SMART 2026

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SMART 2026 Editors

Lasse Berntzen, University of South-Eastern Norway, Norway

SMART 2026

Forward

The Fifteenth International Conference on Smart Cities, Systems, Devices and Technologies (SMART 2026), held between April 19, 2026, and April 23, 2026, in Lisbon, Portugal, continued a series of events covering tendencies towards future smart cities, specialized technologies and devices, environmental sensing, energy optimization, pollution control and socio-cultural aspects.

Digital societies take rapid developments toward smart environments. More and more social services are digitally available to citizens. The concept of ‘smart cities’ including all devices, services, technologies and applications associated with the concept sees a large adoption. Ubiquity and mobility added new dimensions to smart environments. Adoption of smartphones and digital finder maps, as well as increasing budgets for technical support of services to citizens, settled a new behavioral paradigm of city inhabitants.

We take here the opportunity to warmly thank all the members of the SMART 2026 technical program committee, as well as all the reviewers. The creation of such a high-quality conference program would not have been possible without their involvement. We also kindly thank the authors who dedicated time and effort to contribute to SMART 2026. We truly believe that, thanks to all these efforts, the final conference program consisted of top-quality contributions. We also thank the members of the SMART 2026 organizing committee for their help in handling the logistics of this event.

We hope that SMART 2026 was a successful international forum for the exchange of ideas and results between academia and industry for the promotion of progress in the area of smart cities, systems, devices, and technologies.

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Event-Driven Geolocation Validation for Rural Autonomous Systems: TrustGeoScore and Geolocation Name System

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Abstract—**Rural autonomous systems suffer from unreliable geolocation due to incomplete mapping, ambiguous civic addressing, Global Navigation Satellite System (GNSS) drift, and sparse digital infrastructure. These limitations undermine safety and operational reliability for drones, agricultural automation, emergency response, and infrastructure inspection. This paper introduces TrustGeoScore, an event-driven geolocation reliability model, and Geolocation Name System (GNS), a contextual namespace framework for operationally meaningful sub-locations. TrustGeoScore aggregates multi-source evidence—including drone telemetry, Internet of Things (IoT) signals, GNSS stability observations, identity-validated user confirmations, and application-level operational validations—into a dynamic trust value with temporal decay. We present the system architecture, justify the mathematical formulation and calibration methodology, demonstrate how trust integrates into classical routing via a Dijkstra extension, present empirical structural validation using large-scale rural geolocation data, and explicitly discuss system limitations. The proposed framework enables safer and more reliable autonomous operations in rural environments.**

Keywords-Geolocation Reliability; Event-Driven Validation; Autonomous Systems; Trust Modeling.

I. INTRODUCTION

Autonomous systems are now being deployed in rural regions for logistics, agriculture, emergency response, and infrastructure monitoring. However, these environments expose fundamental weaknesses in existing geolocation systems. Traditional maps and civic addresses collapse large, multifunctional properties into single coordinates, ignoring entrances, landing zones, and operational constraints. Global Navigation Satellite System (GNSS) drift further degrades precision due to terrain, vegetation, and sparse correction infrastructure [1]–[4].

In many rural contexts, autonomous systems are expected to operate with the same reliability as in urban environments, despite receiving significantly poorer geospatial inputs. This mismatch creates safety risks, increases operational costs, and limits adoption. Addressing this challenge requires rethinking geolocation not as a static coordinate, but as a dynamic, evidence-backed construct whose reliability can be measured and reasoned about.

Prior work has explored individual components relevant to geolocation reliability, including alternative addressing schemes, GNSS integrity monitoring, and navigation under uncertainty [1][2][4]–[6]. However, these efforts address isolated dimensions of the problem and do not integrate contextual namespaces, event-driven validation, temporal trust decay, and application-level operational confirmation within a single framework. The present work addresses this gap by unifying these dimensions into a cohesive, deployable system.

This paper addresses these challenges by introducing TrustGeoScore and Geolocation Name System (GNS). Together, they provide a contextual, event-driven geolocation framework designed explicitly for rural autonomous operations.

The remainder of this paper is structured as follows. Section II reviews background and motivates the need for dynamic geolocation reliability modeling. Section III introduces GNS. Section IV presents the TrustGeoScore model, including aggregation and decay mechanisms. Section V describes the system architecture. Section VI illustrates practical applications. Section VII presents the empirical structural validation. Section VIII analyzes design trade-offs and limitations, and Section IX concludes the paper.

II. BACKGROUND AND MOTIVATION

Geolocation systems were designed primarily for human navigation. Humans can interpret imprecise directions, identify landmarks, and adapt to uncertainty; autonomous systems cannot. Rural environments amplify this mismatch due to incomplete or outdated maps, ambiguous civic addresses, GNSS drift and multipath interference, and sparse digital infrastructure [2][4][5][7][8]. Recent studies further highlight the vulnerability of GNSS signals to spoofing, interference, and signal integrity degradation in complex environments [9]. These limitations are consistent with longstanding observations in geographic information science that human-generated spatial data and addressing systems are inherently uneven and context-dependent, particularly outside dense urban areas [10].

Puerto Rico provides a representative example of broader rural geolocation challenges. U.S. Census assessments document widespread limitations in civic address coverage, where many residences lack standardized, consistently usable street addresses and instead rely on informal or descriptive location references [11]. Similar challenges in geocoding and address standardization have been documented in broader urban and developing contexts, where heterogeneous and incomplete address data can undermine spatial reliability [12]. Such variability in address-to-coordinate translation further complicates autonomous system operation when geolocation inputs are treated as authoritative. Comparable conditions exist across

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many rural regions in the continental United States, where properties span large areas, contain multiple access points, and are poorly captured by digital maps.

As autonomy expands into rural logistics, precision agriculture, emergency response, and infrastructure inspection, geolocation reliability becomes a limiting factor. A new paradigm is required—one that models reliability dynamically rather than assuming static correctness.

While this work focuses on rural environments, similar shortcomings appear in dense urban areas and developing regions where informal addressing, rapid construction, or incomplete municipal digitization create inconsistencies between physical reality and digital maps. In many developing countries, buildings may lack standardized addresses, entrances may be unmarked, and GNSS multipath effects degrade reliability in narrow streets. In such contexts, TrustGeoScore can complement formal addressing schemes by incorporating operational validation signals, enabling autonomous systems to reason about reliability even when official records are incomplete or outdated.

III. GEOLOCATION NAME SYSTEM

GNS introduces contextual geolocation namespaces that represent operationally distinct sub-locations within a property. Instead of mapping an entire property to a single coordinate, GNS allows multiple semantic identifiers such as:

- `farm.main-entrance`
- `farm.drone-pad.south`
- `farm.irrigation-zone.3`
- `home.dropoff.backyard`

Each namespace maps to coordinates, metadata, access permissions, and a TrustGeoScore value. This enables autonomous systems to reason about what a location represents and how reliable it is, rather than relying on a single ambiguous point.

Namespaces capture operational semantics that raw coordinates cannot express, such as preferred approach direction, obstacle constraints, surface type, and mission suitability. This is particularly important in rural environments where multiple operational sub-locations may exist within a single property boundary.

IV. TRUSTGEOSCORE MODEL

TrustGeoScore assigns a dynamic reliability score to each GNS namespace based on real-world evidence.

A. Evidence Sources

TrustGeoScore aggregates evidence, including:

- drone landings and flight telemetry,
- Internet of Things (IoT) sensor pings from fixed infrastructure,
- GNSS stability and drift observations,
- identity-validated human confirmations,
- application-level operational validations, such as delivery confirmations, inspection completions, or service acknowledgments.

Application-level validations are particularly important because they represent end-to-end confirmation that a geolocation successfully supported a real-world operation. A completed delivery or confirmed service task provides strong evidence that the location was not only reachable, but operationally correct.

B. Aggregation and Decay

Trust is computed using weighted aggregation:

$$TG(v,t) = \frac{\sum_{k=1}^{m} w_k \, TG_k(v,t)}{\sum_{k=1}^{m} w_k} \tag{1}$$

and temporal decay:

$$TG(v,t) = TG(v,t_0)\, e^{-\lambda(t-t_0)} + \mathrm{NewEvidence}(t) \tag{2}$$

where v represents the GNS namespace (location identifier); t is the current time (seconds or any consistent time unit); $TG(v,t)$ is the TrustGeoScore of namespace v at time t, a value in $[0,1]$; m is the total number of evidence source types; w_k is the non-negative weight assigned to source k (calibrated per source reliability); $TG_k(v,t)$ is the trust subscore contributed by source k, in $[0,1]$; t_0 is the time of the most recent trust update (seconds); $\lambda > 0$ is the decay rate constant (s^{-1}, controlling the half-life $t_{1/2} = \ln 2/\lambda$); and $\mathrm{NewEvidence}(t)$ is the incremental trust contribution from validation events arriving at time t, in $[0,1]$.

Weighted linear fusion is chosen for interpretability and robustness under missing data. Weights (w) represent expected source reliability and are calibrated via source characterization and optional data-driven optimization. Contemporary trust management frameworks in IoT and cyber-physical systems similarly emphasize lightweight, interpretable scoring mechanisms suitable for distributed environments [13]. Exponential decay is selected due to its standard use in modeling information staleness and its intuitive half-life interpretation [14]. All parameters are explicitly defined to ensure transparency and reproducibility.

Exponential temporal decay was adopted to model information staleness in a manner consistent with both human intuition and established practices in trust and information reliability modeling. By gradually reducing the influence of outdated evidence rather than imposing hard expiration thresholds, the model avoids abrupt trust discontinuities while still reflecting growing uncertainty over time.

C. Trust Evolution and Interpretation

TrustGeoScore is designed to represent geolocation reliability as a continuous, evidence-driven quantity rather than a static or binary property. This section clarifies the intended semantic meaning of the trust score and the role of its primary components—aggregation, decay, and evidence weighting—without prescribing runtime behavior or decision logic.

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At a conceptual level, TrustGeoScore captures the degree of confidence that a given GNS namespace will successfully support real-world operations under its intended context. Rather than expressing absolute positional accuracy, the score reflects operational reliability, integrating heterogeneous validation signals into a single interpretable measure. Reputation-based and integrity-aware trust mechanisms have been widely studied in sensor networks and distributed systems [15][16], supporting the use of weighted evidence aggregation in safety-critical environments.

By modeling trust as an evolving belief rather than a definitive guarantee, TrustGeoScore provides a semantic abstraction that can be consumed uniformly by autonomous systems, human-in-the-loop workflows, and downstream applications.

D. Role of Application-Level Validation

A distinguishing feature of TrustGeoScore is its explicit incorporation of application-level operational validation as a high-value source of trust evidence. While sensor data and GNSS observations provide important signals about spatial consistency, they do not by themselves confirm that a geolocation successfully supported a complete real-world operation. Application workflows, by contrast, provide end-to-end confirmation that a location was operationally correct.

Examples of application-level validation include successful package delivery confirmations, completed inspection tasks, verified agricultural operations, or acknowledged emergency supply drops. When an application confirms task completion, the system infers that the geolocation used for that operation was reachable, safe, and contextually appropriate. Such confirmations implicitly validate multiple dimensions at once: accessibility, spatial accuracy, environmental suitability, and alignment with operational intent.

In the TrustGeoScore framework, application-level validations are treated as particularly strong evidence when they are identity-validated and associated with a well-defined task. A confirmed delivery, for instance, reinforces trust more effectively than a single GNSS reading because it demonstrates that the geolocation supported a successful outcome under real operating conditions. Conversely, repeated task failures or aborted operations contribute negative evidence, reducing trust and signaling potential issues such as drift, obstruction, or misclassification of the location.

This approach enables a closed-loop validation process in which geolocations are continuously refined through normal system usage rather than through dedicated calibration efforts. As autonomous systems operate, application outcomes feed directly back into trust computation, allowing the system to learn which locations consistently work and which do not. This closed-loop behavior is particularly well suited to rural environments, where explicit ground truth is scarce but operational feedback is naturally generated through routine activities.

By elevating application-level outcomes to first-class trust signals, TrustGeoScore bridges the gap between abstract geospatial correctness and practical operational reliability.

E. Interpretation of TrustGeoScore Dynamics

While the preceding subsection defines the semantic meaning of TrustGeoScore, this section describes how the trust value behaves over time as new evidence arrives, locations are repeatedly used, or validation activity diminishes. These dynamics are essential for enabling safe and adaptive decision-making in autonomous and semi-autonomous systems.

In practice, TrustGeoScore evolves through three characteristic phases:

- *Initialization Phase* — Newly created GNS namespaces begin with a conservative baseline trust value. During this phase, individual validation events may exert a relatively strong influence on the trust score, reflecting uncertainty due to limited accumulated evidence. This conservative initialization discourages premature reliance on unproven geolocations.
- *Stabilization Phase* — As consistent validation events accumulate—such as repeated drone landings, IoT sensor confirmations, or application-level task completions—the trust score converges toward a stable value. Event diversity plays a critical role during this phase, as corroboration from independent sources increases confidence more robustly than repeated confirmation from a single signal type.
- *Decay and Revalidation Phase* — When a namespace is not exercised for extended periods, temporal decay gradually reduces trust, reflecting uncertainty about whether environmental conditions or access constraints may have changed. Subsequent validation restores trust incrementally rather than instantaneously, preventing abrupt trust spikes based on isolated confirmations.

Through these dynamics, TrustGeoScore supports cautious reliance on geolocations whose reliability is continuously reinforced through use, while naturally reducing confidence in locations that become stale or insufficiently validated. This behavior ensures that trust reflects current operational reliability rather than historical correctness alone.

These trust dynamics enable downstream systems to reason about geolocation reliability in a principled and adaptive manner, but their practical impact depends on how they are realized within a deployable system. The following section describes the system architecture that operationalizes TrustGeoScore within the GNS framework, detailing the components and data flows that support evidence ingestion, trust computation, and integration with autonomous and human-in-the-loop applications.

V. SYSTEM ARCHITECTURE

The proposed system architecture operationalizes TrustGeoScore within GNS as a modular, event-driven framework designed to support trust-aware geolocation management under real-world uncertainty. The architecture ingests heterogeneous validation evidence, enforces identity and authorization constraints, computes dynamic trust scores, and exposes trust-aware services to autonomous and human-in-the-loop applications.

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To support deployment in environments with intermittent connectivity and heterogeneous infrastructure, the architecture emphasizes loose coupling, incremental updates, and graceful degradation. Trust quality improves progressively as additional validation events are observed, allowing the system to function effectively even during early or sparse deployment stages.

A. Core Components

The system consists of eight primary components, each responsible for a distinct stage in the trust lifecycle:

- *Event Collector* — Ingests validation events originating from drones, IoT devices, application workflows, and human users. Events are captured opportunistically during normal operations, minimizing the need for dedicated validation procedures.
- *Event Normalizer* — Transforms heterogeneous event formats into a standardized representation that preserves source identity, temporal context, and validation outcome, enabling uniform downstream processing.
- *Authorization and Identity Validation Engine* — Verifies the authenticity of actors generating events and enforces access permissions, enabling differentiated trust weighting while supporting accountability and controlled evidence contribution.
- *Validation Engine* — Evaluates spatial, temporal, and contextual consistency of incoming events relative to the referenced GNS namespace. This step filters inconsistent or implausible evidence before it influences trust computation.
- *Trust Engine* — Computes TrustGeoScore values using the weighted aggregation and temporal decay mechanisms described in Section IV. Trust updates are performed incrementally as new evidence arrives, enabling continuous adaptation.
- *GNS Registry* — Maintains persistent geolocation namespaces along with associated metadata and historical trust trajectories. This registry decouples geolocation identity from transient sensing conditions.
- *API Layer* — Exposes trust-aware geolocation services to external applications, allowing systems to query locations together with their associated reliability metrics without direct access to raw validation events.
- *Analytics Dashboard* — Provides visualization of trust evolution, evidence contributions, and uncertainty trends to support monitoring, auditing, and human oversight.

Figure 1 illustrates the event-driven data flow and cross-stage observability within the proposed architecture.

B. Design Considerations

The architecture is explicitly designed to accommodate uncertain, evolving environments where ground truth is incomplete or unavailable. Incremental trust computation and temporal decay allow the system to adapt naturally to changing conditions without requiring manual reconfiguration. Privacy and accountability are supported through identity validation and controlled evidence exposure, while modularity enables selective deployment of components based on operational needs.

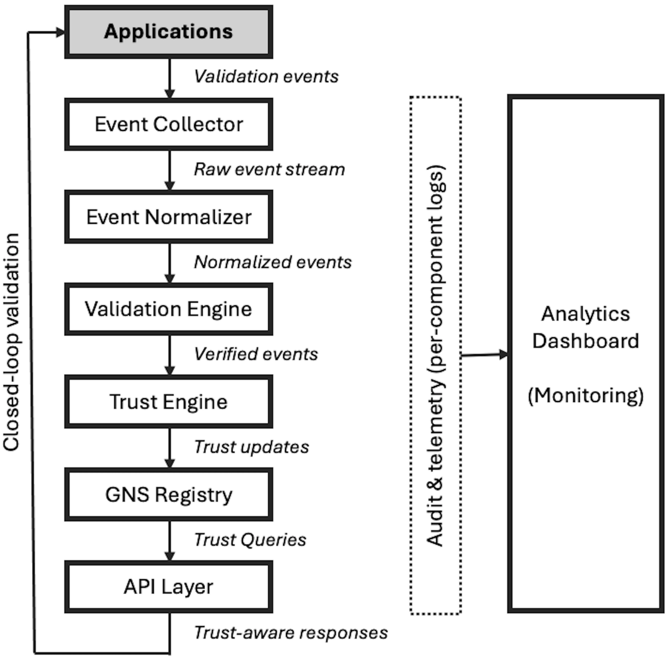

Figure 1. Event-driven TrustGeoScore architecture. Validation events are collected, normalized, verified, aggregated into trust scores, and persisted in the GNS Registry, with per-component audit and telemetry logs supporting monitoring.

C. Operational Lifecycle and Deployment

Deploying TrustGeoScore and GNS in real rural environments requires consideration of the full operational lifecycle of geolocations, from initial creation through long-term maintenance and retirement. Unlike static mapping systems, which implicitly assume that locations remain valid indefinitely, TrustGeoScore treats geolocations as evolving entities whose reliability must be continuously reassessed.

1) Geolocation Initialization and Bootstrapping: New GNS namespaces are typically created through a combination of user input, application workflows, and automated discovery processes. During initialization, namespaces may be populated with approximate coordinates, descriptive metadata, and initial access permissions. At this stage, TrustGeoScore assigns a conservative baseline trust value, reflecting the absence of empirical validation. This design choice prioritizes safety by discouraging autonomous systems from relying heavily on newly defined locations until sufficient evidence has accumulated.

Bootstrapping may be accelerated through contextual priors, such as proximity to existing high-trust namespaces or similarity to previously validated operational patterns. However, these priors are deliberately limited in influence to avoid masking genuine uncertainty.

2) Long-Term Maintenance and Drift Management: Over time, environmental conditions change. Roads erode, vegetation grows, access points shift, and infrastructure is modified.

TrustGeoScore accounts for these dynamics through temporal decay, which gradually reduces confidence in locations that are not revalidated. This mechanism prevents outdated geolocations from remaining falsely trusted and encourages periodic revalidation.

In practice, this means that frequently used and operationally stable locations maintain high trust, while rarely used or abandoned locations naturally decline in reliability.

VI. APPLICATIONS

This section illustrates how TrustGeoScore and GNS are applied in practice to support reliable autonomous operation in rural and infrastructure-sparse environments. Rather than treating geolocation as a static input, the proposed framework enables systems to adapt behavior based on continuously updated trust signals derived from real-world operational evidence.

A. Trust-Aware Drone Operations in Rural Environments

Rural properties often contain multiple entrances, landing zones, and staging areas, yet are typically represented by a single civic address or coordinate. Autonomous systems navigating to such locations may encounter obstacles or unsafe conditions, particularly when GNSS drift shifts approach points by several meters.

Using GNS, a property can define multiple contextual namespaces representing operationally distinct sub-locations, such as landing pads, access roads, or delivery zones. Each namespace is associated with coordinates, metadata, and a TrustGeoScore value that reflects accumulated validation evidence. Prior to execution, an autonomous drone queries the system to identify candidate namespaces and their associated trust scores.

High-trust namespaces indicate locations that have consistently supported successful operations, allowing missions to proceed autonomously with minimal additional verification. When trust values are moderate or declining, the system adapts behavior rather than failing outright. For example, the drone may adopt a more conservative approach strategy, request additional sensing confirmation, or escalate to human oversight before committing to landing.

As missions complete, application-level outcomes feed directly back into the trust computation process. Successful landings, confirmed deliveries, or completed inspections incrementally reinforce trust, while aborted missions or access failures contribute negative evidence. Over time, this closed-loop feedback allows the system to learn which rural sub-locations reliably support operations and which degrade due to environmental change, obstruction, or misclassification.

B. Trust-Aware Routing and Navigation

TrustGeoScore integrates directly into classical routing algorithms by treating geolocation reliability as a first-class routing parameter. In the case of Dijkstra's algorithm [17], the relaxation step is modified to incorporate a trust-based penalty:

$$d[v] = \min\bigl(d[v],\ d[u] + w(u,v) + g\bigl(TG(v)\bigr)\bigr) \qquad (3)$$

where $d[v]$ is the tentative shortest-path cost to node v (meters or cost units); $d[u]$ is the settled cost to the current node u; $w(u,v)$ is the nominal edge weight between nodes u and v (meters or cost units); $TG(v)$ is the TrustGeoScore of node v, in $[0,1]$; and $g(\cdot)$ is a monotonically decreasing penalty function that maps trust to an additive cost (cost units), penalizing low-trust nodes with a larger routing cost.

