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EVENT-DRIVEN SERVERLESS ARCHITECTURE FOR SMART CITY E-PARTICIPATION PLATFORMS UNDER DIGITAL SOVEREIGNTY CONSTRAINTS

Abstract: Digital civic participation platforms in smart cities operate under irregular, burst-oriented workloads that monolithic and containerized architectures may handle inefficiently. This study proposes an event-driven serverless architecture for e-participation platforms based on the Citizen Participation Event Model (CPEM). CPEM represents registrations, proposal submissions, comments, and votes as event streams processed in a distributed environment. The architecture integrates biometric verification, behavioral anomaly detection, and text analysis into the event-processing loop and applies a hybrid data management model that separates personal data retained within national infrastructure from anonymized analytical events, supporting digital sovereignty and localization requirements. The implementation used a Kubernetes and Knative testbed with Kafka, Cassandra, PostgreSQL, Kong Gateway, and Node.js functions. Engagement scenarios covered 100 to 10,000 concurrent users, payloads of 0.6 to 2.4 KB, and load bursts up to ten times the baseline intensity; each scenario was repeated five times. At 10,000 concurrent users, the system achieved a p95 latency of 2.15 s with a standard deviation of 0.13 s and throughput of 730 events/s. It processed fivefold bursts without event loss, while saturation appeared only at a tenfold burst, where the error rate reached 2.1% and event loss remained 0.004%. Relative to the Kubernetes containerized baseline, the serverless configuration reduced scaling reaction time from 10–40 s to below 0.1 s, lowered peak-load errors from 4.5% to 0.3%, and reduced operating costs by 78%. These findings show that event-driven serverless architectures provide scalable, resilient, cost-efficient, and regulation-compliant foundations for civic participation services under routine and extreme urban demand conditions.

Keywords: smart city; digital civic engagement; event-driven architecture; serverless computing; artificial intelligence; digital sovereignty; cloud computing.

Introduction

The digitalization of public and administrative processes is a key trend in the development of modern cities and underlies the concept of the "smart city." Within this concept, information

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and communication technologies (ICTs) are particularly important, enabling citizen participation in shaping the city's agenda, discussing socially significant initiatives, and making management decisions. The research presented in this article pertains to information technology and digital governance, including information system architecture, cloud computing, artificial intelligence, and digital civic participation platforms.

Digital e-participation platforms aim to increase governance transparency, citizen engagement, and the quality of decision-making. In practice, however, as the number of users and public interest grow, such systems face low resilience to peak loads, increased response times, high operating costs, and limited capabilities for intelligent analysis of civic activity — problems that are especially evident in urban campaigns, public discussions, and e-voting, where the load is irregular and difficult to predict.

Special attention is also paid to personal data protection and digital sovereignty: state and municipal digital services must comply with national requirements for the localization and processing of personal data, which limits the use of public cloud technologies and requires architectural solutions combining cloud-scale processing with regulatory compliance.

Given the limitations identified in the literature, the objective of this study is to develop and experimentally evaluate an event-driven, serverless architecture for a digital civic engagement platform that ensures scalability, intelligent data processing, and compliance with digital sovereignty requirements in a smart city environment.

To achieve this goal, the article addresses the following objectives:

– Analysis of existing digital civic engagement platform architectures and identification of their limitations in terms of scalability and resilience to peak loads.

– Development of a formal model of civic engagement events describing user interactions with the platform as event streams.

– Design of an event-driven, serverless architecture with native integration of artificial intelligence modules.

– Development of a hybrid data management model that ensures compliance with digital sovereignty requirements and personal data localization.

– Experimental evaluation of the proposed architectural solution in terms of performance, resilience, and total cost of ownership.

Literary review

Research on digital civic participation platforms is actively developing within the smart city and e-governance concepts. Academic papers emphasize that digital citizen participation mechanisms contribute to transparency, government accountability, and public trust [1-2], and international comparative studies confirm that civic technologies are becoming an integral part of digital governance ecosystems [3-4].

