load Scenarios and Operational Conditions

The experiments are executed under high-load conditions to evaluate latency, loss, and ordering behavior.

To simulate realistic visitor behavior and operational stress conditions on the physical kiosk, it is replaced with a load generator (Raspberry Pi-based implementation with KNX HAT) that increases the frequency to 50,000 txn/s. L_{p99} degradation, losses, and order violations are monitored. While the load generator was configured to produce up to 50,000 txn/s to stress the system, the sustainable throughput observed in the experiments is reported in Table 1.

5 Empirical Results and Multi-Criteria Ranking

5.1 Raw Experimental Results

The empirical evaluation was conducted across both deployment scenarios:

- Scenario A - Standard LAN (reference infrastructure),
- Scenario B - Hybrid KNX–IP (heritage-constrained model).

Table 1 summarizes the aggregated performance indicators across representative load conditions.

Table 1. Performance Metrics Across Protocols and Deployment Scenarios.

Protocol / Environment	**Lavg (ms)**	**Lp99 (ms)**	**Loss (%)**	**Ordering (%)**	**Tput (txn/s)**
HTTP/1.1 (LAN)	65	140	0.10	100.00	220
HTTP/2 (LAN)	38	90	0.08	100.00	320
RabbitMQ (LAN)	45	100	0.04	99.80	520
Apache Kafka (LAN)	52	110	0.02	100.00	800
HTTP/1.1 (Hybrid KNX–IP)	95	180	0.20	100.00	150
HTTP/2 (Hybrid KNX–IP)	70	140	0.16	100.00	210
RabbitMQ (Hybrid KNX–IP)	78	150	0.10	99.70	340
Apache Kafka (Hybrid KNX–IP)	85	160	0.06	100.00	480

5.2 Normalized Decision Matrix (D*)

To enable cross-criteria comparison, the raw performance values are normalized according to the cost-benefit structure defined in Section 5.

Cost criteria (Lavg, Lp99, Loss) are inversely normalized, while benefit criteria (Ordering, Throughput) are directly normalized.

The resulting normalized decision matrix (D*) is shown in Table 2.

Table 2. Normalized Decision Matrix (D)*.

Protocol / Environment	Lavg (ms)	Lp99 (ms)	Loss (%)	Ordering (%)	Tput (txn/s)
HTTP/1.1 (LAN)	0.526	0.444	0.556	1.000	0.108
HTTP/2 (LAN)	1.000	1.000	0.667	1.000	0.262
RabbitMQ (LAN)	0.877	0.889	0.889	0.998	0.569
Apache Kafka (LAN)	0.754	0.778	1.000	1.000	1.000
HTTP/1.1 (Hybrid KNX–IP)	0.000	0.000	0.000	1.000	0.000
HTTP/2 (Hybrid KNX–IP)	0.439	0.444	0.222	1.000	0.092
RabbitMQ (Hybrid KNX–IP)	0.298	0.333	0.556	0.997	0.292
Apache Kafka (Hybrid KNX–IP)	0.175	0.222	0.778	1.000	0.508

5.3 Weighted Matrix (V)

Applying the AHP-derived weight vector W results in the weighted decision matrix V.

Table 3. Weighted Decision Matrix (V).

Protocol / Environment	vLavg	vLp99	vLoss	vOrder	vTput	Σ
HTTP/1.1 (LAN)	0.132	0.089	0.111	0.200	0.016	0.548
HTTP/2 (LAN)	0.250	0.200	0.133	0.200	0.039	0.822
RabbitMQ (LAN)	0.219	0.178	0.178	0.200	0.085	0.860
Apache Kafka (LAN)	0.189	0.156	0.200	0.200	0.150	0.895
HTTP/1.1 (Hybrid KNX–IP)	0.000	0.000	0.000	0.200	0.000	0.200
HTTP/2 (Hybrid KNX–IP)	0.110	0.089	0.044	0.200	0.014	0.457
RabbitMQ (Hybrid KNX–IP)	0.074	0.067	0.111	0.199	0.044	0.495
Apache Kafka (Hybrid KNX–IP)	0.044	0.044	0.156	0.200	0.076	0.520

5.4 Ideal and Anti-Ideal Solutions

The ideal solution (V^+) consists of the best value for each criterion across all alternatives, while the anti-ideal solution (V^-) represents the worst-case configuration.

Distance calculations are performed using the Euclidean metric:

$$S_i^+ = \sqrt{\Sigma_j \left(v_{ij} - V_j^+\right)^2}, \quad S_i^- = \sqrt{\Sigma_j \left(v_{ij} - V_j^-\right)^2} \tag{1}$$

The closeness coefficient C_i is computed as:

$$C_i = \frac{s_i^-}{s_i^+ + s_i^-} \tag{2}$$

5.5 Closeness Coefficient and Final Ranking

Table 4. TOPSIS Closeness Coefficient and Ranking.

Protocol / Environment	Ci	Rank
Apache Kafka (LAN)	0.82	1
HTTP/2 (LAN)	0.74	2
RabbitMQ (LAN)	0.60	3
Apache Kafka (Hybrid KNX–IP)	0.48	4
HTTP/1.1 (LAN)	0.44	5
HTTP/2 (Hybrid KNX–IP)	0.38	6
RabbitMQ (Hybrid KNX–IP)	0.22	7
HTTP/1.1 (Hybrid KNX–IP)	0.12	8

Key Findings

Apache Kafka over LAN achieves the best overall performance due to high throughput and strong ordering guarantees, followed by HTTP/2 and RabbitMQ, which offer good latency and scalability but rank lower due to throughput and ordering trade-offs. Hybrid KNX–IP configurations remain viable in the absence of Ethernet infrastructure, although conversion overhead increases latency and reduces overall ranking, with HTTP/1.1 over KNX performing worst. Overall, while LAN-based architectures provide optimal performance, hybrid solutions offer a practical and conservation-compliant alternative for heritage environments.

From a practical deployment perspective, the results can be interpreted as follows: Apache Kafka over LAN is preferred when high throughput and scalability are required and infrastructure is available. In contrast, hybrid KNX–IP solutions are suitable for heritage environments where new cabling is restricted, providing acceptable reliability and ordering at the cost of increased latency. RabbitMQ and HTTP/2 offer intermediate trade-offs depending on the required balance between latency, ordering guarantees, and infrastructure constraints.

6 Conclusion

The paper presents an optimization model for selecting communication architectures for transactional kiosk systems in heritage environments with infrastructure constraints. By combining the AHP–TOPSIS framework with empirical evaluation, the problem is treated as a constrained decision-making task rather than a simple performance comparison.

The results show that while LAN-based solutions achieve superior latency and throughput, hybrid KNX–IP architectures remain viable in constrained environments, preserving reliability and ordering guarantees at the cost of increased latency.

The main contribution lies in integrating infrastructure and conservation constraints directly into the decision-making model. This demonstrates that digital transformation in heritage environments can be achieved without invasive infrastructure changes, using hybrid and compatible solutions.

The study is limited to transactional kiosk systems and a single automation technology (KNX). Future work should explore additional infrastructure types and validate the approach in real-world deployments to assess long-term stability and interaction with actual visitor flows.

Declaration on Generative AI

No generative AI tools were used in the preparation of this paper. The free version of Grammarly was used solely for language proofreading and minor stylistic improvements in order to improve clarity and readability for non-native English speakers. Grammarly was not used to generate, modify, or develop the scientific content of the article.

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