Trust-aware routing complements existing link-state routing approaches commonly used in distributed and ad hoc networks [18], while preserving the structure of classical shortest-path algorithms.

Low-trust nodes incur higher penalties, steering routes away from unreliable or stale locations while preserving the underlying algorithmic structure. This approach improves navigation robustness without requiring custom routing algorithms or abandoning established graph-based methods.

By integrating trust into routing decisions, autonomous systems can balance distance, cost, and reliability simultaneously. Routes that are slightly longer but more trustworthy may be preferred over shorter paths that terminate at uncertain or poorly validated locations, particularly in safety-critical or time-sensitive operations.

C. Domain-Specific Impact

Projected benefits of trust-aware geolocation are consistent with reported challenges in rural autonomy and infrastructure operations [4][6][19]. Conservative estimates derived from prior failure rates and pilot-scale observations suggest the following improvements:

- *Logistics:* 40–60% reduction in landing misidentification and 15–25% fewer mission aborts.
- *Agriculture:* 25–45% improvement in operational consistency and 10–20% improved sampling repeatability.
- *Emergency Response:* 50–70% reduction in navigation failures and 30–50% faster arrival times.
- *Telecommunications:* 15–25% reduction in inspection time and fewer failed approach vectors.

These figures represent projected improvements rather than results from large-scale deployments. They are not measured outcomes from the empirical analysis presented in Section VII. They serve to illustrate the practical impact of incorporating dynamic geolocation trust into autonomous workflows under rural operating conditions.

D. Closed-Loop Validation via App-Level Events

In deployed applications, TrustGeoScore enables a closed-loop validation process in which operational outcomes feed directly back into geolocation trust. Unlike passive sensing, application workflows provide end-to-end confirmation that a geolocation supported a successful real-world task.

Examples of such application-level events include:

- successful package delivery confirmations.
- completed agricultural missions.
- inspection task completions.
- emergency supply drop acknowledgments.

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TABLE I. SPATIAL METRICS OF INSTANTIATED GNS NAMESPACES

Metric	**Value**
Total unique geolocation IDs	32,019
Geographic coverage area	199.7 km^2
Namespace density	160.4 per km^2
Median nearest-neighbor distance	4.5 m
Median distance to any mapped road	10.4 m
Median distance to major road	179.1 m
75th percentile distance to major road	323.7 m
95th percentile distance to major road	580.9 m

When an application confirms task completion, the system infers that the geolocation used for that operation was not only reachable, but operationally correct. These events are particularly valuable because they implicitly validate multiple dimensions at once: accessibility, safety, spatial accuracy, and contextual suitability.

In the TrustGeoScore framework, application-level confirmations are treated as high-confidence evidence, especially when identity-validated (e.g., authenticated users, delivery systems, or enterprise applications). This creates a closed feedback loop:

1) GNS provides a contextual geolocation.
2) TrustGeoScore selects a high-trust candidate.
3) The autonomous system executes the task.
4) The application confirms success.
5) TrustGeoScore is reinforced.

This loop enables continuous improvement of geolocation reliability without manual intervention and distinguishes TrustGeoScore from purely sensor-based validation approaches.

VII. EMPIRICAL STRUCTURAL VALIDATION

To empirically ground the proposed framework, we conducted a large-scale spatial analysis using 32,019 unique geolocation records instantiated under a United States Department of Agriculture supported delivery initiative in central Puerto Rico. These records were used to bootstrap GNS identifiers, assigning self-validating namespaces to operationally meaningful locations. Although repeated deployment phases were not completed due to program discontinuation, the dataset provides a substantial basis for evaluating spatial structure, infrastructure proximity, and namespace scalability.

A. Dataset Scale and Coverage

As summarized in Table I, the instantiated namespaces span approximately 199.7 km^2, with a density of 160.4 locations per km^2. The region includes dense urban neighborhoods, suburban developments, and peri-urban and rural zones.

The median nearest-neighbor distance between instantiated namespaces is 4.5 meters, indicating localized clustering consistent with residential environments and multi-unit structures. This clustering coexists with broader regional dispersion.

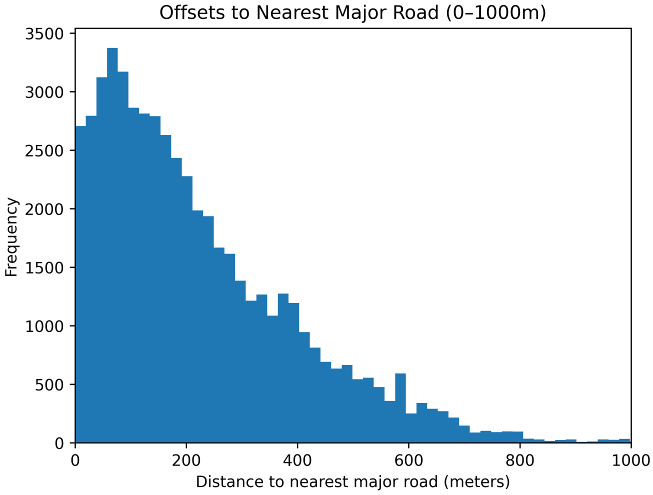

Figure 2. Distribution of distances from instantiated GNS namespaces to the nearest major road infrastructure (motorway, trunk, primary, secondary, tertiary). The right-skewed distribution highlights structural variability in infrastructure proximity across the study region.

B. Proximity to Road Infrastructure

To evaluate the relationship between instantiated namespaces and transportation infrastructure, distances were computed to both (1) any mapped roadway and (2) major road infrastructure (motorway, trunk, primary, secondary, and tertiary classifications from OpenStreetMap).

As shown in Table I, the median distance to any mapped road is 10.4 meters, indicating that most locations are adjacent to some form of roadway. However, the median distance to the nearest major road is 179.1 meters. Furthermore, 75% of locations lie within 323.7 meters of a major road, while 5% exceed 580.9 meters.

The full distribution of offsets to major road infrastructure is illustrated in Figure 2. The right-skewed distribution demonstrates that while many locations are within several hundred meters of major corridors, a substantial portion are located deeper within residential or secondary road networks. Prior analyses of road network hierarchy demonstrate that accessibility and mobility patterns are strongly shaped by hierarchical street classifications, particularly in mixed urban–rural environments [20].

These structural offsets motivate the trust weighting mechanisms defined in Section IV, particularly in scenarios where proximity to primary infrastructure cannot be assumed.

C. Implications for Contextual Geolocation Modeling

These findings reveal a structural distinction between proximity to any roadway and proximity to primary infrastructure. While most geolocations are near some mapped road, operational access frequently depends on minor or residential networks rather than major transportation corridors.

This stratified access structure reinforces the need for contextual namespace abstraction (GNS) and event-driven reliability estimation (TrustGeoScore), rather than assuming static

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correctness based solely on civic addressing or proximity to primary roads.

D. Scope and Future Evaluation

The present analysis validates structural necessity and scalability of the proposed framework. It does not measure operational performance improvement, as repeated validation events were not available. Future deployments will evaluate routing reliability, mission success rates, and trust convergence dynamics under repeated autonomous operations.

VIII. DESIGN TRADE-OFFS, ALTERNATIVES, AND LIMITATIONS

The design of TrustGeoScore and GNS reflects a series of deliberate trade-offs intended to balance rigor, scalability, interpretability, and practical deployability. This section discusses key alternatives and explains why the chosen approach is appropriate for rural autonomous systems.

A. Trust Modeling Versus Deterministic Validation

One alternative to trust-based modeling is deterministic validation, where a geolocation is either considered valid or invalid. While appealing in its simplicity, deterministic approaches fail to capture partial knowledge, uncertainty, and gradual degradation. Rural environments rarely provide binary certainty; access points may be usable under some conditions but not others.

TrustGeoScore instead models reliability as a continuous value, enabling autonomous systems to reason probabilistically about risk, allowing for graceful degradation rather than abrupt failure when evidence is incomplete.

B. Rule-Based Scoring Versus Learned Models

Another alternative is to use machine learning models to predict geolocation reliability directly from raw data. While potentially powerful, such approaches introduce challenges:

- dependence on large labeled datasets,
- reduced interpretability,
- difficulty generalizing across regions,
- sensitivity to data drift.

TrustGeoScore adopts a rule-based, mathematically interpretable formulation that can be calibrated using limited data and domain knowledge. This choice prioritizes transparency, reproducibility, and safety—key requirements for infrastructure and emergency applications.

C. Centralized Versus Distributed Validation

Geolocation validation could be centralized in a cloud service or distributed across edge devices. TrustGeoScore is designed to support hybrid deployment models. Core trust aggregation may occur centrally for consistency, while local validation and evidence collection can occur at the edge. This flexibility is especially important in rural environments with intermittent connectivity.

D. Manual Curation Versus Automated Evolution

Traditional geolocation systems rely heavily on manual curation and infrequent updates. While human oversight remains important, it does not scale to the complexity and dynamism of rural autonomous operations. TrustGeoScore emphasizes automated evolution driven by operational events, reducing reliance on manual intervention while preserving human override where necessary.

E. Why the Chosen Design Is Appropriate

The selected design prioritizes:

- interpretability over opaque prediction,
- gradual trust evolution over binary decisions,
- operational feedback over static assumptions,
- safety over aggressive optimization.

These trade-offs make TrustGeoScore particularly well suited for rural environments, where uncertainty is the norm rather than the exception.

F. Limitations

TrustGeoScore depends on sufficient event density; extremely sparse environments slow convergence and increase variance. New locations face cold-start challenges. Computational overhead, identity-validation latency, sensor integrity, parameter sensitivity, environmental bias, and conservative routing behavior are acknowledged limitations. These define the framework's boundaries of applicability rather than invalidating its contributions.

IX. CONCLUSION AND FUTURE WORK

TrustGeoScore and GNS provide a contextual, event-driven geolocation validation framework tailored for rural autonomous systems. The proposed approach formally defines weighted evidence aggregation and temporal decay mechanisms, integrates trust-aware reasoning into classical routing via a Dijkstra-based extension, and operationalizes the model through a modular system architecture. Empirical structural validation using large-scale rural geolocation data demonstrates the necessity of context-aware reliability modeling in infrastructure-sparse environments. Together, these contributions establish a mathematically grounded and operationally viable foundation for safer and more reliable autonomous deployment beyond traditional static addressing schemes.

Future work will focus on full operational evaluation under repeated autonomous deployments, including routing reliability analysis, mission success rate comparisons, and empirical study of trust convergence dynamics under varying event densities. Additional investigation will explore sensitivity to parameter calibration, scalability under distributed edge deployments, and extension of the framework to dense urban and developing-region contexts with heterogeneous addressing systems.

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Post-Occupancy Evaluation Framework for Smarthomes: A Techno–Human–Social Perspective

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***Abstract*—This paper proposes a new conceptual framework for evaluating smarthome environments from a Techno–Human–Societal perspective. As Artificial Intelligence technologies become increasingly embedded in residential settings, existing Post-Occupancy Evaluation approaches remain predominantly focused on energy savings and technical efficiency, limiting their ability to capture AI-based services that continuously interact with residents. To address this gap, this study introduces the Techno–Human–Societal Post-Occupancy Evaluation framework, organizing evaluation into three core dimensions: technological performance, human experience, and societal acceptance and sustainability. The proposed framework provides a conceptual foundation for future empirical validation and indicator refinement across diverse smarthome contexts, contributing to the broader agenda of human-centered smart city evaluation.**

Keywords- Smarthome; Post-Occupancy Evaluation; Energy Efficiency; Residential Comfort; Sustainability.

I. INTRODUCTION

Advancements in Artificial Intelligence (AI) technologies are rapidly spreading across residential environments. Smarthome systems aim to optimize energy use through automated control, predictive algorithms, and real-time feedback, while enhancing user convenience. However, empirical evidence on how residents perceive and experience these services remains limited, as performance evaluations have largely focused on energy savings and technical efficiency, often overlooking human and social dimensions [1].

Post-Occupancy Evaluation (POE) has been widely used to assess building performance after occupancy, integrating technical criteria and user experience [2]. Nevertheless, existing POE frameworks are limited in evaluating AI-based services that actively interact with residents and influence everyday energy behaviors. To address this gap, this study proposes a smarthome-specific POE framework grounded in a techno–human–societal perspective. The framework was developed through a two-step process involving a comprehensive review of POE and smarthome-related studies, followed by the analysis and restructuring of existing evaluation items, with particular attention to users' understanding of AI systems, perceived control, trust, and social impacts.

The remainder of this paper is organized as follows. Section II reviews the limitations of conventional POE. Section III presents the proposed THS-POE framework. Section IV discusses its characteristics and implications. Section V concludes with directions for future work.

II. LIMITATIONS OF CONVENTIONAL POE AND THE NEED FOR INTEGRATED EVALUATION FRAMEWORKS

POE has developed as a methodology for assessing building performance during actual use, with traditional studies focusing primarily on physical environmental performance—such as thermal comfort, acoustics, and energy consumption—and user satisfaction in residential, office, and public buildings [3]. POE typically employs mixed methods, combining surveys, interviews, on-site observations, and measurements of indoor environmental quality and resource use [1]. However, many POE studies remain one-off assessments, characterized by limited comparability across cases due to non-standardized indicators, unclear cost responsibilities, and weak integration with construction and operational processes [4]. Consequently, prior research has consistently highlighted the need for standardized indicators, data sharing, and stronger links between research and practice [5].

As smart technologies become increasingly embedded in buildings, POE faces new challenges related to user learning and acceptance, data ethics, and platform interoperability [6]. Recent studies have begun to expand evaluation scopes by incorporating usability, user behavior, and operational feasibility alongside conventional performance indicators, while also emphasizing the importance of institutional and regulatory perspectives [7]. These developments indicate that future POE research must move beyond physical performance and user satisfaction toward integrated assessments that account for technological performance, human–service interaction, and broader societal impacts.

III. TECHNO-HUMAN-SOCIETAL POST-OCCUPANCY EVALUATION (THS-POE) FRAMEWORK

The THS-POE framework is designed to integratively assess technological, human, and societal dimensions in smarthome residential environments. Moving beyond the conventional POE focus on physical performance and user satisfaction, it reflects key characteristics of AI-based systems, including autonomy, interactivity, learning capacity, and social implications.

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As illustrated in Figure 1, the THS-POE framework is structured around three interrelated domains—Technology, Human, and Society—each capturing a distinct yet complementary dimension of smarthome performance.

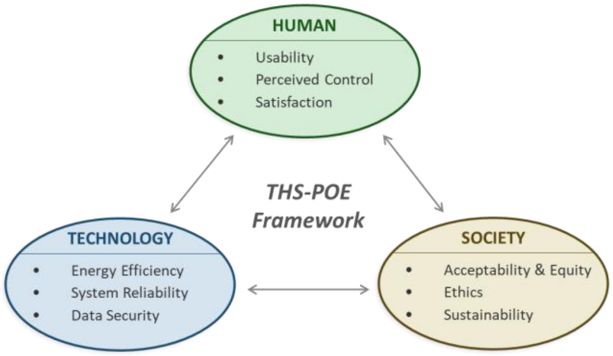

Figure 1. Conceptual Structure of the THS-POE Framework.

The specific indicators and measurement methods for each domain are summarized in Table I. The Technology domain evaluates functional and operational performance, such as energy efficiency, system reliability, and data security, combining measured indicators with users' perceived performance and trust; data are collected through system logs, expert assessments, and user evaluations. The Human domain focuses on user experience and behavior, addressing usability, emotional satisfaction, perceived control, and intention to continue use in recognition of AI systems' ongoing influence on everyday energy-related decisions; measurement relies primarily on user surveys and semi-structured interviews. The Society domain examines social acceptability and sustainability, incorporating equity, accessibility, ethical considerations, CO_2 reduction effects, and institutional support to assess long-term societal implications, drawing on quantitative data and expert assessments.

The THS-POE adopts a technology-neutral and flexible structure, allowing indicator selection and weighting to be adjusted according to research objectives, housing contexts, and policy settings. This openness supports both contextual adaptability and cross-case comparability. Importantly, the framework is not intended as a one-time diagnostic tool, but as a longitudinal evaluation instrument capable of tracking how smarthome systems and their users co-evolve over time. By incorporating both objective performance metrics and subjective user assessments, THS-POE bridges the gap between technical system evaluation and the lived experience of residents, offering a more holistic basis for evidence-based housing policy and smart city planning.

IV. DISCUSSION : CHARACTERISTICS AND IMPLICATIONS OF THE THS-POE FRAMEWORK

The THS-POE framework is proposed as a flexible and extensible POE tool for smarthomes, rather than as a fixed or prescriptive evaluation protocol. It aims to enable systematic and comparable assessments across diverse housing types, technological configurations, and institutional or policy contexts, while remaining responsive to rapid technological change. Central to this framework is the recognition that the success of AI-based smarthome services cannot be measured by technical performance alone, but must also account for how residents understand, trust, and appropriate these systems in their daily lives.

Each of the three domains is designed to serve a distinct set of stakeholders within a single evaluative logic. The Technology domain provides performance-oriented indicators—such as energy efficiency, system reliability, and data security—that are directly relevant to designers, system developers, and facility managers. The Human domain, by focusing on actual user experience, usability, perceived control, and emotional response, serves housing operators, service providers, and user-centered design processes. The Society domain addresses broader concerns such as equity, accessibility, ethics, and sustainability, offering critical insights for policymakers, local governments, and public housing authorities. This three-domain structure allows differentiated interpretation by each stakeholder group while maintaining a coherent and integrated evaluative logic.

In terms of application timing, the framework is intended to be used repeatedly across the full housing life cycle. Unlike conventional POE, which is often conducted as a one-time assessment at a fixed point after completion, it can be applied at different stages—initial operation, stabilization, and long-term use. This enables the capture of not only short-term outcomes such as energy efficiency, but also the evolution of user perception, learning processes, and social acceptance over time.

TABLE I. STRUCTURE AND INDICATORS OF THE TECHNO–HUMAN–SOCIETAL POST-OCCUPANCY EVALUATION FRAMEWORK

Domain	**Primary Indicator**	**Secondary Indicators**	**Measurement Methods**
Technology	Energy efficiency	Energy consumption, reduction rate	Data analysis, User and expert evaluation
	System reliability	Error rate, response time, data privacy	System logs, expert assessment
Human	Usability	Ease of learning, ease of operation	User surveys, interviews
	Satisfaction	Emotional satisfaction, intention of continued use	User surveys
Society	Acceptability	Equity, accessibility, ethics	User and expert evaluation
	Sustainability	CO_2 emission reduction, maintenance systems, policy support	Quantitative data, expert assessment

In AI-based system environments where performance and user interaction continuously change, such temporal flexibility becomes a critical evaluation feature.

Structurally, the framework adopts a technology-neutral design that is not tied to any specific technology or platform. Rather than being tailored to particular buildings, algorithms, or system types, it defines evaluation domains at a conceptual level, allowing individual indicators and measurement methods to be adjusted according to technical conditions and data availability. For instance, energy performance can be assessed through smart meter data or building management system logs, while user experience can be measured via surveys or interviews. This modular design enables comparative analysis across heterogeneous smarthome systems.

V. CONCLUSION AND FUTURE WORK

This study examined the limitations of conventional Post-Occupancy Evaluation (POE) in the context of the rapid diffusion of AI-based smarthome technologies and proposed a Techno–Human–Societal (THS) POE framework. By treating technological performance, user experience, and social acceptability and sustainability as equally important dimensions, THS-POE enables a comprehensive evaluation of AI-based smarthome services beyond energy savings alone.

While this study focuses on conceptual framework development rather than empirical validation, it provides a foundation for future research. Subsequent studies may refine indicators, apply expert-based weighting, and empirically test the framework across diverse residential contexts, positioning THS-POE as a basis for cumulative and comparative evaluation within smart city research.

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A Novel Educational Approach for Volumetric Vehicle Counting Using Artificial Intelligence in Smart Cities

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***Abstract* — This article presents a solution for volumetric vehicle counting using artificial intelligence based on images of specific areas of interest in smart cities. The focus is on collecting data to support urban mobility planning. It includes the development of equipment for collecting images, easy to install with its own power generation, development of software for data processing, covering the identification, tracking and counting of vehicles, to identify the detailed traffic flow with the separation of vehicles by their respective categories: cars, motorcycles, trucks and buses. In this way, the solution developed in this work can directly contribute to the planning of mobility in urban areas through the automated collection of traffic flow data. This solution was developed within a university environment and can also be used in practical educational approaches as an applied framework for learning in artificial intelligence and computer vision, with direct application to smart city contexts.**

Keywords: Volumetric vehicle counting; Urban mobility; Smart city.

I. INTRODUCTION

The term "smart cities" is commonly associated with the application of technology in the urban environment; however, its concept is broad and extends beyond this notion. Cities globally have been exploring methods to address contemporary challenges through solutions that yield long-term economic benefits [1].

The upward trend in human population growth has rendered sustainable urban mobility a significant challenge for municipal authorities [2]. With social and economic development in urban areas, issues such as congestion and increased pollution emerge. To implement effective improvements in this context, it is crucial to understand traffic demand through indicators such as traffic flow [3].

This study presents an Artificial Intelligence (AI)-based solution to acquire traffic flow data on urban roads through volumetric vehicle counting, utilizing images captured in designated zones of interest. To facilitate image acquisition, a custom, easy-to-install station powered by solar energy was constructed.