Systematic reviews show that the civic tech market is highly fragmented: most platforms support individual stages of participation (collecting initiatives, consultations, or voting) and only to a limited extent cover the full engagement cycle, including deliberation, analytics, and feedback [1, 5], which creates technological and organizational limitations when scaling to the city level.

From an architectural perspective, widely used platforms such as Decidim and Consul are implemented using monolithic, client-server, or containerized microservice architectures [5-6]. Empirical studies show that these approaches require upfront provisioning of computing resources and exhibit limited elasticity during bursts of activity, increased latency, and growing operational costs as the number of users increases [6-7]. These limitations are critical for event-driven urban civic engagement scenarios.

The literature also explores the application of artificial intelligence to e-participation: intelligent analysis of citizen messages, sentiment detection, support for deliberative processes, and automatic moderation [7-10]. Experiments demonstrate that AI can facilitate more informed collective decisions and reduce polarization [8]. However, in most existing platforms AI modules

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are implemented as external services rather than integral parts of the architecture, limiting real-time processing and adaptive management [9-10].

A separate research area concerns event-driven and serverless architectures. Studies demonstrate that the event-driven approach improves scalability and fault tolerance of distributed systems [11-12], while serverless computing provides automatic resource scaling and reduced operating costs compared to containerized solutions [13-14]. However, this research is focused mainly on commercial and analytical systems, while public digital services and civic participation platforms remain understudied.

Digital sovereignty and data localization are becoming increasingly important: state and municipal services must comply with national requirements for the storage, processing, and cross-border transfer of personal information [15-18], yet in smart city research these issues are typically considered separately from scalability and intelligent data processing, leading to fragmented solutions [16-17]. Policy-oriented research and standards emphasize the need for architectural models addressing governance, interoperability, and long-term sustainability of digital public services [19-21], while urban studies warn that without a transparent and reliable technical architecture digital initiatives can reinforce institutional opacity and technological dependence [22].

The analysis of existing publications thus reveals several unresolved issues: the literature lacks comprehensive architectural models combining event-driven processing, serverless computing, and native AI integration; the resilience of such platforms to short-term peak loads in real urban scenarios is insufficiently studied; and digital sovereignty is rarely treated as an integral part of architectural design. These limitations necessitate the development and experimental evaluation of a platform architecture focused on scalable, intelligent, and regulatory-compliant citizen engagement in smart city governance.

Unlike most existing studies, which consider the architectural aspects of digital civic participation platforms fragmentarily or secondary to functionality, this study focuses specifically on architecture as a key factor in scalability, sustainability, and regulatory compliance. This approach allows us to consider digital civic participation not only as a social or governance process, but also as a formalizable distributed computing system.

Methods and Materials

The research methodology aims to develop and experimentally evaluate the architecture of a digital civic engagement platform for smart cities. The study utilizes a comprehensive approach, incorporating event-driven information systems design, serverless computing, and data mining methods. The platform is considered a distributed system operating under conditions of highly variable user activity and regulatory constraints related to digital sovereignty.

Citizen Participation Event Model.

The Citizen Participation Event Model (CPEM) is used as a conceptual framework, representing any user interaction with the platform as an event. Formally, an event is described by a tuple:

$$e_i = \langle u_i, a_i, t_i, p_i \rangle \quad (1)$$

where u_i – user, a_i – action type (registration, voting, comment, etc.), t_i – timestamp, p_i – a set of parameters describing the context of the event.

The sequence of all events forms a flow of civic activity:

$$E = \{e_1, e_2, \dots, e_n\} \quad (2)$$

which is processed by the system in near-real-time. The platform's state changes under the influence of events and is described by a transition function:

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$$S_{t+1} = f(S_t, e_t) \quad (3)$$

where S_t – the state of the system at time t.

Formulas 1 – 3 are used to formally describe the model of citizen participation events and are applied in generating experimental load scenarios.