The image processing component predominantly focuses on the detection of objects of interest, specifically motor vehicles categorized by type. Following detection, each object must be tracked to establish its movement, enabling the software to perform counting. Subsequently, the collected data is recorded to create a historical database.

The following sections present the context and development of the system addressed in this work. In Section II, the need for traffic studies in urban mobility is discussed. In Section III, the techniques used for object detection and vehicle tracking in this approach are described. In Section IV, the system architecture and the equipment used are presented. The results obtained are discussed in Section V, and finally, the conclusions are presented in Section VI.

II. URBAN MOBILITY

In various cities around the world, the association between mobility and transportation has encouraged an increasing reliance on motor vehicles and a tendency towards the expansion of urban road networks. Consequently, road structures such as overpasses, bridges, tunnels, and pedestrian walkways have become common and characteristic elements of the modern city [4].

Urban mobility is a critical subject for city management as it pertains to the movement of goods and people. Thus, the analysis of traffic flow is necessary for public transportation planning, parking management, and other related aspects.

According to the Traffic Study Manual by National Department of Transport Infrastructure (DNIT), the quantity, direction, and composition of vehicle traffic flow in a road system over a specified period are determined through Volumetric Counting. This information is invaluable for capacity analysis, identifying the causes of congestion and accidents, as well as for pavement sizing and traffic channeling projects [5].

III. COMPUTER VISION

The demand for computer vision has grown over the years, focusing on solving real-world problems [6]. However, there are several challenges, as many models are deficient in handling adverse situations such as partial occlusion, low contrast, and changing environmental conditions [6]. The challenges and deficiencies highlighted in Sebe's 2005 work remain relevant even after nearly two decades.

You Only Look Once (YOLO) is an algorithm designed for object detection [7]. Its name is self-descriptive since detection occurs in a single stage; in its output, identified objects are displayed with rectangles around each one according to their class [8]. These rectangles are called bounding boxes. The entire image is utilized to predict each bounding box for all classes for which the model is trained; the input is divided into an SxS grid, meaning that if the center of an object lies within one of the cells, that cell will detect it. In each case, a confidence value is assigned to statistically determine which of the generated boxes best fits the detected class [7].

To train the model, although it is possible to create a custom dataset, gathering thousands of images and categorizing objects individually is a slow and labor-intensive process. On the other hand, ready-to-use datasets exist to meet various demands. Launched in 2014, the Common Objects in Context (COCO) dataset consists of 328,000 images, of which over 200,000 are labeled, covering 80 categories [9].

Object tracking becomes useful in certain applications, and for vehicle counting, it is indispensable since it is necessary to obtain information about the movement performed. Once detected in a frame, the object of interest is tracked in subsequent frames; this process is usually lighter than detection [10]. The choice of tracker must take into account the demand and available resources.

Simple Online and Realtime Tracking (SORT) is a method for tracking multiple objects. Proposed in 2016, it was created with an emphasis on real-time applications, considering only the current frame and the previous one for tracking [11]. The object's trajectory is predicted using a Kalman filter, and frame-by-frame data is associated using the Hungarian algorithm.

Although SORT is capable of tracking multiple objects, the fact that it considers only the current frame and its predecessor makes it susceptible to identification changes whenever occlusion occurs. To solve this problem, a derivative called DeepSORT was created, which improves data association [12]. DeepSORT adds information related to the object's appearance, so even if occlusion occurs, when the object reappears, tracking remains, thus maintaining the same identification [13].

IV. SOLUTION DEVELOPMENT

This section details the architecture, as can be seen in Figure 1, of the developed system, highlighting the primary hardware and software components. A prototype for image acquisition was constructed, with images later processed in a cluster equipped with NVIDIA GPUs, providing automated volumetric vehicle counting. Vehicles are categorized into cars, motorcycles, trucks, and buses.

A key component in this equipment set is the camera, specifically the Hikvision DS-2CD1123G0E-IC model used in this research. This device features a 2MP resolution, infrared LEDs with a range of up to 30 meters suitable for capturing nighttime images, an energy demand of up to 5W, and a memory card interface supporting up to 128GB [14]. Additionally, it has IP67 protection, making it resistant to dust and water, ideal for outdoor installations, and IK10 vandalism protection [15].

Based on these specifications, the image collection equipment was installed in a metallic hermetic box. This design protects the water-sensitive battery and charge controller. Besides protection, the metallic box was chosen for its durability, allowing it to be used as part of the structure. Thus, a metal support for ground installation was designed to be fixed directly to the bottom wall of the box. Similarly, a support was created for the photovoltaic module on top, adjustable in angle to fit its size.

To ensure the system is versatile and secure, all energy consumed is generated locally via a solar generator. Thus, no extra installations are required at the collection points. After collecting the images, the data is taken to the cluster, where it will be processed. Seeking to reduce costs and make logistics viable, edge computing was not used; in addition, post-processing allows recounting and subsequent adjustments.

To meet energy demands, a 20W photovoltaic module and a charge controller were included. The module-generated energy powers a Uninterruptible Power Supply (UPS) battery with a 7Ah capacity; the charge controller manages battery charging, preventing overcharging and overvoltage.

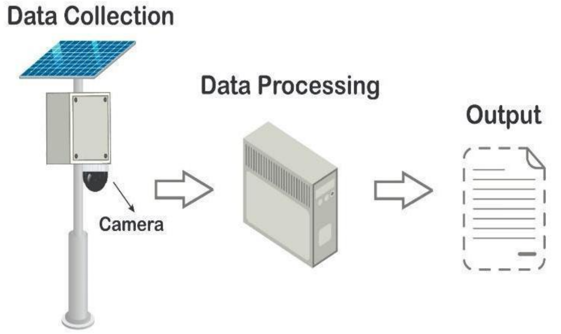


Figure 1. Solution architecture.

The camera was securely mounted at the bottom of the box using screws and nuts. To facilitate field installation and support, the previously mentioned metal bracket was employed. This setup enables the image capture system to be easily transported, adjusted, and deployed at various points of interest. Upon activation, the camera captures images and stores them on a memory card.

For image processing, the captured images are transferred to a cluster outfitted with six NVIDIA RTX 3070 GPUs, as depicted in Figure 2.

The algorithm for volumetric vehicle counting operates through a series of steps including detection, tracking, counting, and logging of objects of interest, such as cars, buses, motorcycles, and trucks.

For object detection, the YOLOv5 algorithm was employed. This version of YOLO offers a range of model variations, from YOLOv5n (nano) to YOLOv5x (extra-large) [16].

Upon detection, each vehicle is assigned a unique ID and tracked using the DeepSORT algorithm. The DeepSORT algorithm's robustness allows it to maintain tracking continuity even in the presence of short occlusions, preventing ID switches and enhancing accuracy in the volumetric vehicle counting process.

Additionally, a virtual grid system was implemented to precisely define the movement patterns of each vehicle, as illustrated in Figure 3. With this approach, it is possible to identify the traffic flow in different locations, based on the quadrants present in the image. To achieve this, it was necessary to separate the grid system into zones, so that the movement carried out by the vehicle is established by the zone in which it is first identified and the zone in which it disappears. This counting strategy is flexible, can identify complex movements in busy locations and eliminate unwanted movements. As an example, Figure 4 shows four zones with their respective movement in relation to the origin and destination.

Figure 2. GPU cluster for processing artificial intelligence software.

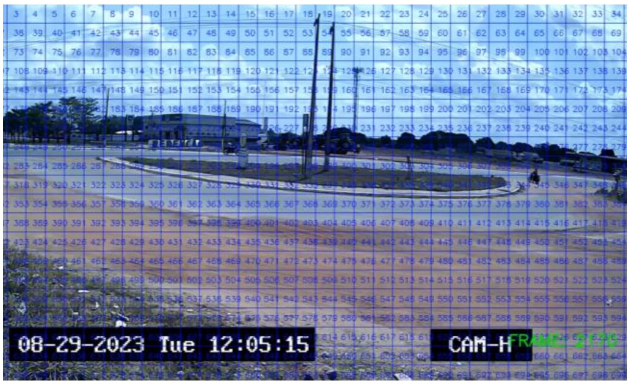
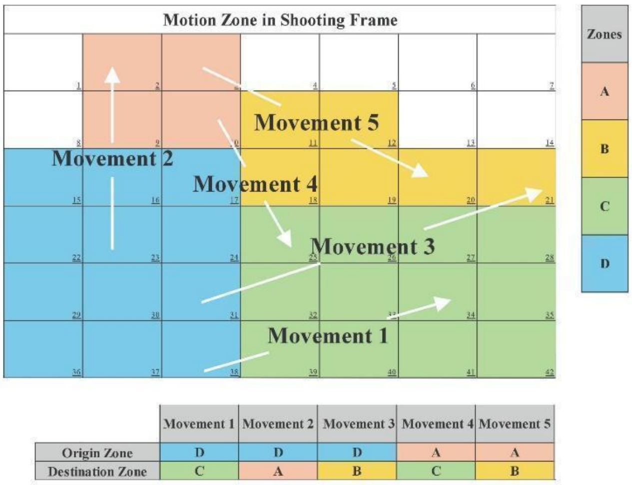


Figure 3. Virtual grids for identifying conversions.



	Movement 1	Movement 2	Movement 3	Movement 4	Movement 5
Origin Zone	D	D	D	A	A
Destination Zone	C	A	B	C	B

Figure 4. Zones delimitation.

Defining zones and including movements are separate processes from generating the analysis spreadsheet, so that traffic engineers have freedom in delimiting the scope of what will be evaluated. Furthermore, by considering each vehicle category individually, it is possible to identify peak hours in a segmented version. The data is generated in spreadsheet form, as this makes access to the data more palatable and opens space to calculate other metrics, create graphs, etc.

V. RESULTS

A prototype for image capture was successfully developed at the Federal University of Tocantins. This setup enabled the validation of its continuous image recording capabilities, encompassing both camera functionality and the reliability of the self-sustaining power generation system. It was verified that image capture remained uninterrupted, with the generated energy effectively maintaining battery charge and system operation, including nocturnal periods.

Following operational validation, an additional eight image capture units were manufactured. These units were meticulously installed to proactively identify potential operational issues during a week-long continuous runtime. Six units performed as anticipated, seamlessly operating without interruptions as per the initial testing phase, while two necessitated battery replacements.

With all nine image capture units functioning at full capacity, they were transported to Redenção-PA, a city in the northern region of Brazil boasting a population exceeding 100,000 inhabitants. Strategically placed in areas characterized by high vehicular activity, one of the deployment units is shown in Figure 5.

Following the installation, all units underwent testing. By connecting a notebook directly to the camera using an Ethernet cable, it was ensured that the camera was effectively recording images.

Figure 5. Image acquisition system installed and operating.

Utilizing the implemented grid system, specific movement identification zones were established for each counting area based on the monitoring roadways' requirements, as depicted in Figure 5. Therefore, after processing, it was possible to obtain the traffic flow in each zone established by day and time, as shown in Figure 6. Complementarily, Figure 7 shows how the results are exported after the counting process.

Figure 6. Vehicles and their conversions identified through the AI algorithm.

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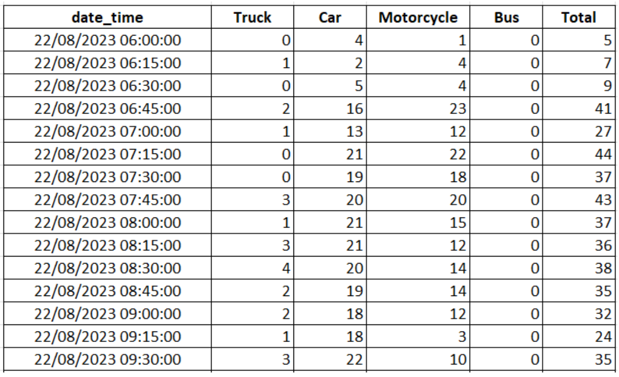

date_time	Truck	Car	Motorcycle	Bus	Total
22/08/2023 06:00:00	0	4	1	0	5
22/08/2023 06:15:00	1	2	4	0	7
22/08/2023 06:30:00	0	5	4	0	9
22/08/2023 06:45:00	2	16	23	0	41
22/08/2023 07:00:00	1	13	12	0	27
22/08/2023 07:15:00	0	21	22	0	44
22/08/2023 07:30:00	0	19	18	0	37
22/08/2023 07:45:00	3	20	20	0	43
22/08/2023 08:00:00	1	21	15	0	37
22/08/2023 08:15:00	3	21	12	0	36
22/08/2023 08:30:00	4	20	14	0	38
22/08/2023 08:45:00	2	19	14	0	35
22/08/2023 09:00:00	2	18	12	0	32
22/08/2023 09:15:00	1	18	3	0	24
22/08/2023 09:30:00	3	22	10	0	35

Figure 7. Traffic flow in one of the observed zones.

Considering that the image capture stage is completely independent of processing, in challenging scenarios such as the city of Redenção – PA, the analyses can be repeated, if necessary, until all the desired criteria are observed, which would not be possible in a situation with local processing, without video storage.

VI. CONCLUSION AND FUTURE WORK

This paper sets out to develop an artificial intelligence-based solution for volumetric vehicle counting in urban environments, aiming to support smart city mobility planning. To achieve this, an integrated system was designed combining a self-powered image acquisition unit with a computer vision pipeline for vehicle detection, tracking, and counting.

The proposed system for volumetric vehicle counting aligns with the concept of smart cities by integrating advanced technologies such as artificial intelligence, Internet of Things (IoT), and renewable energy sources. By implementing a smart image acquisition system powered by a photovoltaic generator, the solution promotes autonomous and sustainable operations, two key pillars in the development of smart cities. The software component, comprising vehicle detection, tracking, and data analysis, contributes to enhancing urban mobility planning and traffic management efficiency, vital aspects for the development of smarter and more interconnected urban environments.

The successful field testing in Redenção demonstrates the practical application of these smart city principles to improve traffic monitoring and city infrastructure, showcasing how innovative solutions can contribute to the advancement of urban living standards.

In addition to its technical contributions, the proposed system also contributes to the educational context, as higher education institutions play a fundamental role in training professionals capable of addressing smart city challenges and overcoming contemporary urban issues.

As future work, it is intended to improve the system to operate under adverse conditions, such as low illumination, occlusions, and weather variations. In addition, the inclusion of edge computing techniques will be investigated to enable real-time data processing at the point of collection, as well as to expand traffic analysis capabilities, including vehicle speed estimation and the detection of traffic irregularities.

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Smart Cities under the Lens of Cultural Branding and Education: The Case of Palmas - TO in Northern Brazil

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***Abstract*— The development of smart cities has traditionally been associated with technological infrastructure and data-driven governance. However, recent studies highlight the importance of integrating cultural identity, education, and civic participation into urban innovation processes. This study explores the role of cultural branding and educational institutions in promoting smart city strategies in emerging urban contexts. The research adopts a qualitative exploratory approach, combining a literature review with a case study analysis of the city of Palmas, the capital of the state of Tocantins in Northern Brazil. In addition, the study includes documentary analysis and observation of institutional initiatives related to urban innovation, cultural promotion, and digital inclusion. The findings suggest that cultural assets, local identity, and educational institutions can play a strategic role in the development of smart city ecosystems, particularly in medium-sized cities in developing regions. This research contributes to the debate on alternative pathways for smart city development by highlighting cultural branding and education as key elements in urban innovation strategies.**

Keywords*—*Smart City; Soft Power; Branding; Palmas - TO.

I. INTRODUCTION

This study contributes to the smart city literature by integrating cultural branding and educational dynamics into the analysis of urban innovation ecosystems, particularly in emerging cities in developing regions. Considering the idiosyncrasies of a culturally rich country like Brazil, it is crucial to emphasize the importance of integrating local culture with public policies to strengthen urban identity. The composition of a Smart City project must take into account dynamics involving knowledge, context, interactions, foundation, time, and space. Given Brazil's geospatial conditions, the country's cultural expressions are diverse and vary significantly between regions [1]. In this sense, cultural appreciation can become a great ally in improving quality of life, promoting digital inclusion, and fostering democracy. Based on these concepts, this research aims to support the innovative development of cities by intersecting modernity and tradition, emphasizing the importance of Cultural Branding for urban growth and evolution.

Despite its contributions, this study presents some limitations that should be acknowledged. First, the research adopts an exploratory qualitative approach based primarily on a literature review and a single case study. Another limitation is that the empirical analysis relies mainly on documentary sources and institutional initiatives, which may not fully capture the perspectives of all actors involved in the local smart city ecosystem, such as citizens, entrepreneurs, and public managers.

Furthermore, the long-term impacts of cultural branding strategies and educational policies on urban development cannot yet be fully evaluated. However, these limitations also create opportunities for future research that may incorporate comparative analyses, quantitative data, and broader participation from different social actors.

This article is structured as follows: Section I presents the introduction, contextualizing the research and outlining the limitations of the study. Section II describes the methodology used. Section III discusses soft power and cultural branding within the concept of smart cities. Section IV addresses smart cities in the Brazilian context. Section V examines Palmas–TO as a model of cultural branding for the Northern region of Brazil. Section VI discusses the relationship between culture, education, and digital literacy in the development of smart city ecosystems. Finally, Section VII presents the conclusions of the study and highlights how future research can contribute to this topic.

II. METHODOLOGY

This research adopts a qualitative exploratory approach in order to analyze the relationship between cultural branding, education, and the development of smart city strategies in emerging urban contexts. The methodological design combines a literature review and an empirical case study analysis, focusing on the city of Palmas, located in the state of Tocantins in Northern Brazil.

A systematic literature review was conducted to identify the main theoretical frameworks related to Smart Cities, Cultural Branding, Soft Power, and the role of education in urban innovation ecosystems. Academic articles, books, and public policy reports published in international databases were analyzed in order to establish the conceptual foundation of the study. In addition, the research employed a qualitative case study methodology [7], considering Palmas as an emerging urban environment with potential for the development of smart city initiatives.

The collected data were analyzed through qualitative content analysis, allowing the identification of patterns related to cultural identity, knowledge production, digital inclusion, and citizen participation. This methodological framework makes it possible to explore how cultural branding and educational institutions can contribute to the development of smart city ecosystems, particularly in medium-sized cities located in developing regions.

III. SOFT POWER AND CULTURAL BRANDING IN THE CONCEPTUAL FRAMEWORK OF SMART CITIES

Transforming into a Smart City requires specific changes and likely demands systemic transitions involving the co-evolution of technology, culture, and governance. Cultural and historical attributes create unique and special urban areas for local communities and visitors [2]. Additionally, the authors emphasize that culture can act as a special driver for regenerating economic growth; information and communication technologies (ICTs) enable the uniqueness and special qualities of cities to be integrated into a smart culture approach. When discussing governance, the authors suggest that this pillar shapes the economic development of cities and that, with the incorporation of ICTs, it is possible to enhance inclusion and the opportunities offered.

In this context, the term "Soft Power" was developed in the mid-1980s by the American political scientist Joseph Nye [3]. This term defines a country, state, or city's ability to use its image to attract business and progress through the dissemination of its ideas, culture, and values. In other words, soft power is a form of influence exercised through non-coercive means, such as cultural, ideological, and diplomatic influences.

The economy strengthens education, which in turn strengthens culture, ultimately reinforcing the economy and generating a significant global impact [3].

Soft power generates financial returns, investments, and recognition for cities. Through technology, creative industries strategically exploit intellectual property to foster local digital development. South Korea exemplifies this approach, with substantial investments in creative industries, including music, audiovisual production, and digital games, projecting the country's global image.

Contributing to these concepts, Place Branding is the network of associations in consumers' minds, based on the visual, verbal, and behavioral expression of a place, embodied through its objectives, communication, values, and local culture [4]. In other words, branding is the process of creating and managing a brand's identity in the market, involving the identification and definition of distinct characteristics that differentiate a place from its competitors.

When considering branding for cities, the process is multidimensional, requiring an analysis of history, culture, ecosystem, policies, and other characteristics of the location. By applying branding techniques and marketing strategies, economic, political, and cultural development can be promoted for cities, regions, and countries. Rio de Janeiro is Brazil's most internationally projected city in terms of image, as few places in the world combine abundant natural beauty with a vibrant urban lifestyle [5]. In 2012, Rio de Janeiro became the first city in the world to be designated a "World Heritage Site as a Cultural Landscape" by UNESCO. Additionally, it hosts renowned events such as Rock in Rio, Rio Carnival, and the New Year's Eve celebration at Copacabana Beach. The city’s cultural identity is further strengthened by its signature musical styles, including samba, bossa nova, choro, and funk carioca.

Promoting a city's cultural branding through innovation and technology requires integrating unique cultural elements with digital tools, creative practices, and innovative strategies. The goal is to create a strong and authentic city image while leveraging technology to amplify its reach and engage both local and global audiences.

IV. SMART CITIES IN THE BRAZILIAN CONTEXT

To evaluate the smart development of cities in Brazil, the Connected Smart Cities [6] initiative assesses municipalities through the Connected Smart Cities Ranking, which identifies the most smart and connected cities in the country. The ranking seeks to map cities with the greatest potential for development by analyzing a comprehensive set of indicators related to intelligence, connectivity, and sustainability. The initiative also promotes collaboration among companies, public institutions, and government entities, creating a platform that identifies innovative practices capable of improving urban management and the quality of life of citizens.

The Connected Smart Cities Ranking evaluates urban development through multiple dimensions that reflect the complexity of contemporary urban systems. Among the aspects analyzed are mobility solutions, urban infrastructure, environmental sustainability, technological innovation, health services, public safety, education, entrepreneurship, governance, and economic development. Together, these indicators provide a multidimensional perspective on how cities integrate technological solutions, institutional capacity, and public policies to foster urban development.

In terms of mobility, the ranking considers the adoption of intelligent transportation systems and the implementation of digital technologies that improve urban circulation and accessibility. Examples such as electronic ticketing systems in public transportation and the use of smart traffic lights, particularly in large metropolitan areas such as São Paulo, demonstrate how digital technologies can enhance traffic management and public transportation efficiency.

Urban infrastructure is also a fundamental element in the evaluation of smart cities. Indicators related to urban planning include the coverage of water supply systems, sewage treatment services, land use regulation, and the existence of strategic master plans guiding urban expansion and development. In addition, the use of digital tools in urban governance—such as computerized and georeferenced real estate registries accessible to citizens and the availability of online systems for issuing construction permits—reflects the integration of technological solutions into public administration.

Environmental sustainability represents another central component of the ranking. The analysis includes monitoring of risk areas associated with natural disasters, such as landslides, erosion processes, and hydrological events including floods and flash floods. The evaluation also considers indicators such as access to water supply services, sewage treatment coverage, solid waste collection, recycling rates, and the monitoring of mapped environmental risk areas. These elements are fundamental for understanding how cities address environmental challenges while pursuing sustainable development.

Technological infrastructure and innovation capacity are equally important in the assessment of smart cities. The ranking evaluates indicators related to entrepreneurship, technological services offered by public institutions, and the adoption of digital technologies across sectors such as mobility, urban planning, security, and governance. Particular attention is given to the expansion of digital connectivity, including broadband access, the average speed of internet connections, the level of population coverage by broadband networks, and the presence of emerging technologies such as 5G networks. Additionally, the proportion of the workforce employed in technology and innovation sectors provides insights into the capacity of cities to generate knowledge-based economic activities.

The analysis of urban development also incorporates indicators related to healthcare infrastructure and social well-being. Access to healthcare services, availability of hospital beds, presence of qualified professionals, and public investments in the health sector are considered in the evaluation. Basic sanitation infrastructure is also included in this analysis, since inadequate sanitation conditions can significantly impact population health outcomes, including infant mortality rates. This perspective highlights the interconnected nature of urban systems, where infrastructure, public services, and social well-being are closely linked.

Public security indicators are also examined as part of the evaluation of urban quality of life. These indicators include homicide rates, the number of municipal civil guards and traffic officers, per capita investments in public security, and the existence of integrated operations control centers that monitor urban dynamics and coordinate emergency responses. Such elements demonstrate the role of institutional capacity and technological tools in promoting safer urban environments.

Education is another fundamental dimension in the assessment of urban development. Indicators related to educational opportunities include the availability of public university places relative to population size, student performance in national educational assessments such as the Brazilian National High School Examination (ENEM), the ratio of computers available to students in schools, and public investments in education, research, and development. These elements reflect the importance of human capital formation and knowledge production in supporting long-term urban innovation processes.

Economic and entrepreneurial dynamics are also considered in the ranking. The analysis evaluates the creation of new businesses, the presence of innovation ecosystems, and the economic sustainability of municipalities. Indicators related to income levels, employment availability, and the diversification of economic activities help measure the capacity of cities to generate economic growth while maintaining social stability. Governance indicators complement this analysis by examining aspects such as municipal transparency, opportunities for social participation, the educational level of public managers, and public investments in strategic sectors including education, health, urban planning, and security.

The results of the Connected Smart Cities Ranking reveal significant regional disparities in Brazil. Cities located in the South and Southeast regions generally perform better across most indicators, reflecting higher levels of infrastructure development, technological adoption, and institutional capacity. This disparity is particularly evident in the environmental dimension, where the majority of the highest-ranked cities are concentrated in these regions. In contrast, cities located in the North and Northeast regions tend to present lower performance levels in several indicators of urban development.

However, when analyzing the criteria used to evaluate the smartest cities in Brazil, it becomes evident that cultural aspects are largely absent from the assessment framework. Despite the comprehensive nature of the ranking, the role of cultural identity in urban development strategies is not explicitly considered. This omission is particularly relevant in a country such as Brazil, where cultural diversity represents an important social and economic asset.

From the perspective of cultural branding, the promotion of local culture may represent an important pathway for strengthening urban development strategies, especially in regions that present lower technological and infrastructural indices. The North and Northeast regions of Brazil, for example, are widely recognized for their rich cultural heritage, including traditional festivals, music, gastronomy, architecture, and historical traditions. By leveraging these cultural assets, cities in these regions may develop distinctive urban identities capable of enhancing their attractiveness and competitiveness.

In this context, the valorization of cultural heritage can contribute to the construction of strong city brands that reinforce symbolic identity and promote social cohesion. Cultural activities, artistic production, and the preservation of local traditions allow cities to build narratives that extend beyond their geographic boundaries, increasing their visibility in national and international contexts. This process not only strengthens local identity but also stimulates economic and social development by attracting tourism, investments, cultural events, and creative talent.

Thus, incorporating cultural dimensions into smart city strategies may represent an important complement to existing technological and governance-based approaches. By integrating cultural assets with innovation policies, educational initiatives, and participatory governance, cities may develop more inclusive and sustainable pathways toward smart urban development.

V. PALMAS-TO AS A MODEL OF CULTURAL BRANDING FOR THE NORTHERN REGION OF BRAZIL

Palmas, the capital of the state of Tocantins in Northern Brazil, represents an emerging urban environment with significant potential for the development of smart city strategies. Founded in 1989, Palmas is one of the youngest state capitals in Brazil and was planned according to a modern urban design that favors territorial expansion, mobility, and environmental integration. These characteristics provide a favorable structural basis for the adoption of innovative urban development strategies aligned with contemporary smart city frameworks.

Despite its relatively recent development, the city has progressively incorporated initiatives related to innovation, digital governance, and urban sustainability. Such initiatives contribute to the creation of an environment conducive to the implementation of smart city strategies that combine technological infrastructure with social participation and the strengthening of local identity. In this sense, Palmas illustrates how emerging cities can gradually build institutional and technological capacities that support more integrated models of urban development.

One of the most relevant institutional actors in this context is the Federal University of Tocantins (UFT), which plays an important role in promoting research, innovation, and knowledge transfer in the region. Through research groups, academic programs, and extension activities, the university contributes to initiatives related to digital inclusion, technological experimentation, and civic engagement. Universities therefore function as knowledge hubs that connect academic production, technological innovation, and community participation, reinforcing the development of local innovation ecosystems.

In addition to its academic ecosystem, Palmas also presents cultural and environmental assets that can support a cultural branding strategy aligned with smart city development. Landmarks such as Praia da Graciosa and the city's cultural circuit reinforce local identity while simultaneously creating opportunities for tourism development, cultural events, and community interaction. These assets contribute to the symbolic construction of the city's image and reinforce the potential of cultural resources as drivers of urban development.

These characteristics illustrate how medium-sized cities located in developing regions may adopt alternative pathways to smart city development. Rather than relying exclusively on large-scale technological infrastructures, cities such as Palmas can leverage cultural identity, educational institutions, and participatory governance mechanisms to foster innovative and inclusive urban ecosystems. From this perspective, smart city development is not limited to technological advancement but also depends on social, cultural, and institutional dynamics.

The case of Palmas, therefore, provides empirical evidence that smart city development can emerge from the intersection of culture, education, and local institutional capacity. This perspective highlights the relevance of cultural branding as a strategic element in urban innovation processes, particularly in emerging urban contexts where cultural resources and local identity represent important development assets.

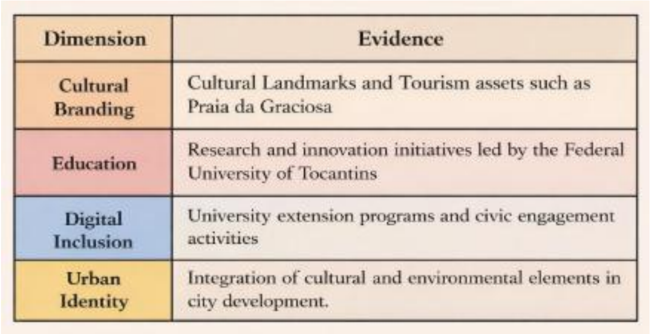
Recent recognition further reinforces this potential. For the fourth consecutive year, Palmas was ranked as the smartest city in Northern Brazil according to the Connected Smart Cities Ranking [6]. In addition to this recognition, the municipality benefits from a geographically strategic location that places it near the center of Brazil's territory, creating favorable logistical conditions that may strengthen its economic development potential. The presence of extensive natural reserves also contributes to the promotion of ecotourism and supports the city's sustainable development strategies.

In the Cultural Branding dimension, cultural landmarks and tourism assets—such as Praia da Graciosa—stand out as important elements that contribute to the city's identity and attractiveness. In the Education dimension, research and innovation initiatives led by the Federal University of Tocantins highlight the role of academic institutions in local development.

Digital Inclusion is represented through university extension programs and civic engagement activities that expand community participation and access to knowledge. Finally, the Urban Identity dimension reflects the integration of cultural and environmental elements in urban planning and city development, reinforcing the territorial identity of Palmas.

Within this context, cultural policies must consider the diversity of audiences and cultural expressions present in urban environments. However, the first step for effective cultural policy development is the recognition, by public authorities, of the intrinsic value of cultural expressions and diversity. From this understanding, it becomes possible to value and accommodate the various cultural manifestations present in different segments of the city [7].

From this perspective, Palmas presents distinctive characteristics that may enable it to become a reference model for place branding in the Northern region of Brazil as illustrated in Figure 1. By integrating culture and technology, the city can strengthen public policies focused on digital inclusion, the development of intelligent citizenship, and the appreciation of local cultural heritage. Such an approach contributes to the construction of an urban development strategy in which cultural identity becomes a central component of smart city initiatives.



Dimension	Evidence
Cultural Branding	Cultural Landmarks and Tourism assets such as Praia da Graciosa
Education	Research and innovation initiatives led by the Federal University of Tocantins
Digital Inclusion	University extension programs and civic engagement activities
Urban Identity	Integration of cultural and environmental elements in city development.

Figure 1. Dimension and evidence in Palmas- TO.

In this sense, the cultural branding strategy of Palmas could be structured around three main dimensions. The first dimension involves culture and local identity, encompassing the history and cultural heritage of Palmas and Tocantins, traditional handicrafts, regional gastronomy, and diverse cultural manifestations, as well as cultural and sustainable tourism initiatives. The second dimension relates to digital inclusion and citizen participation, focusing on the development of basic and advanced digital literacy programs that enable citizens to actively participate in digital environments. The third dimension concerns digital governance and sustainable development, including the implementation of participatory platforms, e-governance initiatives, technological tools that facilitate dialogue between citizens and public administrators, training programs for public managers focused on smart city policies, and educational initiatives aligned with the Sustainable Development Goals (SDGs).

From a practical standpoint, the development of the Palmas cultural brand should begin with structured studies aimed at integrating technological tools that improve public services and expand access to information for both residents and visitors. Given the presence of universities and research institutions in the city, Palmas has strong potential to establish partnerships with academic actors in order to identify local needs and develop technological solutions that promote quality of life and strengthen the tourism sector.

Moreover, Palmas can be strategically positioned as an influential hub in both national and international contexts, not only due to its cultural heritage but also because of its natural landscapes and environmental resources. Iconic locations such as Palmas Lake, the waterfalls of Taquaruçu, the Serra do Lajeado mountain range, and the region's characteristic sunsets constitute symbolic elements capable of reinforcing the city's identity and attractiveness.

The cultural branding strategy of Palmas should therefore align the promotion of cultural identity with innovative technological solutions capable of enhancing visitor experiences and strengthening the city's international visibility. The integration of culture and technology enables the connection between tradition and modernity within the broader framework of intelligent urban development. Examples of such initiatives include the development of cultural tourism applications featuring digital itineraries that highlight indigenous, quilombola, and regional traditions, combined with immersive virtual reality experiences that present local dances such as Sússia (also known as Suça or Súcia) and Catira. Additional initiatives may involve the digitization of archives related to local festivals, such as the Taquaruçu Gastronomic Festival, enabling the virtual promotion of regional gastronomy and cultural traditions.

Interactive technological resources may also contribute to strengthening the city's cultural identity. For example, digital panels installed in parks and other high-traffic areas could present historical information about Palmas and Tocantins, while nighttime projections might showcase local legends and cultural narratives. By promoting the development of such solutions through partnerships with universities and local innovation actors, the city can strengthen its cultural branding strategy while simultaneously expanding its technological capabilities.

In this context, technology becomes a powerful enabler for building and disseminating the city's image. Initiatives such as gamification based on local cultural narratives, digital platforms centralizing information about cultural heritage, virtual and augmented reality experiences, digital archives of historical records, documentary productions, podcasts, and artificial intelligence–based cultural assistants could significantly enhance public engagement and expand global access to the city's cultural assets. Furthermore, the use of big data analytics to monitor tourism trends may support more strategic cultural planning and improve the effectiveness of urban branding initiatives.

Finally, as an ecological hub with extensive natural resources, Palmas also has the potential to strengthen its tourism sector through the development of a nautical events agenda centered around Palmas Lake. Activities such as wakeboarding, rowing, kayaking, canoeing, and flyboarding could contribute to the diversification of tourism experiences while reinforcing the city's image as a destination that integrates nature, culture, and innovation.

VI. CULTURAL ASSETS, EDUCATION AND DIGITAL LITERACY IN THE DEVELOPMENT OF SMART CITY ECOSYSTEMS

Believing that the challenges inherent to Smart Cities encompass the integration of economic development with public service planning, the maintenance of a pragmatic orientation through investments in practical, feasible, and financially sustainable projects, and the assurance of active participation by community representatives, local businesses, and residents in order to align initiatives with the city's opportunities and challenges [8].

Thus, considering local culture as a pillar of smart city development is essential, as public policies should be directed toward technological, social, and governmental solutions that respect the needs, values, and identities of the population.

Figure 2 presents the conceptual model proposed in this study, highlighting the interactions between cultural assets, education, digital literacy, and civic engagement in the formation of smart city ecosystems. Cultural assets such as heritage, local identity, and tourism resources constitute the symbolic foundation for cultural branding strategies, enabling cities to construct narratives that strengthen their identity and expand their visibility within broader social and economic networks.

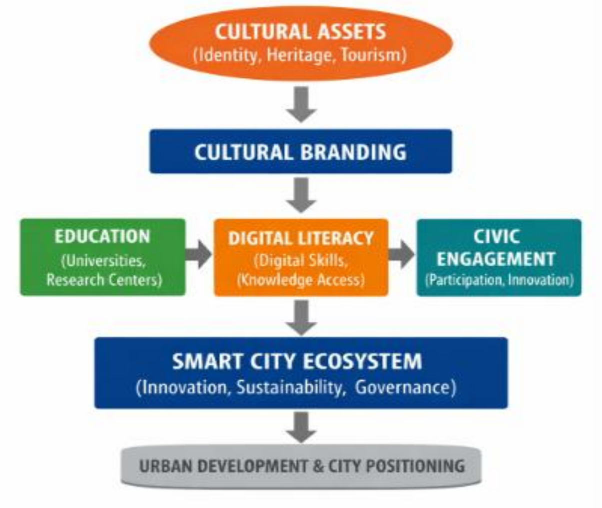


Figure 2. Conceptual model linking cultural assets, education, and digital literacy in the development of smart city ecosystems.

In these educational institutions, particularly universities and research centers, play a central role in the development of human capital, digital competencies, and innovation processes. Through the production and dissemination of knowledge, these institutions contribute to strengthening digital literacy and to the formation of citizens capable of actively participating in urban development processes. In this context, digital literacy functions as a connecting element between education and social participation, allowing citizens to access information, interact with digital infrastructures, and contribute to participatory governance processes.

The interaction among these elements fosters the development of urban ecosystems characterized by innovation, social participation, and sustainable urban growth, thereby offering an alternative pathway for smart city development in emerging urban contexts. In this regard, technology should be understood as inherently social in nature. Consequently, citizens' needs must serve as a guiding principle for technological development initiatives, ensuring that such efforts are oriented toward addressing and resolving local social challenges [9].

Furthermore, the configuration of smart cities necessitates the adoption of new governance models in which public authorities and citizens cultivate sustainable and collaborative relationships. Within this framework, the integration of sustainable public management practices with collective governance becomes essential, grounded in and reinforced by active citizen participation [10].

VII. CONCLUSION AND FUTURE WORK

This study explored the relationship between cultural branding, education, and the development of smart cities in emerging urban contexts, using the city of Palmas, in Northern Brazil, as an empirical case. The results suggest that the development of smart city ecosystems should not be understood exclusively from a technological perspective, but rather through a broader approach that integrates cultural identity, education, and social participation.

The case of Palmas illustrates how medium-sized cities in developing regions can leverage cultural assets and educational institutions to promote innovative urban environments. Instead of relying exclusively on large-scale technological infrastructures, these cities can develop alternative pathways toward smart city development by strengthening local identity, promoting knowledge production, and encouraging civic engagement.

In this context, cultural branding emerges as a strategic mechanism capable of reinforcing urban identity and positioning cities within broader networks of tourism, knowledge exchange, and economic development. At the same time, educational institutions play a central role in developing the human capital and digital competencies necessary for the functioning of smart city ecosystems.

Future research can expand this study in several directions. Comparative analyses involving other emerging cities in Brazil and Latin America may provide a broader understanding of how cultural branding strategies interact with smart city initiatives across different socioeconomic contexts. In addition, future studies may incorporate quantitative methods, surveys, and interviews with local stakeholders in order to more accurately capture citizens' perceptions, levels of digital literacy, and the role of community engagement in the development of smart city ecosystems.

Another promising line of investigation involves analyzing the role of universities as innovation hubs in regional development, particularly with regard to knowledge transfer, entrepreneurship, and digital inclusion initiatives.

Therefore, the integration of cultural assets, educational initiatives, and participatory governance is understood as an important framework for understanding how emerging cities can pursue more inclusive and sustainable strategies for urban innovation.

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IoT System for Monitoring the Physicochemical Quality of Irrigation Water: Towards Efficient Agricultural Management

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Abstract— **This paper describes the development and evaluation of an Internet of Things (IoT) system for monitoring physicochemical parameters in water, with potential applications in irrigation systems for crops, and was developed using low-cost sensors and an ESP32 microcontroller programmed with the Arduino® IDE. The system allows the real-time measurement of variables such as turbidity, Total Dissolved Solids (TDS), and water temperature. The acquired data is processed at the acquisition level and transmitted via Wi-Fi to the ThingSpeak cloud platform for storage and visualization, making it available for subsequent analysis and decision-making support. To evaluate accuracy, stability, and viability, experimental tests were carried out using standard solutions of different concentrations, comparing the measurements with laboratory equipment and theoretical values to ultimately develop a polynomial calibration model. The results show high performance of the TDS sensor, with relative errors of 6%-21% and a stable temperature measurement, with an error of about 4.7% compared to the reference instrument. In contrast, the turbidity sensor showed high variability, with errors ranging from 13% to 77% depending on the measured concentration. Furthermore, the influence of environmental factors on sensor response was demonstrated, highlighting the importance of calibration and control processes in water monitoring systems.**

Keywords- Internet of Things (IoT); Water quality monitoring; Arduino ESP32; Low-cost sensors; ThingSpeak.

I. INTRODUCTION

Water quality is a key factor in agricultural productivity as its physicochemical properties directly influence crop development and soil sustainability. Parameters such as turbidity, Total Dissolved Solids (TDS), and water temperature enable characterization of the water resource's condition and detection of factors that may affect irrigation systems. In this context, the periodic monitoring of these variables is essential to support more efficient water management, especially in environments where access to specialized instrumentation is limited [1].

The advancement of the Internet of Things (IoT) has driven the development of monitoring systems based on microcontrollers and low-cost sensors, capable of acquiring real-time data and transmitting it to cloud platforms for storage and remote visualization. These solutions facilitate access to relevant information on environmental variables and provide a technological foundation for subsequent analysis and informed decision-making. However, the reliability of these systems depends mainly on the accuracy of the sensors and the implementation of appropriate calibration and validation processes [2][3].

This paper presents the development and implementation of an IoT system for monitoring physicochemical water parameters, with potential applications in crop irrigation systems. The system is based on an ESP32 microcontroller programmed in the Arduino® IDE and integrates low-cost sensors for measuring turbidity, TDS, and temperature. The acquired data is transmitted via Wi-Fi to the ThingSpeak platform for cloud storage and visualization, making it available for subsequent analysis. This study focuses on the experimental evaluation of the system's performance and the sensors used, while considering the influence of environmental factors on the measurements. The paper is organized as follows: Section II presents related work, Section III describes the materials and methods, Section IV presents the results and discussion, and Section V presents the conclusions and future work.

II. RELATED WORKS

To ensure the rigor and transparency of the literature review process, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) methodology was adopted. This methodology defines a systematic procedure structured in four phases: identification, screening, eligibility, and final inclusion of relevant studies [4]. This approach enabled the objective organization and refinement of the literature on IoT systems and data acquisition.

The conducted search spanned widely recognized scientific databases and specialized repositories, including IEEE

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Xplore, Scopus, ScienceDirect, MDPI, and Google Scholar, which focus on IoT systems for water quality monitoring. The considered works were published between 2019 and 2025 and describe experimental implementations of low-cost sensors, embedded platforms, and cloud-oriented data transmission. This review lets us identify technological trends, design approaches, and major limitations on IoT-based water monitoring systems.