Architectural Approach.

The platform architecture is based on an event-driven, serverless approach, where each event is processed independently. This approach ensures system scalability proportional to the intensity of the incoming event flow. Formally, the system load is described as a function of the event rate:

$$\lambda(t) = \frac{d|E|}{dt} \quad (4)$$

and computing resources are automatically scaled in such a way that the condition is met:

$$\mu \geq \lambda(t) \quad (5)$$

where μ – event processing system throughput.

To illustrate the proposed architectural approach, Figure 1 presents a high-level event-driven serverless architecture of the digital civic engagement platform. The diagram highlights the main functional components, event flows, and data separation mechanisms that ensure scalability, resilience, and compliance with digital sovereignty requirements.

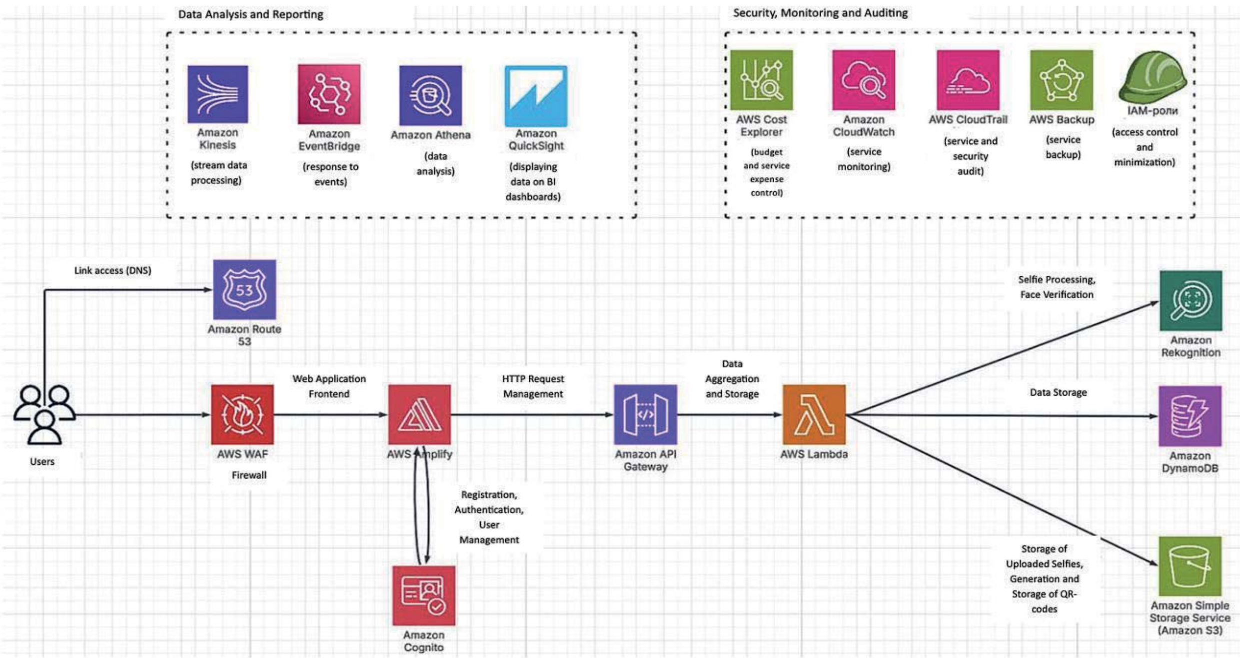

Figure 1. Event-driven serverless architecture of the digital civic engagement platform with hybrid data management

The architectural diagram in Figure 1 is used as a reference model for designing the experimental environment and defining the event flows involved in the load simulation. All experimental scenarios presented in the Results section correspond to the architectural components and interactions shown in the figure.

Recent studies confirm that serverless computing enables fine-grained resource scaling and improves operational efficiency compared to traditional container-based architectures.