TABLE I. RESULTS OF LITERATURE REVIEW.

Reference (Year) Title	Sensors / Hardware	Main result
Tavares de Camargo (2023) — *Low-Cost Water Quality Sensors for IoT: A Systematic Review [5]*	pH, TDS, turbidity, temperature.	Analyzes the performance and limitations of low-cost IoT sensors
Flores-Iwasaki (2025) — *IoT Sensors for Water Quality Monitoring in Aquaculture Systems [6]*	Physicochemical Sensors + IoT	Technological trends and applications in water monitoring
Rojas (2025) — *Sensors and IoT for Water Quality Monitoring [7]*	pH, TDS, turbidity, temperature.	Identifies gaps between laboratory and field
Jayaraman (2024) — *Critical review on water quality analysis using IoT [8]*	Various IoT Sensors	It points out challenges in calibration and reliability.
Lal (2024) — *Low-cost IoT based system for lake water quality monitoring [9]*	pH, TDS, turbidity	Functional, low-cost system validated in a lake
Bogdan (2023) — *Low-Cost IoT Water-Quality Monitoring System for Rural Areas [10]*	ESP8266, pH, TDS, turbidity	Viability in rural contexts; calibration dependence
Suriasni (2024) — *IoT Water Quality Monitoring in MBBR [11]*	Physicochemical Sensors + IoT	Stable monitoring in water treatment
Kanwal (2024) — *IoT-Driven Intelligent Decision-Making System [12]*	pH, temperature, turbidity	Advanced system with decision-making
Rosliana Eso (2024) — *IoT Water Quality Monitoring for Shrimp Farming [13]*	pH, TDS, temperature.	Improved control in aquaculture
Zafi (2024) — *Monitoring System Based on IoT and TDS Sensor [14]*	TDS, microcontroller	Validate the use of the TDS sensor in IoT
Jan (2025) — *IoT Based Water Quality Monitoring Using ESP32 [15]*	ESP32, basic sensors	Economic and replicable platform
Carriazo (2022) — IoT-Based Drinking Water Quality Measurement System (2022) [16]	—	Overview of IoT systems for drinking water
F. Jan (2021) — *IoT Based Smart Water Quality Monitoring [17]*	IoT sensors	Open challenges and future directions
Islam (2025) — Prediction Model of Aqua Fisheries Using IoT Devices (2025) [18]	ESP32, sensors, ThingSpeak	It integrates monitoring and prediction
Ayon (2026) — IoT-Enabled Smart Aquarium System (2026) [19]	ESP32, multiple sensors	Real-time monitoring in aquariums

The key approaches and contributions of the literature review are summarized and organized thematically, enabling analysis of trends in IoT systems applied to water quality monitoring.

Studies conducted by Tavares de Camargo, Flores-Iwasaki, Rojas, Jayaraman, Carriazo-Regino, and Jan on IoT-based water quality monitoring unveil the increasing use of low-cost sensors and communication platforms for the remote, real-time measurement of physicochemical parameters such as pH, temperature, turbidity, conductivity, and total dissolved solids. These systematic reviews and state-of-the-art analyses demonstrate the adoption of IoT architectures supported by low-power communication technologies and cloud platforms for data management and visualization, while also identifying persistent challenges related to interoperability, field validation, and the scalability of water monitoring systems [5]–[8][14][15].

The work presented by Flores-Iwasaki, Suriasni, Kanwal, Eso, Zafi, Islam, and Ayon demonstrates that, in aquaculture applications, IoT systems represent an effective solution for the continuous monitoring of critical conditions in fish farming, aquaponics, biofloc systems, and shrimp farming. These approaches integrate commercial sensors with microcontrollers such as Arduino and ESP32, enabling early detection of water-quality variations and, in some cases, implementing automatic control strategies to optimize system conditions. The reported experimental validation confirms their technical feasibility and their contribution to the sustainable management of aquaculture systems [6][11]–[14] [16]-[19].

Likewise, the work proposed by Lal, Bogdan, and Carriazo-Regino focuses on developing low-cost IoT systems for rural and natural environments, emphasizing accessibility, energy efficiency, and operational autonomy. These solutions facilitate continuous monitoring of water bodies in areas with limited infrastructure using widely available hardware platforms, thereby enabling environmental monitoring and timely access to relevant water-quality information [9][10] [14].

Finally, the studies conducted by Jayaraman, Kanwal, Jan, Islam, and Ayon show that integration of cloud-based IoT platforms with machine learning techniques significantly expands the capabilities of water monitoring systems. These approaches enable remote data visualization, alert generation, and intelligent water-quality classification with high accuracy, reinforcing the potential of IoT solutions as key tools for efficient and sustainable water resource management across diverse contexts [8][12][15]-[19].

III. METHODOLOGY

The development of the water physicochemical parameter monitoring system enabled a gradual evolution from basic data acquisition to the integration of IoT capabilities. Initially, the ATmega328P microcontroller was used to read and perform preliminary processing of the variables, thereby enabling validation of sensor functionality and system stability. Subsequently, an ESP32 development board was employed to enable Wi-Fi connectivity and automatically transmit data to the ThingSpeak platform, allowing for storage, management, and visualization in the cloud.

The system is designed to measure relevant physicochemical variables for assessing irrigation water quality, specifically temperature, TDS, and turbidity. These parameters allow for an initial characterization of the water resource's condition and its suitability for agricultural applications. Additionally, auxiliary modules were integrated to ensure proper data management, including a microSD card for local storage, a Real-Time Clock (RTC) for accurate date and time recording, and a Liquid Crystal Display (LCD) screen with an I2C interface, which facilitates immediate visualization of readings during field monitoring. The general scheme is illustrated in Figure 1.

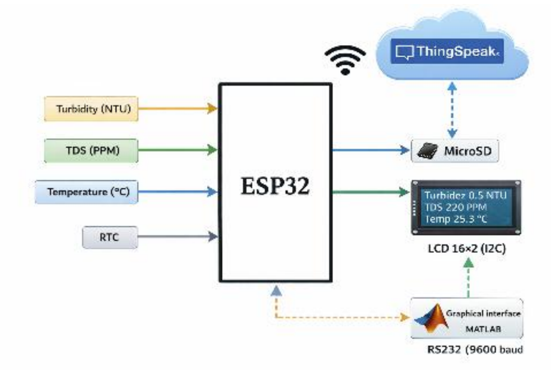

Figure 1. General scheme of the monitoring system.

The system's timing is defined using timer-based interrupt routines, ensuring the sequential execution of critical tasks, as shown in the flowchart in Figure 2. TMR0, configured with a 1-second interval, controls sensor sampling, LCD-based variable visualization, and data storage on the microSD card with RTC timestamps. Additionally, TMR1, configured with a 15-second interval, defines the interval for transmitting data to ThingSpeak via Wi-Fi and for visualization in MATLAB via RS232 at 9600 baud, enabling local monitoring without affecting the main algorithm.

The monitoring system incorporates turbidity, TDS, and temperature sensors, parameters widely used in the physicochemical evaluation of irrigation water quality. In this case, temperature is considered a critical variable because it directly influences dissolved solids measurements. Turbidity is measured using an analog optical sensor based on light transmission and scattering, capable of detecting suspended particles over a range of 0 to 1000 NTU. This sensor delivers an output signal between 0 and 4.5 V, allowing for continuous measurements with adequate resolution for environmental monitoring applications [20].

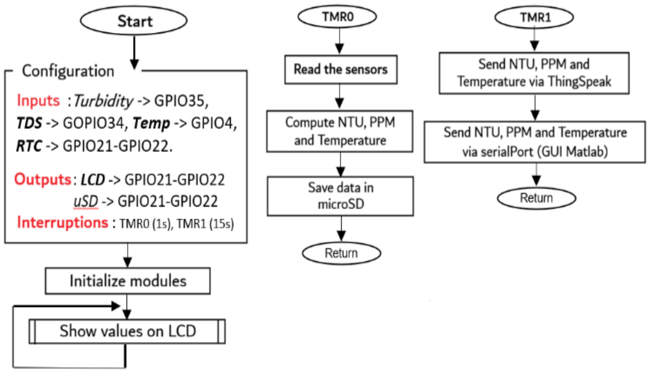

Figure 2. Flux diagram for the system.

TDS is measured using an electrical conductivity sensor with two electrodes. The analog signal from this sensor corresponds to the concentration of dissolved solids in the water and is converted to PPM units through an experimental calibration process. Since this sensor is sensitive to thermal variations, it requires temperature compensation to improve its accuracy [21]. For this purpose, the water temperature is recorded using a DS18B20 submersible digital sensor, designed for liquid applications. This sensor offers high stability, reliable digital communication, and a suitable measurement range, facilitating its integration with the microcontroller and the required thermal compensation [22]. The calibration of the turbidity and TDS sensors was performed by preparing standard solutions with known concentrations. This procedure was carried out in the Water Treatment Laboratory of the Department of Environmental Engineering at the Pedagogical and Technological University of Colombia, under specialized technical supervision. For turbidity, formazin, the primary standard recommended by APHA regulations, was used, starting from a 4000 NTU stock solution, from which solutions between 10 and 100 NTU were obtained by controlled volumetric dilution, applying the relationship shown in (1).

$$C_1V_1 = C_2V_2 \tag{1}$$

where C_1 and V_1 correspond to the concentration and volume of the stock solution, and C_2 and V_2 to the desired concentration and volume. The actual turbidity values of the standard solutions were determined using a Merck TurbiQuant® 1500 T benchtop turbidimeter, a reference instrument designed for precise and repeatable measurements in NTU units. Similarly, the TDS sensor was calibrated using a 10,000 PPM stock solution prepared with soluble salts in ionized water, obtaining concentrations between 200 and 2000 PPM by controlled volumetric dilution. The actual TDS values were measured using a Hanna Instruments HI 9811-5 multiparameter meter, which integrates pH, electrical conductivity, and TDS measurements with automatic temperature compensation, ensuring reliable readings. The turbidity and TDS sensors were characterized by measuring their output voltage against solutions of known concentration, recording three readings per point to reduce noise. Average values were used to plot voltage-concentration curves. The analysis revealed polynomial behavior in the sensor response, so regression was applied to obtain quadratic models implemented on the microcontroller, allowing real-time conversion of analog voltages to physical turbidity and TDS values. To evaluate the sensors' stability under ambient conditions, the influence of temperature on their response was analyzed, as shown in Figure 3. The results show a slight thermal drift, evidenced by a systematic shift in the calibration curves across different temperatures. This effect is greater in the TDS sensor because electrical conductivity depends on temperature, whereas in the turbidity sensor, the variation is less significant.

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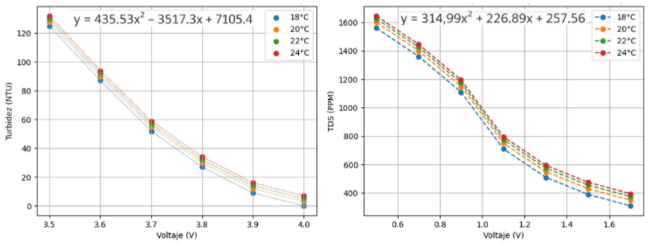

Figure 3. Characteristic equations of Turbidity and TDS.

IV. RESULTS AND DISCUSSION

The system performance was validated by comparing measurements from turbidity (NTU) and TDS sensors with values recorded by standard instruments and with the theoretical concentrations of the prepared solutions. The results are presented in Tables II and III.

TABLE II. COMPARISON OF TURBIDITY VALUES.

	Obtained data from turbidity sensor (NTU)						
Theoretical value	**Reference instrument measurement**	**Data 1**	**Data 2**	**Data 3**	**Data 4**	**Mean**	**Error**
10	11.6	11.68	16.5	16.7	16.8	16.72	44%
20	22.3	16.2	16.0	16.2	16.33	16.18	27%
30	36.1	31.29	31.1	31.2	31.45	31.37	13%
40	48.5	86.36	86.36	85.0	85.9	85.98	77%
50	56.6	88.52	88.7	88.21	87.0	88.26	56%

(*) Nephelometric turbidity unit
(**) Squared error with respect to the value of the reference instrument

TABLE III. COMPARISON OF TDS VALUES.

	Obtained data from TDS sensor (ppm)							
Theoretical value	**Reference instrument measurement**	**Data 1**	**Data 2**	**Data 3**	**Data 4**	**Mean**	**Mean deviation**	**Error**
400	509	631	536	586	558	571	42.7	12%
600	774	938	900	954	978	938.2	26.8	21%
800	1095	1211	1201	1220	1250	1216	18.7	11%
1000	1300	1377	1358	1360	1377	1372	11.4	6%
1200	1524	1424	1420	1430	1400	1417.2	10.4	7%

(*) Parts per million
(**) Error calculated with respect to the reference instrument

The results for turbidity, presented in Table II, show that the sensor's performance is strongly dependent on the measurement range. For low turbidity values (10 and 20 NTU), high error rates of 44% and 27%, respectively, were observed, indicating a notable tendency toward overestimation compared to the reference instrument. Although the standard deviations were low, indicating good repeatability, the systematic differences from the reference values suggest limitations in the sensor calibration within these ranges.

The best performance was observed at around 30 NTU. The results show that the error was reduced to 13% and that the average measured value approached that of the reference instrument, while maintaining low dispersion. This behavior indicates that this range corresponds to the optical sensor's optimal sensitivity point. In contrast, for concentrations above 40 and 50 NTU, a significant loss of linearity was observed, with errors of 77% and 56%, respectively. In these cases, the sensor recorded values much higher than the actual values, suggesting saturation of the optical system, a common phenomenon in transmissivity-based sensors.

Overall, the turbidity sensor produces an average error of 44%, limiting its reliability, especially outside the 20-30 NTU range. These results suggest either restricting its operation to intervals where it shows greater stability or implementing more robust calibration models that compensate for nonlinear effects and saturation phenomena observed at higher concentrations.

The TDS sensor exhibited more stable and consistent performance, as shown in Table III. At low concentrations of 400 and 600 PPM, a systematic overestimation was observed, with errors of 12% and 21%, respectively, attributable to the sensor's sensitivity at low conductivities and the thermal influence of the measurement method. From 800 PPM upwards, performance improved significantly, with the error decreasing to 11% and the standard deviation decreasing. The best performance was observed in the 1000 and 1200 PPM ranges, with errors of 6%-7%, high stability, and good reproducibility. The overall system error was 11%, demonstrating greater accuracy and reliability of the TDS sensor compared to the turbidity sensor. These results show that error tolerance depends on the application context. In agricultural irrigation, larger margins can be accepted without significantly affecting decision-making, while urban applications or wastewater management require stricter levels of accuracy and stability. Consequently, it is necessary to define specific performance metrics for each implementation scenario.

The system demonstrates stable performance in the remote transmission and visualization of turbidity, TDS, and temperature data via the ThingSpeak IoT platform. As shown in Figure 4, the measurement system works along with the communication infrastructure and graphical interface, assigning each variable to an independent field within the configured channel. The data are stored and graphically represented over time, enabling temporal monitoring of the measured physicochemical parameters.

Data transmission was performed at 15-second intervals, ensuring reliable communication in accordance with ThingSpeak's restrictions. This interval prevents congestion, optimizes energy consumption, and provides adequate resolution for continuous monitoring, validating the system's viability for remote supervision. However, Wi-Fi connectivity can be limited in rural environments with restricted coverage. In this context, LPWAN (Low-Power Wide-Area Network) technologies, designed for long-range, low-power communication, emerge as a viable alternative. In particular, LoRa (Long Range) enables the implementation of distributed monitoring networks with greater coverage and energy efficiency.

The graphical user interface (GUI) enabled real-time local monitoring of turbidity, TDS, and temperature, as well as data logging and exporting for later analysis. This graphic environment was developed in MATLAB using App Designer and provides an interactive application with control buttons, tables, graphs, and display panels, as shown in Figure 4. The GUI included menus for each measured variable, allowing dynamic switching between signals from the microcontroller. It also included options to start and stop data acquisition, generate Excel files, and implement a basic authentication mechanism. Overall, the interface proved to be a functional

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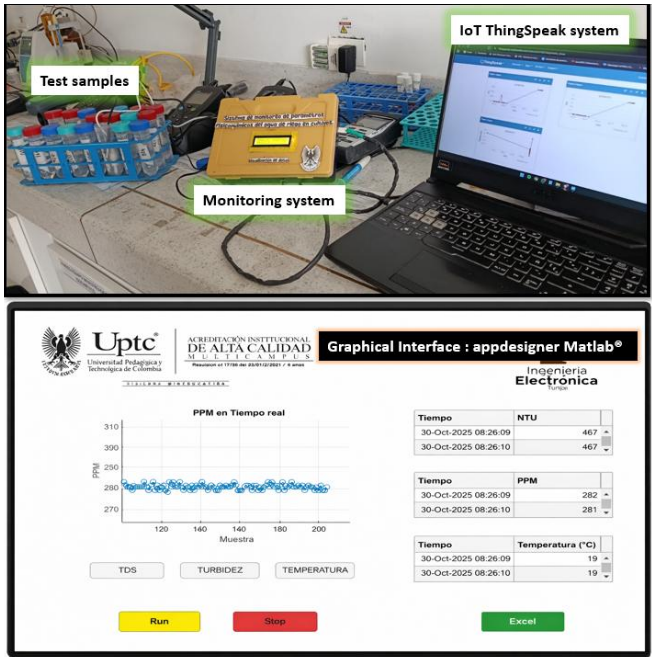
tool for local monitoring, data management, and system control, complementing remote cloud-based visualization.



Tiempo	NTU
30-Oct-2025 08:26:09	467
30-Oct-2025 08:26:10	467

Tiempo	PPM
30-Oct-2025 08:26:09	282
30-Oct-2025 08:26:10	281

Tiempo	Temperatura (°C)
30-Oct-2025 08:26:09	19
30-Oct-2025 08:26:10	19

Figure 4. Characteristic equations of Turbidity and TDS

From an economic perspective, the developed IoT system significantly reduces costs compared to commercial instruments. As stated in Table IV, the final cost is about USD 59, much lower than commercial equipment, such as portable turbidimeters or professional TDS meters, which range from USD 150 to over USD 3,900 (Table IV). As for functionality, our prototype features turbidity, TDS, and temperature measurements, local storage, graphical interface visualization, and remote cloud monitoring. In comparison, commercial equipment generally does not offer integrated monitoring or native data transmission. Furthermore, some commercial devices require additional software licenses for graphical interfaces or data management. This difference positions our IoT system as a viable alternative for educational settings, rural applications, and continuous monitoring with limited budgets. Although commercial equipment offers greater certification and accuracy, our prototype meets the functional requirements for measurement, visualization, and transmission; under these conditions, our device becomes an accessible, integrated option for water quality monitoring.

The presence of thermal drift and the variability observed in the turbidity sensor highlight the need to implement specific calibration processes and compensation mechanisms to improve measurement accuracy. Despite these limitations, the system exhibits stable data acquisition and transmission, validating its viability as a low-cost monitoring solution for agricultural applications and resource-constrained environments. Furthermore, its architecture, based on low-cost sensors and IoT connectivity, enables adaptation to urban scenarios, such as monitoring in storage tanks or drainage networks. However, these applications require higher precision and reliability, necessitating calibration process adjustments tailored to the specific usage context.

TABLE IV. COMPARISON OF COSTS.

Developed IoT system	Associated Variable	Cost (USD)
Turbidity sensor	Turbidity	14.5
TDS Sensor	TDS	15.2
Temperature Sensor	Temperature	2.9
LCD + I2C module	Visualization	6.5
SD module	Data recording	1.3
RTC module	Time	2.1
Power source	Energy	1.8
ESP32	Processing / IoT	9.2
Structure and wire	Hardware assembly	6.6
IoT system subtotal	Turbidity, TDS, Temperature	**59**
Commercial solutions		
Professional Portable Turbidimeter	Turbidity **(Hanna Instruments)**	**315 – 920**
TDS meter / Professional Conductivity	TDS **(Extech Instruments)**	**158 – 395**
Commercial multiparameter system	Multiple variable **(Hanna Instruments)**	**1580 – 3950**

V. CONCLUSIONS

The monitoring system has demonstrated the feasibility of integrating low and mid-cost sensors, IoT platforms, and experimental calibration to measure turbidity, TDS, and temperature in real time. The prototype, based on an ESP32 microcontroller, includes data storage, local visualization, and transmission to the cloud via ThingSpeak, recording continuous and structured information. The preparation of standard solutions and the construction of polynomial calibration models enabled a quantitative evaluation of the sensors' performance; the results reveal their metrological capabilities and limitations.

The results show that the system's performance depends on the concentration range, sensor characteristics, and the physical conditions of the medium. The TDS sensor exhibited an overall error of 11%, with greater stability in the mid- and high-range measurements. In comparison, the turbidity sensor reached an error of 44%, with overestimations in the low and high ranges. On the other hand, the temperature measurement, with an error of approximately 4.76%, allowed for the required thermal compensation. Data transmission via Wi-Fi and the ThingSpeak platform enables remote monitoring of the variables, though it can be limited in rural environments with restricted connectivity. In general, the system is a functional, scalable, and low-cost solution; however, its long-term viability depends on optimizing energy consumption and implementing appropriate maintenance strategies to ensure its continuous operation.