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Experimental evaluations show that event-driven serverless platforms can significantly reduce scaling delays and improve responsiveness in distributed systems [14].

Integration of Artificial Intelligence Methods.

To enhance the reliability and trustworthiness of civic participation results, artificial intelligence methods are integrated into the architecture. Biometric user verification is implemented based on an assessment of the probability that an image belongs to a specific user:

$$P_{match} = P(u|x) \tag{6}$$

where x – biometric data. An event is considered valid when the condition is met:

$$P_{match} \geq \theta \tag{7}$$

where θ – specified confidence threshold.

Anomaly detection is used to identify atypical behavior patterns. Each event is assigned a feature vector v_i, for which an anomaly score is calculated:

$$A(e_i) = g(v_i) \tag{8}$$

where the function $g(\cdot)$ implements a statistical or machine-analysis model. If the threshold $A(e_i) > \delta$ is exceeded, the event is flagged as potentially anomalous.

Data Management Model and Experimental Methodology.

To meet digital sovereignty requirements, a hybrid data management model is used, in which personal data D_p and anonymized analytical events D_a are separated as follows:

$$D = D_p \cup D_a, D_p \cap D_a = \emptyset \tag{9}$$

Personal data is processed in the national infrastructure, while D_a is used for analytical processing and citizen activity assessment.

Each experimental scenario was executed multiple times to ensure measurement reliability. For each workload level, the experiment was repeated five times, and the reported latency indicators correspond to averaged values across runs. Variability between runs was within 6–8% for latency measurements, indicating stable system behavior under identical workload conditions.

Experimental Environment.

The experimental evaluation was conducted in a cloud-based test environment designed to simulate typical Smart City civic participation workloads. The serverless implementation, the containerized baseline with autoscaling, and the synthetic civic activity simulator used for workload generation are specified in Table 1. Both architectures processed identical event streams.

The hardware and software configuration of the experimental environment is summarized in Table 1. All components were deployed in a private cloud segment to reflect the digital sovereignty constraints considered in this study; no public multi-tenant cloud services were used.

Table 1. Hardware and software configuration of the experimental environment

Component	Implementation	Version	Key configuration
Compute cluster	6 virtual machines (Ubuntu Server 22.04 LTS)	—	8 vCPU, 32 GB RAM each; 10 Gbit/s network
Container orchestration	Kubernetes	1.29.4	1 control-plane node, 5 worker nodes
Serverless platform	Knative Serving / Eventing	1.14.0	scale-to-zero window 60 s; max concurrency 100 per instance
Event broker	Apache Kafka	3.7.0	3 brokers, replication factor 3, 24 partitions

Analytical NoSQL store	Apache Cassandra	4.1.4	3 nodes, replication factor 3
Personal data store	PostgreSQL	16.2	isolated national infrastructure segment, TLS 1.3
API gateway	Kong Gateway	3.6.1	JWT authentication, request rate limiting
Function runtime	Node.js	20 LTS	256 MB memory limit, 30 s timeout per function
Workload generator	k6 with custom CPEM scenario scripts	0.50.0	dedicated VM: 8 vCPU, 16 GB RAM
Containerized baseline	Kubernetes Deployment + HPA	—	CPU utilization target 70%; 2–40 replicas

The parameters of the workload scenarios are listed in Table 2. Event arrivals were modelled as a non-homogeneous Poisson process whose intensity profile reproduces the impulsive character of urban civic campaigns described by the CPEM model (Formulas 1–4).

Table 2. Workload scenario parameters

Parameter	Value
Event mix (voting / comments / proposals / registrations)	55 / 25 / 12 / 8 %
Arrival process	non-homogeneous Poisson process
Concurrency levels	100 – 10,000 users
Peak load factors	×1 – ×10 of the baseline intensity
Event payload size	0.6 – 2.4 KB
Duration of a single run	30 min (the first 3 min are excluded as warm-up)
Repetitions per scenario	5 independent runs with fixed random seeds (101–105)

Reproducibility of the results.