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The Impact of Logistics Systems' Digital Transformation on the Development of Healthy Cities

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Abstract—**The development of smart cities is a response to the need to integrate the interests of various stakeholder groups in order to ensure a high quality of life for residents. In this regard, the city's logistics system plays a pivotal role in supporting the operation of public services, including healthcare. Healthy cities serve as hubs for healthcare systems. These hubs generate complex logistical needs that require the integrated management of material, information, and knowledge flows. This article aims to determine the impact of logistical conditions and digital transformation processes on the smart development of healthy cities. The study proposes a knowledge management concept for the city's logistics system to improve the efficiency of flows related to medical and health facilities. This concept emphasises the importance of stakeholders' participation in these flows and their role in gathering and sharing knowledge. It also considers the function of a coordinator responsible for integrating knowledge from various sources. A review of literature and empirical research confirms that digital transformation is a key factor in supporting smart urban development for health. Key features of organisations acting as knowledge coordinators and methods of acquiring tacit knowledge - the foundation for building resilient and sustainable urban logistics systems - were also identified.**

Keywords: healthy cities, knowledge management, digital transformation, healthcare logistics, resilient urban systems.

I. INTRODUCTION

A smart city should cater to diverse stakeholder groups while maintaining a strong focus on ensuring a high quality of life. In this context, the city's logistics system plays a pivotal role in providing the infrastructure necessary for the operation of essential public services, particularly healthcare. This article aims to determine the impact of a city's logistics system on smart urban development for health, and to conceptualise a knowledge management model that supports adapting logistics systems to the specific needs arising from urban healthcare systems. The article proposes a knowledge management concept that integrates knowledge generated by the city and its stakeholders into the logistics system.

The developed concept emphasises the importance of the role of stakeholders involved in the movement of people and goods in healthy cities. It also highlights their function as coordinators responsible for integrating knowledge from dispersed sources, as well as their role in the processes of gathering, processing and sharing knowledge. Additionally, particular attention was paid to identifying sources of explicit knowledge and methods of acquiring tacit knowledge. The following research questions were formulated in this context:

Q1. What elements of the digital transformation of a city's logistics system support smart urban development for health?

Q2. What characteristics should an organisation acting as a knowledge management coordinator in the logistics system of a healthy city have?

Q3: What are the sources of open knowledge, and how can closed knowledge be acquired for knowledge management purposes in the logistics systems of healthy cities?

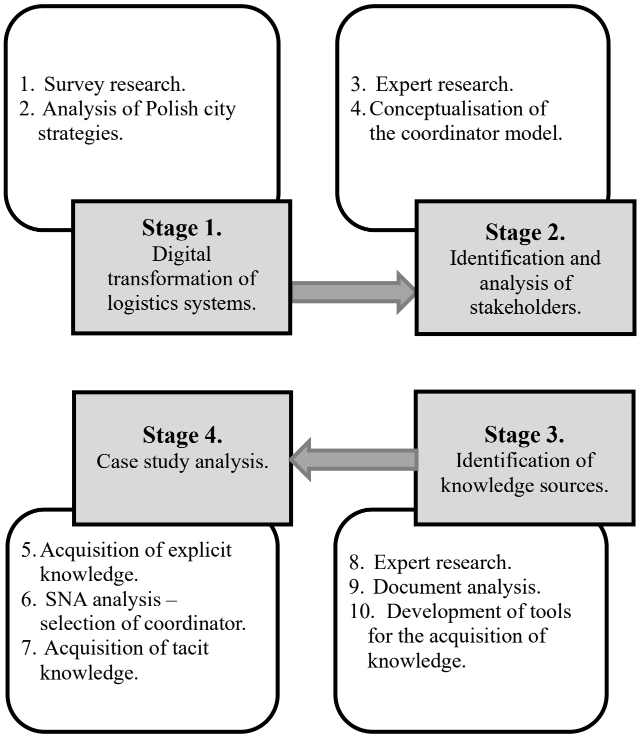

Figure 1. Research methodology.

These questions required a systematic review of the literature, integrating the concepts of 'healthy cities' and the 'smart city' approach, as well as the issue of the city's logistics system. The methodology combined stakeholder identification and role definition with open knowledge source

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analysis and tacit knowledge acquisition tool development. This methodology enabled the development of a coherent knowledge management concept for a city's logistics system. The empirical part consisted of a case study conducted in one of the 62 cities covered by the study. This city was chosen because it fulfilled the attributes of a “city for health”. The article concludes with a discussion of the results and findings.

II. LITERATURE BACKGROUND

Health issues have become the foundation for the development of modern urban centres. This approach aims to stimulate social, economic and environmental progress, while prioritising the quality of life of residents, which has a direct impact on their physical and mental well-being [1]. In 1988, the WHO launched the Healthy Cities programme, which has since evolved into a global initiative [2]. The concept of a healthy city is based on the fundamental values of the right to health and well-being, peace, social justice, gender equality, solidarity, social integration and sustainable development, and involves placing health, social well-being, equality and sustainable development at the centre of local policies, strategies and programmes. The Healthy Cities initiative is guided by the principles of health for all, universal health coverage, intersectoral governance for health, health in all policies, community participation, social cohesion and innovation [2]. These principles align well with the concept of smart cities, which have the potential to promote health and wellbeing.

Logistics systems play a key role in developing healthy smart cities. The evolution of these systems towards 'green' approaches that prioritise environmental issues, as well as sustainable systems that address social and economic concerns, helps create efficient, effective and inclusive urban environments [3]. One of the main dimensions of smart cities is smart mobility, which is also part of the logistics system. In this regard, strategies must be developed to meet current and future mobility needs in urban centres [4]. Researchers highlight the connection between various mobility options and the development of healthy smart cities. Cycling and walking are identified as solutions that are more resistant to pandemics, enabling safe travel and providing additional benefits in terms of physical activity, mental health and sustainable development. Furthermore, pedestrian-friendly neighbourhoods have been found to reduce stress [5]. These issues align with the concept of the 15-minute city. This concept can contribute to reducing transport emissions and noise pollution, promoting active modes of transport, reducing inequalities (including health inequalities) and building resilience to future epidemics and threats from climate change [5]. The ability to walk or access public transport, combined with reduced dependence on cars, mitigates the effects of climate change [6]. Access to reliable public transport is an important factor in potential urban social disparities, which translate into inequalities in access to medical services [5]-[7].

In summary, it should be emphasised that climate change has been identified as one of the main threats to public health. Furthermore, equal access to health and social care in cities must be improved. Additionally, good health is both a consequence of and a prerequisite for sustainable development [7].

III. RESULTS AND DISCUSSION

In accordance with the stages presented in Figure 1, the conceptualisation of a knowledge management system that integrates medical mobility needs with the conditions of the city's logistics system, with a distinct role for a central coordinator, was carried out.

The first stage of the research involved identifying key stakeholders in the city's health logistics system. These included medical facilities, residents, local government units, scientific and research units, uniformed services, organisations involved in medical waste management and logistics companies. A search was then conducted among these stakeholders for an entity capable of acting as a knowledge management system coordinator. This coordinator would be responsible for integrating dispersed knowledge resources and initiating the development of logistics solutions that meet cities' health needs. The proposed model assumes that the coordinator should possess strong relational skills. The coordinator acts as a centralised intermediary with a large number of relationships, which are more numerous and important than those of other network participants. This assumption was verified using Social Network Analysis (SNA), which identifies entities of key relational importance within a given system.

The second assumption of the model is that it combines high relational skills with knowledge and experience in technology development. The knowledge management system's purpose is not only to collect information, but also to identify the city and medical facilities' needs and link them with the possibilities of meeting these needs by developing technologies that support the flow of people and goods in the city. Due to the scientific nature of the knowledge management system and the need for continuous improvement, the coordinator should be an organisation with the necessary expertise, analytical skills and technical resources. While the attributes of the coordinator are universal in terms of the model, their practical implementation depends on the potential of a particular city.

In an empirical study investigating the impact of digitalising logistics systems on smart urban development for health, Zabrze was selected as a case study from among the 62 cities analysed in the study's initial stage. Zabrze has extensive medical facilities and significant academic potential. It is home to the Silesian University of Technology and the Medical University of Silesia, among others. The Silesian University of Technology has two key departments in Zabrze: Biomedical Engineering and Organisation and Management. These departments have significant experience in medical technology, ICT, logistics, and knowledge management. The Faculty of Organisation and Management is also associated with the Transport and Logistics Observatory, which collects and analyses information on the development of logistics technologies in the Silesian Province.

Analysis of social networks confirmed the Silesian University of Technology's high relational competence within the network connecting the city's logistics system stakeholders with medical facilities. Notably, the European HealthTech Innovation Centre (EHTIC), which operates within the Faculty of Biomedical Engineering and involves employees from both the Faculty of Biomedical Engineering and the Faculty of Organisation and Management (including the Department of Logistics), was found to act as a bridge between key network clusters. These clusters include medical facilities, medical waste management organisations, logistics companies, municipal administration units, and uniformed services. Based on this, it was assumed that EHTIC could coordinate the developed knowledge management system concept as an entity capable of integrating knowledge, initiating cooperation between stakeholders, and supporting the intelligent development of the city's health logistics system.

Further research showed that such systems involve highly dispersed explicit and tacit knowledge among numerous stakeholder groups. This fragmentation of information and knowledge resources poses a significant challenge to the effective management of urban flows, particularly in health-oriented cities where the requirements for reliability, response times and safety are high. Implementing innovations in urban logistics systems facilitates the acquisition and processing of data, particularly that related to traffic intensity, transport times, and various types of disruption in urban transport systems. Intelligent transport systems play a special role in this regard.

The data necessary for the sustainable management of urban flows for health comes from many sources and is characterised by varying rates of change over time. Consequently, the frequency of collection and updating is not uniform and must be adapted to the nature of the analysed phenomenon. Table I presents examples of data collection mechanisms.

TABLE I. DATA ACQUISITION MECHANISMS IN THE CITY LOGISTICS SYSTEM FOR HEALTH

Data type	**Source and method of collection**	**Frequency of collection**
Deviations in collective transport	Public Transport Authority	Once a month
The amount of medical waste generated in medical facilities	Medical facilities (aggregation of data reported to UTK)	Once a year
Traffic intensity in road transport	Intelligent Transport Systems (ITS)	Every day (5 measurements during the day)
Environmental pollution	IoT sensors	Every day (5 measurements during the day)
Availability of parking spaces near medical facilities.	Urban systems	Once a month (summary)
Intensity of specialist vehicle traffic (e.g. ambulances, blood and organ transport vehicles).	Central Statistical Office, data from medical facilities	Once per quarter
New technologies in passenger transport	Analysis of industry documents and expert studies	Once a year
New technologies in freight transport	Analysis of industry documents and expert studies	Once a year
New ICT technologies in logistics	Analysis of industry documents and expert studies	Once a year

As with data, the process of acquiring knowledge requires the adaptation of acquisition mechanisms to the type of knowledge and stakeholder. In a city's health logistics system, explicit knowledge primarily concerns formally defined processes, procedures, and transport demand, while tacit knowledge encompasses the decision-making conditions, preferences, and experiences of stakeholders that cannot be observed directly. The knowledge acquisition mechanisms are presented in Table II.

TABLE II. KNOWLEDGE-GATHERING MECHANISMS IN THE CITY LOGISTICS SYSTEM FOR HEALTH

Kind of knowledge	**Type of knowledge**	**Stakeholder group**	**Method of acquisition**
The transport needs of residents	Explicit knowledge	Inhabitants	Surveys
Demand for transport by various modes	Explicit knowledge	Logistics companies	Operational data analysis
Factors that determine the choice of transport method for passengers	Tacit knowledge	Inhabitants	Surveys
Assessment of communication exclusions	Tacit knowledge	Inhabitants	Surveys
Assessment of digital exclusion	Tacit knowledge	Inhabitants	Surveys

The concept of knowledge gathering requires the design of appropriate research tools to enable systematic acquisition of knowledge. The current stage of research on the knowledge management system involves identifying and acquiring tacit knowledge using tools developed in earlier analysis stages. Empirical research enables the identification of individual stakeholder group needs, as well as the assessment of the city's logistics system's current potential in the context of health services. Based on this, key barriers and development challenges for the logistics system that determine its ability to support the effective flow of people and goods in the city for health purposes can be identified.

IV. CONCLUSION

For intelligent urban development to promote health, the concepts of the healthy city, the smart city and sustainable logistics must be systematically integrated within a coherent knowledge management architecture. Analyses have shown that a city's logistics system is a key part of its health infrastructure.

The developed concept of a centralised knowledge management system with a dedicated coordinator role has provided a theoretical and empirical basis for integrating the explicit and tacit knowledge resources generated by various stakeholder groups. The effectiveness of the digital transformation of urban logistics systems for health has been demonstrated to depend not only on the implementation of technologies such as ITS, IoT and analytical tools, but also on the capacity for institutional coordination, effective knowledge transfer and the formation of lasting network relationships between entities in the public sector, academia and industry.

The case study confirmed that it is possible to appoint a knowledge management system coordinator given high academic potential and developed medical infrastructure.

The study's focus on a single case limits its scope. Another limitation is the dynamic nature of digital transformation, which implies the need to continuously update the adopted model assumptions.

Further research should include comparative analyses of cities with varying levels of logistical and digital development, as well as empirical verification of the long-term impact of transforming logistics systems on reducing health inequalities, strengthening the resilience of cities' logistics systems and achieving sustainable development goals.

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Understanding the Role of Scaling in Smart City Strategies: Evidence from German Municipalities

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***Abstract*—Future cities, or smart cities, aim to use information and communication technologies in ways that improve efficiency across all aspects of urban infrastructure. While an increasing number of smart city projects can be observed, many tend to decline after their piloting phase. In this paper, we seek to identify whether the lack of scaling constitutes a strategic issue. By investigating the central thematic structures within 70 German smart city strategies and employing Structural Topic Modeling (STM), we explore the extent to which thematic priorities vary across municipalities. This topic modeling approach allows us to identify the strategic priorities emphasized by municipalities and to assess the extent to which topics within these strategies can be linked to project success. In a broader sense, we examine whether and how considerations of project scaling are integrated during the strategy development phase. Based on this analysis, it becomes possible to evaluate whether the observed lack of scaling beyond successful pilot projects can be attributed to insufficient long-term planning at the strategic level and, by extension, help to better understand the efficiency of future cities.**

Keywords-Smart city strategy; STM; upscaling; project success; future cities.

I. INTRODUCTION

Smart cities are increasingly recognized as vital instruments for future-oriented urban development, particularly in addressing pressing environmental and social challenges. Despite the strategic planning underpinning these initiatives, many smart city projects struggle to scale beyond their initial pilot phase [1].

For the purpose of this paper, long-term success is measured through scaling activities, which may take the form of horizontal scaling, such as expansion or roll-out [2], or vertical scaling in terms of replication [3]. Even when municipalities actively pursue smart city initiatives, often supported by external funding, these projects frequently remain confined to pilot or experimental phases, thereby limiting their broader societal impact. This issue is particularly critical because most smart city initiatives reveal their full potential only over extended periods. The objectives of being safer, more efficient, and greener can only be achieved if cities fully adopt the initiatives [4]. As demonstrated by the Scalable Cities Initiative of the European Commission, across all participating cities of Horizon 2020, energy consumption was reduced by 53% and CO_2 emissions by 88% [5].

Smart city projects, like most complex initiatives, are guided by strategic frameworks. These strategies aim to align stakeholders, coordinate resources, and facilitate the successful implementation of projects to achieve predefined objectives. However, governments frequently face challenges in planning and executing smart city development [6][7].

This observation raises an important question: Does the limited scalability of smart city projects indicate a strategic shortcoming?

To explore this question, this study analyzes the smart city strategies of municipalities funded by the Federal Office for Building and Regional Planning. The aim is, first, to identify the thematic priorities emphasized in these strategies and, second, to examine which dimensions, particularly those related to scaling and long-term institutionalization, are often overlooked. For this purpose, we extracted 70 strategy documents from the Ministry's publicly available sources, covering projects issued between 2018 and 2024. To systematically categorize and analyze these strategies, we employ Structural Topic Modeling (STM) [8], a probabilistic modeling approach that uncovers latent topics within textual data while incorporating relevant metadata. This method enables a rigorous assessment of both thematic focus and potential gaps in strategic planning for smart city initiatives.

While previous research has investigated smart city strategies focusing on large cities, such as Amsterdam, Barcelona, or New York [9], this study contributes to the discourse by focusing on the topic of scaling across a broad set of German cities. This approach allows us to examine the effects of city-based differences, such as city size, economic stability, and regional context, on strategic success, which so far has not been exhausted. In doing so, the study seeks to clarify whether the lack of scaling constitutes a strategic issue and therefore requires adjustments in the strategic phase of smart city project planning.

Building on existing research, section two of this paper first summarizes important literature and related work. In section three, the applied methodology is outlined, followed by the presentation and discussion of the interim results in the fourth and final section.

II. RELATED WORK

In general, well-designed and effectively executed strategies are believed to enhance competitive advantage, generate economic value, and structure project phases, thereby ensuring both short-term and long-term success [10]. Accordingly, the role and relevance of strategies within organizations have

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long been established. However, smart city development in particular faces additional layers of complexity that go beyond the deployment of new technologies and therefore require more systematic and coordinated approaches.

While closely related, strategy, governance, and policy fulfill distinct functions and should be analytically differentiated. Policy plays a crucial role in operationalizing strategic goals [11]. In the sustainability literature, Lafferty and Hovden [12] conceptualize policy through vertical and horizontal policy integration. Vertical integration concerns the alignment of goals, budgets, and supervisory mechanisms across governance levels, whereas horizontal integration focuses on long-term strategic coherence, including national action plans and conflict-resolution mechanisms. From a scaling perspective, this linkage is particularly relevant, as policies can facilitate access to funding and institutional support [13]. Strategies may initiate policy development, while policies in turn reinforce strategic objectives.

Within this context, governance is widely recognized as a key instrument embedded within development strategies [14]–[16]. Kardos [15] conceptualizes governance as an iterative process that builds a shared vision through consensus and translates it into concrete objectives. For smart city initiatives, governance models are also critical enablers of upscaling [1]. Mora [17] further argues that governance mechanisms can generate synergies by coordinating and allocating tasks and responsibilities, although these mechanisms may follow different archetypical forms [18].

Therefore, it is evident that strategies alone do not render cities “smart”. Angelidou [11] argues that strategies are a necessary but not sufficient condition, as they must reflect the underlying smart city architecture and local context. Similarly, Letaifa [19] emphasizes that strategies serve to align stakeholders around a coherent vision tailored to local challenges. Given the heterogeneity of cities in terms of social, cultural, and institutional conditions, local adaptation is therefore essential.

Additionally, smart city development can be examined either from an innovation management perspective [17] or from a socio-economic perspective [20]. City examples, such as Amsterdam and Barcelona illustrate that successful smart city initiatives involve a wide range of stakeholders who jointly deploy technologies to address social and environmental challenges while strengthening urban competitiveness [1]. These observations highlight the necessity of strategic frameworks that structure a shared vision and clearly define roles and responsibilities across actors. Building on this, Dai et al. [21] emphasize that strategies must not remain abstract but should explicitly translate smart city visions into concrete and operational action plans.

A closer examination of the literature shows broad agreement that project success depends on the inclusion of multiple strategic elements [22][23]. Earlier research predominantly relied on the “triple constraint” model, which defines success through time and cost adherence [24]. While this model captures short-term performance, it fails to account for long-term outcomes, such as scalability. To overcome these limitations, Poli and Shenhar [10] propose an expanded framework that incorporates additional dimensions, including strategic focus, competitive advantage, value creation, and business orientation.

Although these frameworks originate from corporate project contexts, their underlying logic is transferable to smart city development. Smart city strategies similarly aim to coordinate multiple projects and actors toward shared objectives [7]. A central component of this coordination is governance, which structures responsibilities and decision-making processes [13][14][16][25]–[27]. However, a structural challenge arises from the fact that strategy formulation and project implementation are often carried out by different actors [21].

To better capture competitiveness and long-term impact, more comprehensive strategic models have been proposed. One prominent example is the SMART framework by Letaifa et al. [19], which integrates Strategy, Multidisciplinary collaboration, Appropriation, Roadmap, and Technology. These components are distributed across macro, meso, and micro levels, ranging from overarching urban strategies and stakeholder coordination to concrete action plans and technological implementation [26].

Complementary insights emerge from software project management, where poorly defined scope is a major determinant of project failure. Ul Hassan et al. [28] address this issue through a Software Project Scope Rating Index (SPSRI) comprising 45 elements, including tools, managing uncertainty, and estimating costs. Adding to that, Mora et al. [29] synthesize key development principles, including moving beyond technology-centric approaches, adopting quadruple-helix collaboration, combining top-down and bottom-up processes, and embedding projects within an integrated strategic framework.

Building on these contributions, Dai et al. [21] distinguish between the strategy level and the project level of smart city development. They argue that while strategy formulation requires flexibility and iterative refinement, project implementation focuses on operationalizing predefined objectives. Their proposed five-stage transformation framework, ranging from goal definition to evaluation, highlights the importance of monitoring and performance assessment mechanisms [17]. At the same time, recent research increasingly calls for citizen-centric strategies to avoid an overreliance on technological solutions, often referred to as “technological solutionism” [17].

Taken together, the reviewed frameworks converge on two central questions: how strategies should be developed and which components they should include. Strategically, development follows a continuous cycle of definition, implementation, and evaluation (Figure1). Substantively, effective strategies integrate vision, action planning, resource identification, governance structures, and financial considerations. This understanding aligns with Winden and Van den Buus’s scaling framework [2], which emphasizes economies of scale, knowledge transfer, supportive policy environments, and return on investment, including financial sustainability [27]. Consequently, smart city strategies

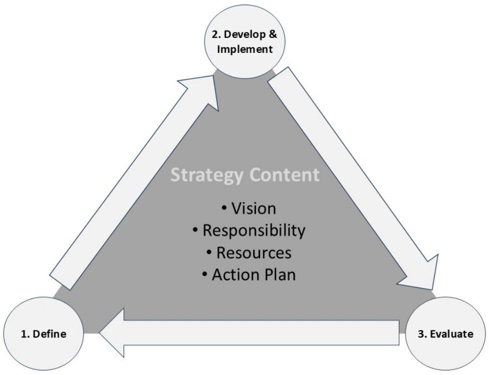

Figure 1. Strategy Development Cycle.

must articulate a locally grounded vision [30], specify implementation pathways, mobilize institutional and societal resources, and clearly assign responsibilities to enable long-term scaling.

III. METHODS

As previously outlined, this study employs STM to analyze a corpus of 70 smart city strategies. Roberts et al. [8] describe STM as a probabilistic mixed-membership model that builds upon Latent Dirichlet Allocation (LDA). Its primary objective is the semi-automatic identification of latent thematic structures within large collections of text documents.

STM assumes that each document is composed of a mixture of multiple topics and that each topic is characterized by a multinomial probability distribution over words. Within the generative process, each word in a document is assigned to a topic based on response-specific topic distributions. In contrast to classical LDA, STM allows topics to be correlated and enables the inclusion of covariates. This extension makes STM particularly suitable for analyzing strategic documents, as it allows the examination of how thematic emphases vary systematically across different contextual characteristics. In addition to identifying the dominant thematic structures within the strategies, the analysis specifically investigates the role of scaling in smart city strategies. By examining whether and how scaling-related aspects appear in the strategic phase, the study aims to assess whether the limited scaling of smart city projects beyond successful pilot phases may be linked to insufficient long-term strategic planning. This, in turn, provides insights into whether it would be beneficial to establish scaling as a distinct and explicit strategic focus within municipal smart city initiatives. The analysis follows the standard workflow for estimating a STM. First, a preprocessing phase is conducted to prepare the textual data for modeling. This is followed by the selection of relevant covariates, the specification of the model through the determination of an appropriate number of topics (K), and the final estimation of the STM. Text preprocessing includes common steps in topic modeling and text mining, such as the removal of stop words. Concerning stemming and lemmatization, special consideration is required due to the German language of the strategy documents. While stemming is relatively straightforward in English because of regular conjugation patterns, German morphology and compound nouns significantly increase complexity. To avoid semantic distortion, aggressive stemming and lemmatization are therefore not applied. Text segmentation, which is necessary for languages without explicit word boundaries, is not required in this case. Furthermore, compound splitting is not performed, as German compound words often carry specific semantic meanings that could be altered through decomposition.

The optimal number of topics was determined using a combination of held-out likelihood, residuals, and semantic coherence, which are commonly used diagnostic measures in topic modeling. Based on these criteria, a final model with K = 8 topics was selected. Following the approach proposed by Lucas et al. [31], several document-level covariates were incorporated into the model. These include city size, region, population, and federal state GDP, all of which are relevant to the research question. The secondary data was collected from Statista and Federal Statistical Office of Germany (Destatis) [32][33]. Since the study aims to investigate potential regional and structural differences in thematic priorities across municipalities, the chosen covariates describe key socio-economic and geographic characteristics of the cities.

Topic Identification and Labeling Initially, a model with ten topics was estimated based on diagnostic comparisons. However, a closer qualitative inspection of the most representative words and documents revealed substantial thematic overlap between some topics. Consequently, closely related topics were merged, resulting in a final set of eight distinct and interpretable topics:

- Cooperation and Collaboration
- Sustainable Urban Development
- Economy and Scalability
- Data Infrastructure
- Urban Development Strategy
- Traffic Management and Tourism
- Mobility Concepts
- Efficient Urban Infrastructure Design

These topics form the basis for the subsequent analysis of thematic priorities and scaling considerations within German smart city strategies.

IV. RESULTS

Based on our review of the literature, we examined whether key elements, such as co-creation, business models, scaling, and funding are addressed in the analyzed strategies. The results show that all strategies at least acknowledge the importance of involving citizens in project development and implementation. Scaling is mentioned in 41 strategies, business models are described in ten, and future funding is addressed in 37 strategies. However, most strategies outline the importance of funding and the need for scaling mechanisms but do not elaborate. We first provide an overview of the relative frequency of each topic across the analyzed documents. As

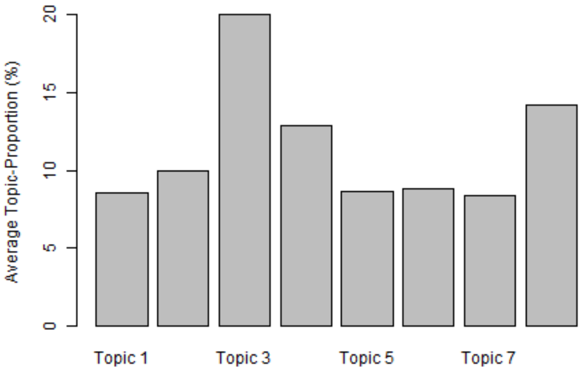

Figure 2. Average Topic-Proportion.

illustrated in Figure 2, Topic 3 (“Economy and Scalability”) emerges as the most prominent theme, with an average share of 20% across all documents. This is followed by Topic 8 (“Efficient Urban Infrastructure Design”), with an average prevalence of 14.21%, and Topic 4 (“Data Infrastructure”), accounting for 12.85%. Overall, these three topics dominate the content of the smart city strategies examined in this study.

The results from the STM show that population size has a clearly non-linear influence on the thematic focus of municipal smart city strategies. While Topic 1 is largely independent of city size, Topics 2 (Sustainable Urban Development), 3 (Economy and Scalability), and 4 (Data Infrastructure) become significantly more important as population size increases. Topic 4 occurs almost exclusively in larger cities, indicating a greater concentration of complex strategic content in urban centers. While Topic 7 (Mobility Concepts) occurs largely independently of population size, Topics 5 (Urban Development Strategy), 6 (Traffic Management and Tourism), and 8 (“Efficient Urban Infrastructure Design”) show differentiated, non-linear correlations. Topic 6 is particularly prevalent in medium-sized cities, whereas Topic 5 and Topic 8 occur more frequently in smaller municipalities. This highlights the importance of considering municipal size classes in a differentiated manner when analyzing thematic priorities.

V. DISCUSSION

As discussed in the related work section, we have summarized the key insights from the literature into a framework that we used to evaluate the strategies beyond the initial STM. This was done to better understand the insights derived from the STM. The literature underlines the need for a clear vision, governance models clarifying responsibilities, the resources needed to realize these goals, and a clear action plan describing each step within the transformation process toward a future city. Nevertheless, these components are relatively general and not focused on the final stage of most smart city initiatives, the scaling phase.

This phase can be divided into two types, similarly to what Lafferty and Hovden [12] proposed for policy integration. Either a project is scaled horizontally, meaning, for example, that it is rolled out on a larger scale, or it is scaled vertically, meaning that the project is replicated elsewhere. Therefore, it is important to address scaling already in the strategy phase.

Winden and Van den Buus [2] argue that not all projects are meant to be scaled. In some cases, the main objective is to test a technology and its usefulness. This applies mostly in smaller cities or cities with little technological advancement. However, even if a project is not intended for future use, the findings need to be documented and preserved, either as a blueprint for other cities or for future projects. In order to do so, it is necessary to determine within the strategy not only what the objectives are, but also how the project results are supposed to be documented and preserved for future use. While most of the 70 strategies have a clear vision for what they want to achieve, there is little mention of how to preserve the insights.

Further, many municipalities face the challenge of funding and financing their initiatives after the initial funding runs dry. Many researchers underline the importance of creating and improving projects together with stakeholders from all parts of society, not only for long-term user satisfaction. Public–private partnerships are not only promising for developing useful tools, but can also be a way to share costs and serve as a foundation for business models [34]. While most strategies emphasize the need for scaling, especially smaller cities often do not elaborate on how they intend to achieve this within the context of their local environment. This may be because smaller cities primarily focus on testing whether the initiative actually generates incremental value. They do, however, mention a broad list of stakeholders with whom they plan to work together.

VI. CONCLUSION AND FUTURE WORK

This research aims to identify the thematic priorities emphasized in the smart city strategies of 70 German municipalities. By conducting STM, we examine which dimensions are most dominant, whether there are city-wide differences, and which aspects may relate to scaling. In conclusion, the analysis shows that while the topic of scaling is addressed in most strategies, it often remains at a rather superficial level. The study identified that “Economy and Scalability”, “Efficient Urban Infrastructure Design”, and “Data Infrastructure” are the dominant themes across the analyzed strategies. When further examining these themes, the results indicate that topics such as “Sustainable Urban Development”, “Economy and Scalability”, and “Data Infrastructure” occur more frequently in cities with larger populations.

However, the explanatory power of these findings is limited, as all examined cities are still in their pilot phase. As a result, it is not yet possible to determine whether the outlined strategies will lead to a successful transformation into smart cities or enable effective scaling processes. Expanding the dataset to include additional strategy documents could further improve the robustness and generalizability of the results. In the long term, this research aims to address its shortcomings and provide a foundation for stakeholders to develop more comprehensive strategies that support the transition from pilot projects to sustainable, scalable smart city solutions.

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Smart Mobility as a Key Enabler of Smart Cities: Technologies, Governance, and Sustainability Challenges

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Abstract— **Rapid and continuous urbanization is placing increasing pressure on urban transport systems, infrastructures, and city energy systems. In response to these challenges, the concept of the Smart City has emerged as a strategic framework aimed at improving urban efficiency through the integration of digital technologies and sustainable energy solutions. Among its various components, Smart Mobility occupies a central position, as it directly conditions access to services, economic performance, and environmental sustainability. This paper provides a literature review with an analysis of Smart mobility as a structuring lever of the smart city. It demonstrates that smart mobility goes well beyond the mere technological modernization of transport systems, constituting a genuine data infrastructure able to transform urban management from a reactive approach to a predictive and integrated one. The study highlights the essential role of Geographic Information Systems (GIS), geospatial intelligence, intelligent transport systems, and digital twins in optimizing mobility flows, reducing gas emissions, and improving the safety and reliability of travel. However, these technological advances are accompanied by significant challenges. Issues related to data governance, privacy protection, territorial equity, and social inclusion limit the effectiveness of purely technology-driven approaches. The analysis also draws attention to the persistent tension between traffic optimization and genuine sustainability, particularly with regard to the energy footprint of digital infrastructures. Overall, smart mobility emerges as a fundamental component of the smart city, provided it is conceived as a comprehensive form of urban intelligence in which technical, social, and environmental dimensions are inseparable. Its success ultimately depends on the ability to reconcile technological innovation, spatial justice, and long-term sustainability.**

Keywords- Smart City; Smart Mobility; Geographic Information Systems; Intelligent Transportation Systems; Digital Twins.

I. INTRODUCTION

Urbanisation worldwide has reached historic levels, with more than 55 % of the population living in urban areas, a share expected to rise to 68 % by 2050 according to the United Nations Department of Economic and Social Affairs [14]. This demographic concentration creates strong pressure on infrastructure networks, air quality, and social cohesion. In response, the Smart City concept has become the dominant framework for modern urban management. Built on the massive integration of Information and Communication Technologies (ICT), a smart city aims to optimise resource use in order to ensure economic growth and environmental sustainability [1].

The Smart City rests on six fundamental pillars: economy, citizens, governance, environment, lifestyle, and mobility and it is mobility that forms the true circulatory system of the city [4]. Smart Mobility does not simply mean vehicle electrification; it is a digital intelligence layer that overlays the physical space. Through geospatial intelligence, Geographic Information Systems (GIS), and digital twins, every movement is turned into usable data, allowing a shift from reactive to predictive territory management [11].

The main challenge of smart mobility lies in its ability to reduce negative externalities. By synchronising flows in real time, it promises a major time saving for users, a significant reduction in CO_2 emissions, and increased efficiency of existing infrastructure without requiring costly extensions [7]. However, the academic literature highlights blind spots, especially regarding personal data protection and the social inclusion of marginalized populations [2].

This study is based on a qualitative review of existing literature on smart mobility and smart cities, without primary data or empirical case studies. As a result, the analysis reflects published concepts and theoretical perspectives, which may overlook emerging practices. In addition, the selection of sources is limited by database coverage and language constraints. Finally, the study does not empirically assess the actual sustainability impacts of smart mobility initiatives, highlighting the need for future research to evaluate their effects on energy efficiency and greenhouse-gas emissions.

The rest of the paper is organized as follows. Section III presents the concept of smart city, with a focus on smart mobility, and reviews prior research and recent advances in intelligent cities and urban mobility systems. And also provides a definition and examines the central role of smart mobility, its technical foundations (with special attention to GIS and geospatial intelligence), and its importance in urban transformation, highlighting contributions to efficiency, sustainability, and resilience, as well as the concept of Mobility-as-a-Service (MaaS) in urban development. Section IV integrates the main findings from the literature and offers a critical analysis of strengths, gaps, and emerging trends.

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II. SMART MOBILITY AS A STRATEGIC PILLAR OF THE SMART CITY

A. Smart city and smart mobility: conceptual background

A smart city is not just a city equipped with Wi-Fi cameras and various gadgets; it is a comprehensive concept that aims to improve citizens quality of life, environmental sustainability, and public-service efficiency through the combined use of ICT and Artificial Intelligence (AI).

The smart city is portrayed as an urban ecosystem that employs ICT to enhance urban-service quality and lower costs. It rests on six interconnected dimensions [4]. The smart city is also described as an urban system where information technologies act as a lever to improve service efficiency [1]. The "Smart Mobility" dimension goes beyond installing sensors; it includes multimodal mobility, Intelligent Transportation Systems (ITS), and sustainable logistics, thereby creating a genuine travel ecosystem that serves the entire city.

B. Definition and Central Role of Smart Mobility

First, the smart city is based on six dimensions as illustrated in Figure 1; Economy, Citizens, Governance, Environment, Lifestyle and Mobility, so Smart Mobility functions as the physical and digital connector [12]. Without smooth mobility, the other pillars (such as the economy or lifestyle) collapse under urban congestion. A city cannot claim to be "Smart" if its transport flows are inefficient [2], because mobility determines access to all other urban resources. By ensuring fluid movement, it creates the necessary foundation for the proper functioning of the other pillars; otherwise, road congestion threatens economic competitiveness, quality of life, and environmental sustainability [2].

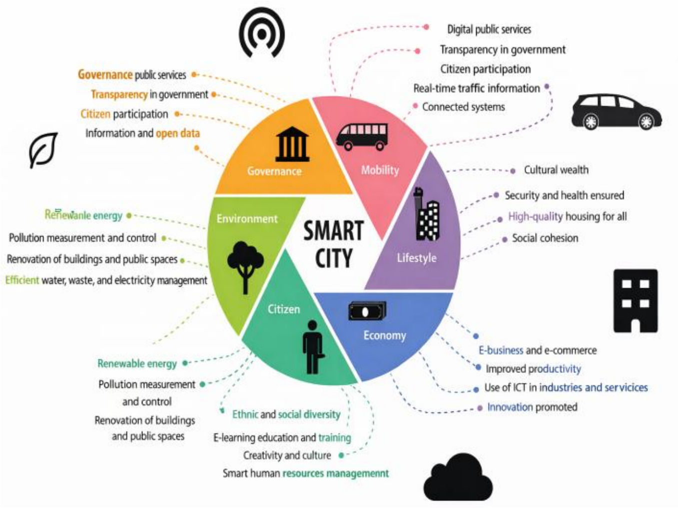

Figure 1. The six pillars of a Smart City [13].

The work of Albino et al. [1] shows that smart mobility is not limited to optimizing physical flows; it also includes digital platforms that can collect, analyse, and deliver real-time data from sensors, GIS, and mobile apps. This "big-data" approach enables reference models that anticipate travel needs, cut travel times, and improve energy efficiency [5].

Figure 2 illustrates how these digital infrastructures such as GIS, IoT (Internet of Things) sensors, real-time data streams, ITS, digital twins and MaaS are woven together with the physical connectors (roads, public transport, bike lanes, pedestrians, electric vehicles) to form an integrated Smart Mobility ecosystem.

Moreover, sustainable-mobility initiatives especially in medium-sized northern cities demonstrate how combining multimodal infrastructure (public transport, shared bikes, autonomous vehicles) with incentive policies reduces CO_2 emissions while strengthening social inclusion [6]. Studies by Biyik et al. [3] and by Pribyl et al. [7] underline that the uptake of these solutions depends heavily on user perception, the availability of reliable services, and transparent governance.

In sum, smart mobility acts as the physical and digital "connector" of the smart city; it determines access to services, urban resilience, and a metropolis's ability to become an attractive, sustainable hub.

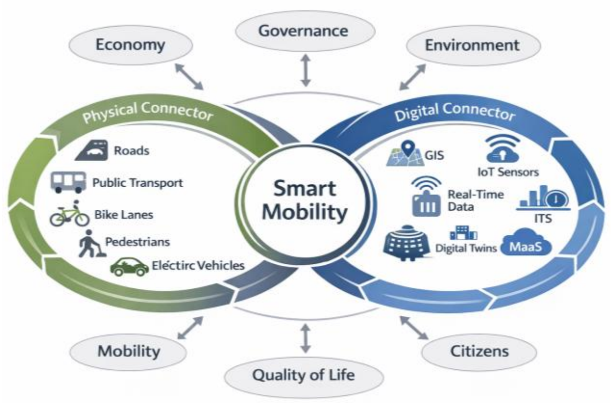

Figure 2. Smart Mobility in a Smart City.

C. Maintaining the Integrity of the Specifications

The proper functioning of smart mobility depends on a dense technical infrastructure, with GIS and geospatial intelligence forming its cognitive core. By aggregating massive real time, geo located data streams, GIS can model travel supply and demand with fine spatial and temporal precision, enabling dynamic decisions such as traffic signal adjustments, public vehicle reallocation, or congestion forecasting [5].

However, this approach mainly emphasizes a technico-operational view of mobility, giving limited attention to territorial inequalities and social dynamics that shape actual network use.

ITS converts these data into concrete actions by linking infrastructure (sensors, lights, signs) with users [7]. Dynamic signalling, automated intersection control, and real time information services illustrate how ITS improves overall flow while enhancing safety. Although these tools boost the

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efficiency of the smart mobility network, their performance is often evaluated with city wide average indicators, which can mask spatial disparities between well served central neighborhoods and less favoured peripheral areas.

Digital twins are among the newest and most powerful contributions to Smart City. By creating a dynamic virtual replica of a city that is continuously fed by IoT sensors, they provide simulations where mobility scenarios (e.g., road works, accidents, new traffic directions) can be tested before real deployment [5]. This approach lets planners assess impacts on traffic flow, CO_2 emissions, and the resilience of the urban transport network without disrupting daily traffic. As a result, digital twins support more predictive and data-driven approaches to urban transport management.

To achieve these capabilities, however, digital twins rely on advanced digital infrastructures, including extensive sensor networks, high-capacity data transmission systems, and integrated data platforms. In cities where digital infrastructure remains uneven, these technological and financial requirements may limit the deployment and effectiveness of digital twin technologies for real-time urban management [5], [11]. Furthermore, their integration with ITS depends on reliable data flows and interoperable urban platforms, which remain significant challenges for many cities undergoing digital transformation [7], [8].

Furthermore, Yigitcanlar et al. [8] highlight that integrating these technologies must be paired with transparent governance and citizen participation to ensure acceptance and service equity. Savastano & al. [9] also stress the need for a continuous evaluation framework to measure the true “smart-ness” of mobility solutions and steer policies toward greater sustainability. Yet, the literature still struggles to offer fully integrated frameworks that combine fine-grained spatial analysis, multicriteria evaluation, and citizen participation, leaving a gap between technological innovation and territorial equity.

D. *The Importance of Smart Mobility in Urban Transformation*

GIS and sensor technologies constitute a technological foundation for making urban mobility genuinely sustainable. By combining spatial data with real-time flow information, they deliver three major benefits:

- Time optimization: Synchronizing traffic signals and providing dynamic routing shorten trips and waiting times, easing congestion and increasing user productivity [2].
- Energy efficiency and emission reduction: Fewer unnecessary stops lower greenhouse-gas emissions, aligning the city with a sustainability-first goal and the four pillars of smart mobility: technological, economic, social, and governance. This also reduces negative externalities and supports the transition to MaaS as a sustainability lever [6], [8].
- Safety and reliability: Better visibility of traffic flows enables effective actions, reduces vehicle conflicts, decreases accident numbers, and makes public-transport schedules more predictable, thereby strengthening user confidence [7].

By bringing together these effects, the technologies enable the emergence of MaaS, where dynamic planning, energy savings, and safety act as a single lever to transform the city into a resilient, inclusive system with a low carbon footprint [1], [5].

Figure 3 visualises this framework, placing Smart Mobility at the centre and linking the Technological, Economic, Social and Governance pillars to the shared outcomes of time optimisation, energy efficiency and safety.