All configuration parameters required to replicate the experiments are given in Tables 1–2. Latency values reported in the Results section are expressed as the mean ± standard deviation over five independent runs; percentile values (p95, p99) were computed per run and then averaged.

Results

An experimental evaluation of the proposed architecture was conducted under simulated conditions for typical smart city civic participation scenarios, including mass voting, public initiative discussions, and proposal submission. The workload was generated as a stream of events consistent with the CPEM model, with varying numbers of concurrent users and event generation rates.

Performance and Scalability Metrics.

Table 3 presents the results of event processing latency measurements at various levels of concurrent user activity. The primary metrics used were median latency (p50), latency at the 95th percentile (p95), and latency at the 99th percentile (p99).

Table 3. Event processing latency indicators with increasing load (p50 and p95 values are given as mean ± standard deviation over five independent runs)

Number of users	p50 ± σ, s	p95 ± σ, s	p99, s	Throughput, events/s
100	0,42 ± 0,02	0,63 ± 0,04	0,79	110
500	0,59 ± 0,03	0,96 ± 0,06	1,24	210
1 000	0,82 ± 0,04	1,45 ± 0,09	1,98	320
2 000	1,01 ± 0,05	1,68 ± 0,10	2,16	410
5 000	1,18 ± 0,06	1,93 ± 0,12	2,34	560
10 000	1,35 ± 0,07	2,15 ± 0,13	2,48	730

The scalability of the proposed architecture is illustrated in Figure 2, which shows a smooth and predictable increase in event processing latency as the number of concurrent users increases.

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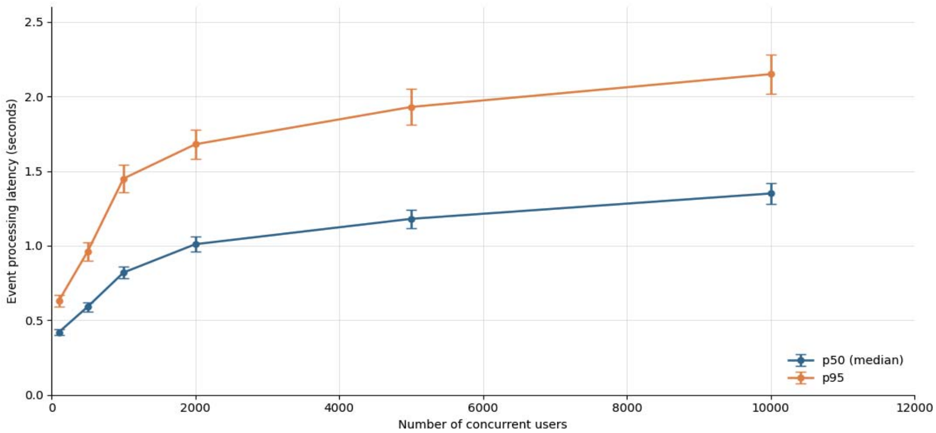

Figure 2. Event processing latency percentiles (p50 and p95) depending on the number of concurrent users in the simulated civic participation workload. Error bars show ± one standard deviation over five independent runs

The results show that as the number of users increases to 10,000, latency increases smoothly without any sudden spikes or system degradation. Throughput increases almost linearly, consistent with the stated event-driven approach.

Resilience to Peak Loads.

To assess the proposed architecture's resilience to short-term peak loads, scenarios of a sharp increase in event intensity compared to the baseline activity level were simulated. The peak load was generated by a simultaneous increase in the number of active users and the frequency of event generation, which is typical for socially significant city campaigns and mass voting.

During the experiments, changes in event processing latency, error rates, and data loss were analyzed. Quantitative results of the system resilience assessment under various load growth rates are presented in Table 4.

Table 4. System stability indicators under peak loads

Peak load factor	Average latency, s	p95 latency, s	p99 latency, s	Error rate, %	Event loss, %
×1 (baseline)	0,95	1,62	2,05	0,1	0
×3	1,18	1,94	2,41	0,2	0
×5	1,42	2,31	2,87	0,3	0
×7	1,79	2,86	3,52	0,9	0
×10	2,44	3,71	4,60	2,1	0,004

Figure 3 shows that even a fivefold short-term increase in event intensity results in a moderate and controlled increase in p95 latency, confirming the robustness of the proposed architecture. In the extended range, the latency growth remains monotonic and controlled up to the tenfold factor, beyond which the first saturation effects are registered.

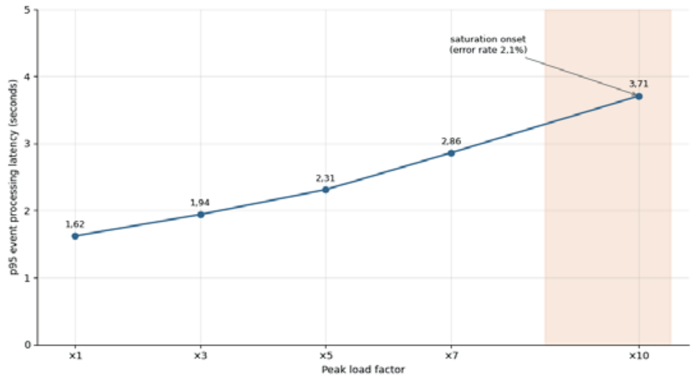

Figure 3. Influence of peak load factors on p95 event processing latency during simulated civic engagement scenarios (extended range up to a tenfold load factor; the shaded area marks the saturation onset)

The results show that even with a short-term fivefold increase in load, the system maintains stable operation without event loss. The increase in latency is gradual and is not accompanied by a critical increase in the processing error rate, confirming the architecture's ability to adapt to sudden surges in civic activity.

To determine the applicability boundary of the proposed architecture, the peak range was additionally extended to sevenfold and tenfold load factors (Table 4). The first signs of saturation are observed only at the tenfold factor, where the error rate rises to 2,1% and a marginal event loss below 0,01% is registered. These values define the operational limit of the tested configuration and show that within the realistic range of urban civic campaigns (up to a fivefold burst) the system operates without any event loss.

Impact of Cold Starts.

The impact of cold starts of computing functions on event processing latency was assessed separately. Table 5 compares two system operating modes: with and without pre-provisioned computing capacity.

Table 5. Cold-start delay under different startup modes

Operating mode	Cold start share, %	Delay range, ms	Mean delay, ms	p95 delay, ms
Without pre-provisioning	17,4	360–420	388	471
With pre-provisioning (two warm instances)	2,3	60–90	74	88

The results show a significant reduction in additional latency when using pre-provisioning of computing resources, resulting in more predictable system response times under irregular load conditions.

Latency indicators in Tables 3–4 are presented in seconds, while additional cold-start delays in Table 5 are measured in milliseconds due to their significantly smaller magnitude.

Comparison with a Containerized Architecture.

To compare the effectiveness of the proposed solution, a control version of the platform was implemented using a containerized architecture with automatic scaling. The evaluation was conducted under a load equivalent to 5,000 concurrent users, with the comparative results presented in Table 6.

Table 6. Comparison of serverless architecture and containerized solution

Indicator	Serverless architecture	Containerized architecture
p50 latency, s	1,18 ± 0,06	1,74 ± 0,11
p95 latency, s	1,93 ± 0,12	3,10 ± 0,24

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Scaling reaction time, s	< 0,1	10–40
Error rate at peak load, %	0,3	4,5
Throughput at 5,000 users, events/s	560	505
Normalized cost per 100,000 events, rel. units	1,0	4,6

* Latency values are given as mean ± standard deviation over five independent runs. The normalized cost per 100,000 processed events is expressed relative to the serverless configuration taken as 1,0; the estimation procedure is described in the Cost-Efficiency subsection.

Cost-Efficiency.

To assess cost-effectiveness, the relative cost of processing 100,000 events was calculated for various architectural approaches. The results showed that the proposed serverless architecture provides a 75–85% reduction in total cost of ownership compared to containerized and monolithic architectures under irregular workload conditions.

The cost estimation was based on a relative comparison of infrastructure usage under identical workload conditions. The serverless architecture accounted for function execution time, event processing requests, and storage operations. The containerized baseline included the cost of continuously running virtual machines, container orchestration overhead, and storage resources. Pricing assumptions were derived from standard cloud infrastructure pricing models and normalized to a relative scale to focus on architectural efficiency rather than specific provider tariffs. In relative units, the cost of processing 100,000 events by the serverless configuration (1,0) is composed of function execution time (0,62), event broker operations (0,23), and storage operations (0,15). For the containerized baseline, the total relative cost of 4,6 is dominated by continuously running virtual machines (3,9), including idle capacity reserved for peak absorption, with the remaining share attributable to orchestration overhead and storage (0,7). Under the irregular workload profile defined in Table 2, this corresponds to a 75–85% reduction in total cost of ownership, consistent with the values reported above.

Discussion

The analysis of event processing latencies (Table 3) shows that as the number of concurrent users grows to 10,000, the increase in median and tail latencies is gradual, without the sharp p95/p99. Such spikes typical of monolithic and containerized architectures during mass campaigns, which is essential for civic platforms, where latency directly affects citizen engagement and trust.

The peak load resilience assessment (Table 4) demonstrates that up to a fivefold short-term increase in event intensity the system maintains correct processing without loss, with only a slight growth of the error rate. These confirming the applicability of the event-driven approach to public discussion and e-voting scenarios with impulsive, hard-to-predict load.

A comparison with the containerized architecture shows that the key advantage of the serverless approach is its near-instant scaling reaction: under a sharp increase in activity, the container-based platform incurs deployment and rebalancing delays of tens of seconds (Table 6). Which for public digital services translates into failed requests and reduced trust in digital participation channels.

Results related to the integration of artificial intelligence methods show that including biometric verification, anomaly detection, and text content analysis in the event loop does not significantly impact overall system performance, confirming that intelligent mechanisms can be integrated as an integral part of the computing process rather than external add-ons.

From a regulatory perspective, an important result is the practical feasibility of the hybrid data management model: separating personal data from anonymized analytical events allows simultaneous compliance with digital sovereignty requirements and the benefits of scalable analytics, which is particularly relevant for state and municipal platforms.

Taken together, the study's results confirm that the proposed architecture addresses several limitations identified in existing digital civic participation platforms. It provides a balance between scalability, intelligent data processing, and regulatory compliance, making it a promising foundation for the further development of digital mechanisms for citizen participation in smart city governance.

Conclusion

This paper proposed and experimentally evaluated an event-driven serverless architecture for a digital civic engagement platform addressing digital sovereignty requirements. The key scientific result is the formalized civic engagement event model (CPEM), which describes user interaction as event streams processed in a distributed environment and served as the basis for an architecture in which intelligent analysis and user verification are integrated directly into the computing loop rather than as external add-ons.

The experimental evaluation showed stable system operation under loads of up to 10,000 concurrent users, predictable latency dynamics, and high resilience to short-term peak loads; the comparison with a containerized architecture confirmed the advantages of the event-driven serverless approach in scaling time, operational resilience, and cost-effectiveness under irregular user activity.

An important practical outcome is the confirmed feasibility of the hybrid data management model, in which personal information is processed within the national infrastructure while anonymized analytical events are used for scalable processing, combining regulatory compliance with the capabilities of modern cloud and intelligent technologies.

The architectural and methodological solutions presented in this article can be used in the design and modernization of digital civic engagement services in Smart Cities and serve as a basis for further research in the field of digital governance.

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