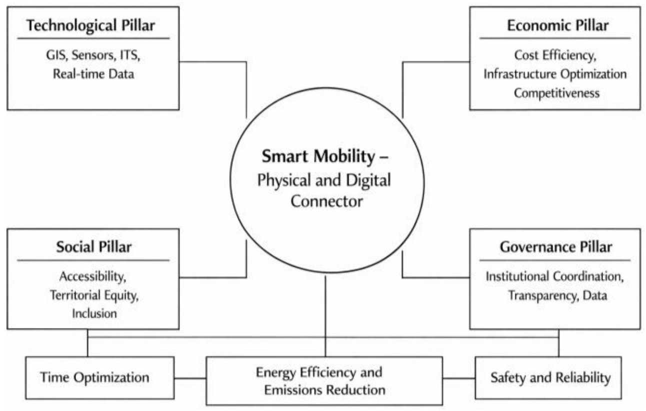

Figure 3. Smart Mobility as a physical and digital connector within the Smart City.

E. *Smart Mobility and MaaS in Urban Development*

MaaS refers to a digital platform that integrates heterogeneous transport options: public transit, shared mobility, bike-sharing, and on-demand ride-hailing into a single user-centric service providing real-time routing, booking, and payment [2], [8]. By leveraging GIS and sensor networks, MaaS transforms spatial temporal mobility data into actionable services, enabling dynamic multimodal trip planning that adapts to congestion, incidents, and changing travel conditions [7].

The main benefits of MaaS align with the core pillars of smart mobility. First, time optimization is achieved through integrated traffic management and adaptive routing, reducing travel time and minimizing waiting periods [3], [7]. Second, energy efficiency and emission reduction result from fewer unnecessary trips and a greater modal shift toward low-carbon transportation options, positioning MaaS as an important lever for sustainable urban mobility [6], [8]. Third, safety and reliability are enhanced through continuous traffic monitoring and improved coordination between different transportation modes [7].

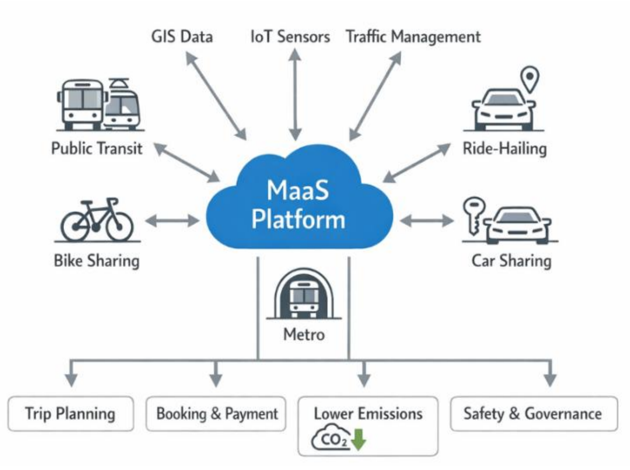

Figure 4. Integrated MaaS Platform for Multimodal Urban Transportation.

Figure 4 visualizes the integrated MaaS ecosystem: a central “MaaS Platform” cloud links eight mobility services such as public transit, metro, bike-sharing, ride-hailing, car-sharing, IoT sensors, traffic-management, and GIS data and feeds into four benefit blocks (trip planning, booking payment, reduced CO_2 emissions, and safety/governance). The figure also underscores how a single digital hub orchestrates diverse transport modes, turning real-time data into seamless, multimodal journeys for citizens.

Beyond these operational benefits, MaaS also supports governance and social equity by enabling data-driven mobility planning and providing digital platforms that improve accessibility to urban services [9]. However, the increasing reliance on mobility data requires transparent governance frameworks and robust data-privacy policies to mitigate potential surveillance risks. Successful implementation therefore depends on collaboration between city authorities, mobility providers, and citizens, ensuring that MaaS platforms remain interoperable, affordable, and responsive to local mobility needs [3], [8].

III. SYNTHESIS AND DISCUSSION

Smart Mobility operates continuously and adaptively; it captures the city’s real-time state, identifies needs through geospatial intelligence, and then adjusts mobility flows to optimize efficiency. It is no longer just a transport service but an intelligent layer that makes the urban environment predictable and resilient. As researchers such as Benevolo et al. [2] note, the goal is to create a “seamless city” where movement is no longer an obstacle to daily activity.

Current solutions often rely on centralized data platforms. This creates technological dependence, raises privacy-violation risks, and can exacerbate inequalities if the data do not equally reflect the usage patterns of the most vulnerable neighborhoods. Implementing a federated model where data are processed locally without distinction between center and periphery and where learning algorithms are aggregated without transferring raw information can strengthen system resilience and facilitate citizen participation in flow governance. Alternatively, a pilot Smart Mobility program could be launched in a midsize city, then compared on congestion, CO_2 emissions, user satisfaction, and territorial equity indicators against a centralized scenario. This would allow analysis of how decentralized governance influences public trust and long-term sustainability.

In the literature, two clear strands can be distinguished: the “systems” approaches and the “user-oriented” approaches. Pribyl et al. [7] argue that cyber-physical infrastructure (V2X) can improve efficiency, reduce congestion, and ease traffic flow. By contrast, Yigitcanlar et al. [8] claim that this view is incomplete unless environmental sustainability is placed at the core of design as a primary constraint. Where Pribyl treats technology as a direct solution, Yigitcanlar suggests a more suitable answer by introducing “Smart and Sustainable Mobility,” noting that smooth traffic is meaningless if it simply induces a larger overall vehicle volume.

Regarding adoption, a comparison of Biyik et al. [3] with Müller-Eie and Kosmidis [6] reveals fundamental differences. Biyik adopts a methodology focused on the individual psychology of users, while Müller-Eie emphasizes urban design and municipal planning. Müller-Eie’s method appears more effective for public policymakers because it demonstrates that physical infrastructure (connected bike lanes, pedestrian zones) is a more powerful lever than mere technological or psychological incentives.

Finally, the debate over data governance pits Lim et al. [5] against Savastano et al. [9]. Lim proposes a reference model that centralizes big-data to optimize services, a method that prioritizes overall network performance. In contrast, Savastano adopts a far more critical stance that aligns with current democratic concerns: he argues that a city’s intelligence should be measured by its ability to remain resilient and inclusive without relying on massive surveillance. This clash highlights that Savastano’s approach, although less “optimizing” on paper, offers a more sustainable solution for urban social cohesion by avoiding the algorithmic biases inherent in the centralized models advocated by Lim.

IV. CONCLUSION AND FUTURE WORK

Smart mobility should no longer be seen merely as a transport service but as the core data infrastructure that truly makes a city “Smart” [1]. Its concrete contribution to urban performance relies on the integration of geospatial intelligence and GIS. These tools transform static territorial management into dynamic, predictive management, helping to reduce congestion and CO_2 emissions through ITS [8]. The MaaS model merges public and private offerings into a single interface, encouraging a shift away from private-vehicle use [2].

In the literature, two clear currents are distinguished; the “systems” approaches, which rely on cyber-physical infrastructure (V2X) to ease traffic, and the “user-oriented” approaches, which place environmental sustainability in the heart of design. The former treats technology as a direct solution, while the latter stresses that improving traffic flow must not encourage an increase in vehicle numbers.

On the adoption front, studies contrast an individual-psychology perspective of the user with an approach focused on urban design and municipal planning. The latter demonstrates that physical infrastructure such as connected bike lanes and pedestrian zones serves as a more powerful lever than purely technological or behavioral incentives.

Finally, the debate over data governance pits a centralized model, optimized for network performance, against a critical vision that prioritizes resilience and inclusion without massive surveillance. This contrast highlights the need for governance frameworks that supports urban social cohesion.

Future research could further explore how these technological, spatial, and governance dimensions can be effectively integrated in real urban contexts. In particular, empirical studies and case-based analyses would help assess the actual sustainability impacts of Smart Mobility solutions and evaluate how emerging tools such as digital twins or MaaS platformscan contribute to more resilient and inclusive urban mobility systems.

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A New Approach to Urban Planning Based on Daily Life Rhythms Using Human Mobility Data

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***Abstract*— Modern urban planning has treated space as the main variable and time as a secondary element. This study reviews the development of time concepts in urban planning from the viewpoint of how measurement technologies have changed. It also reinterprets Lefebvre's rhythmanalysis in the context of recent technological advancements. By organizing existing research along two axes, spatiotemporal granularity and description mode, this study shows that the area of setting target states and designing interventions based on micro-scale quantitative data from dense sensing remains undeveloped. This study proposes Rhythmopolis as a theoretical framework to address this gap. Rhythmopolis would change urban planning from a forward problem of predicting activity from space to an inverse problem of tuning space from target rhythms. To solve this inverse problem, this study introduces the Music Information Retrieval framework and presents a method for structuring rhythm quality, which was previously dismissed as error, into multi-dimensional vectors. In the history of urban concepts, Metropolis addressed the organic development of single cities, and Megalopolis addressed regional networks connected by infrastructure. Rhythmopolis is positioned as a third concept that aims at distributed urban management at the district level through temporal structure optimization.**

Keywords- rhythmanalysis; time geography; human mobility data; inverse problem; music information retrieval.

I. INTRODUCTION

Modern urban planning has treated space as the main variable and time as a secondary element. Traditional planning methods, such as zoning assume that arranging urban functions in physical space will organize people's activities in a reasonable way. In current cities, however, people with various lifestyles interact in complex ways, and there is a gap between static spatial plans and the dynamic rhythms of daily life.

The French philosopher Lefebvre [1] defined arrhythmia as a state where social disorder occurs due to conflicts between rhythms. According to Lefebvre, cities are originally dynamic places where various organic rhythms interact and produce space. Space-centric urban planning, however, blocks this dynamism and causes structural arrhythmia. In this study, urban rhythm is defined as the spatiotemporal overlapping of human activities in urban space, representing the dynamic pulse of the city generated in each area. While traditional planning focused on static arrangement, urban rhythm captures the dynamic interaction between people and space.

In recent years, Lefebvre's theoretical framework has been reconsidered in the context of urban informatics with the spread of Global Positioning System (GPS) and smartphones. Using human mobility big data, it has become possible to visualize rhythms, which were previously qualitative concepts, as quantitative patterns [2][3]. In these quantitative studies, however, the challenge of connecting diagnosis of the current state to prescription for the future remains. Existing research has succeeded in visualizing and classifying rhythm patterns, but methods for tuning spatial interventions to resolve arrhythmia have not been established.

This study aims to propose Rhythmopolis as a theoretical framework for quantitatively evaluating the spatiotemporal structure of cities based on human mobility data and developing it into concrete planning theory. The main feature of this framework is reconstructing the urban planning process from a space-centric forward problem to an inverse problem that tunes spatial forms and policies based on target rhythms.

In the history of urban concepts, this study is positioned as follows. In the early 20th century, Geddes [4] conceptualized post-industrial revolution urban concentration as Metropolis and discussed the organic relationship between cities and regions. Later, Gottmann [5] analyzed the connected urbanization of the northeastern United States and named the regional urban area where multiple metropolitan areas are connected by transportation and communication infrastructure as Megalopolis. The Megalopolis concept assumed that regional infrastructure connections bring economic efficiency. In the 21st century, however, this infrastructure-dependent urban model has shown problems, such as increasing maintenance costs, vulnerability to disasters, and environmental burden [6]. In contrast, Rhythmopolis proposed in this study introduces time as a variable and provides a framework for autonomous management at smaller district levels. This is positioned as a form of distributed approach to the challenge of how to sustainably operate existing stock in mature cities.

This study is organized as follows. Section II reviews the development of time concepts in urban planning from the viewpoint of how measurement technologies have changed. Section III examines how urban rhythms have different characteristics depending on mobility infrastructure and

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cultural practices and identifies factors that determine rhythms. Section IV proposes Rhythmopolis as a theoretical framework for quantitatively evaluating urban rhythms and developing them into planning theory, based on the discussions in Sections II and III. Section V presents the contributions and future challenges of this study.

II. THE DEVELOPMENT OF TIME CONCEPTS IN URBAN PLANNING

This section reviews how time concepts have been treated in urban planning and related fields from the viewpoint of how measurement technologies have changed.

Literature was collected from databases, such as Web of Science, Scopus, and Google Scholar using keywords including rhythmanalysis, time geography, and human mobility, focusing on papers in urban planning, transportation engineering, and geography. It should be noted that rhythmanalysis and related temporal approaches face recognized limitations in the existing literature, including challenges in applying frameworks across diverse urban contexts, difficulties in precisely operationalizing temporal variables, and the blurred boundaries between spatial and temporal dimensions of rhythm.

This study sets four time periods based on the development stages of measurement technologies for understanding human movement and activity in cities. Table 1 shows each period, the main measurement technologies and data sources available, and the scope of analysis they enabled.

TABLE I. PERIODS AND MEASUREMENT TECHNOLOGIES

Period	*Time Frame*	*Main Data Sources*	*Analysis Focus*	*Representative Work*
Period 1: Aggregate	-1960s	Census, registration	Static population	CIAM, Athens Charter (1933)
Period 2: Flow Structure	1960s-1990s	Person trip surveys, traffic counts	OD flows, time allocation	Time geography [7], four-step model
Period 3: Individual Tracking	1990s-2010s	GIS, GPS, digital cameras	Individual space-time paths	Geocomputation [8][9][10]
Period 4: Dense Sensing	2010s-	Smartphone GPS, Wi-Fi probes, beacons, LiDAR, camera analytics	Crowd behavior, semantic analysis	Urban computing [11]

A. Period 1: Aggregate Data (Before 1960s)

In pre-industrial society, time was embedded in natural cycles and the nature of labor. As Thompson [12] pointed out, after the industrial revolution, time concepts shifted from task-oriented time to clock time. Data on population and movement available in this period depended on censuses. In Western countries, modern census systems were established from the late 18th to early 20th centuries (US: 1790, UK: 1801, France: 1801). These data captured where people lived at specific points in time, with time resolution limited to years and spatial resolution limited to administrative units. It was technically difficult to capture the temporal structure of people's daily movements and activities.

These measurement technology constraints determined the scope of theory. In functionalist urban planning by the Congrès Internationaux d'Architecture Moderne (CIAM) in the early 20th century, time was positioned as a secondary element subordinate to space [13]. The 1933 Athens Charter classified urban functions into four categories of housing, work, recreation, and transportation, and proposed separating these spatially through zoning. This method focused on dividing and fixing urban space by function [14] and did not consider temporal changes in activities. As Virilio [15] critically analyzed in his dromology, maximizing movement speed was considered the indicator of progress, and time was recognized as a cost to overcome. Lynch [16] early pointed out time and memory perception in cities, but this was not positioned in the mainstream of planning technology that prioritized efficiency. As a result, spatiotemporal distortions, such as commuting congestion and suburban sprawl from job housing separation became structurally fixed. In response to this situation, Jacobs [17] criticized that zoning type planning blocks urban vitality and discussed the importance of mixed uses and diverse streets.

B. Period 2: Flow Structure (1960s-1990s)

From the 1960s, with urban expansion and motorization progress, the need to understand dynamic flows increased. Person trip surveys were developed and institutionalized to meet this need. In the United States, large-scale transportation surveys starting with the Chicago Area Transportation Study were conducted from the late 1950s, and transportation demand forecasting methods based on Origin-Destination (OD) data were established. Person trip surveys recorded all trips of sample household members on the survey day, improving time resolution to hours and spatial resolution to zones.

In 1963, the Buchanan Report published in the UK presented how urban structure should respond to increasing automobile traffic [18]. The report viewed cities as a structure of rooms and corridors and proposed hierarchically separating environmental areas and the primary road network. This urban skeleton concept implicitly assumed temporal relationships between traffic flows and land use but did not treat rhythm itself as a planning variable.

An important theoretical contribution of this period was time geography proposed by Hägerstrand [7]. Hägerstrand built a theoretical framework that treats time as a scarce resource equal to space. Time geography visualized individual movement as trajectories in space-time and enabled quantitative description of constraints. At the national scale, Gottmann pointed out that cities are defined not by buildings but by movements of people, goods, and information, and described commuting flows as tidal waves. Space syntax by Hillier and Hanson [19] showed that spatial layout determines movement patterns, but these theories did not sufficiently address variation by time of day.

Time geography tends to discard the qualitative aspects of creativity and difference by focusing on structure and regularity. Time geography asks how individuals move efficiently while avoiding constraints and does not consider the quality of time [20].

C. *Period 3: Individual Tracking (1990s-2010s)*

From the 1990s, with the spread of personal computers, Geographic Information Systems (GIS) became widely used. With the spread of Integrated Circuit (IC) transit cards and cell phones, it became technically possible to track individual movement continuously with high accuracy.

Miller [8] proposed methods for representing and analyzing space-time prisms in 3D within GIS environments, and Kwan [9][10] visualized differences in space-time accessibility by gender and socioeconomic attributes. In transportation engineering, activity-based models that treat travel as derived demand from activities developed [21]. While the four-step model treats trips independently, activity-based models simulate entire daily activity schedules of individuals, enabling more realistic transportation demand forecasting.

During this period, activity surveys based on observing pedestrian behavior also developed with the spread of digital cameras. Whyte [22] conducted systematic behavioral observation in public spaces in New York and quantitatively recorded patterns of people staying and moving in plazas and streets. This method is pioneering work that empirically analyzes relationships between physical characteristics of space and user behavior. Gehl [23] conducted long-term observation of pedestrian behavior in Copenhagen and other European cities and presented activity categories of necessary activities, optional activities, and social activities. Gehl's method evaluates public space quality by pedestrian stay time and activity diversity and was later systematized as Public Space Public Life Surveys. These surveys succeeded in describing behavioral patterns at specific locations in detail but did not develop into frameworks for understanding city wide rhythms in an integrated way.

Meanwhile, from the 1980s, critical examination of homogenized time also progressed. The concept of duration proposed by Bergson refers to time that changes qualitatively within consciousness, contrasted with clock time, and became the theoretical source of this criticism. Lefebvre extended Bergson's philosophical concept to the social dimension of urban space under capitalism and proposed rhythmanalysis [24]. Lefebvre critically analyzed the situation where cyclical rhythms from nature and the body are suppressed by linear rhythms demanded by capitalism. However, as Lefebvre himself stated that rhythm can be measured but cannot be reduced to quantitative, methods for using the qualitative concept of rhythm as indicators applicable to planning practice were not established. Rosa [25] argued in social acceleration theory that time scarcity in modern society is the root cause of arrhythmia.

D. *Period 4: Dense Sensing (2010s-Present)*

From the 2010s, with the spread of smartphones and various sensing technologies, it became possible to measure urban flows with high accuracy. Main measurement technologies include smartphone GPS (time resolution of seconds, spatial accuracy of meters), Wi-Fi probes and beacons (tracking flows including indoors), Light Detection and Ranging (LiDAR) (3D measurement at centimeter level), and camera analytics (person detection, tracking, and attribute estimation using deep learning). González et al. [2] analyzed location data from 100,000 mobile phone users and showed the predictability of human movement patterns.

In the field of urban computing systematized by Zheng [11], research is progressing on integrating various data sources to understand and predict the dynamic state of cities. Song et al. [26] proposed a system that treats human mobility data as time series images and classifies city states, such as sleeping, working, and rush hour through unsupervised learning. Sparks et al. [27] derived temporal signatures of cities using Point of Interest (POI) operating hour data and quantitatively compared rhythm differences across cultures.

Most of this research focuses on pattern classification, anomaly detection, and monitoring the current state. While these studies have succeeded in identifying urban states, discussion of how urban planning should intervene in these rhythms is not sufficient.

From the planning side, chrono-urbanism [28] proposed in Europe in recent years and the 15-Minute City by Moreno [29] have attracted attention. These present visions, such as daily life being completed within a 15-minute walk and adapting cities to human rhythms and show directions for urban planning. The significance of this approach is that it can show planning directions based on clear value judgments. However, sufficient discussion has not been made to deepen plans quantitatively and in detail at the district level.

Based on the above discussion, the treatment of time concepts in urban planning can be organized along two axes of spatiotemporal granularity and description mode, as shown in Figure 1.

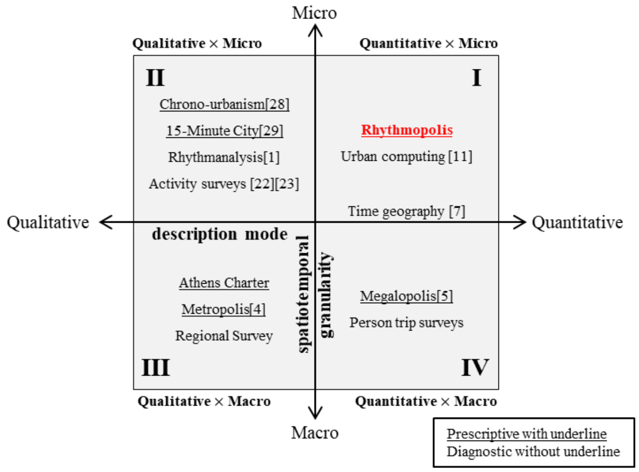

Figure 1. Treatment of Time Concepts in Urban Planning.

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

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Geddes' Metropolis and CIAM's Athens Charter are positioned in Quadrant III as qualitative prescription at the macro scale. Gottmann's Megalopolis and the four-step model are positioned in Quadrant IV as macro scale and quantitative approaches based on statistical data. At the micro-scale, Lefebvre's rhythmanalysis is positioned in Quadrant II as qualitative diagnosis, while chrono-urbanism and the 15-Minute City aim to return to human scale. Time geography, which deals with individual space-time paths, is positioned to bridge quadrants in that it deals with social structure through micro-scale quantitative description. Recent urban computing has enabled ultra-high-resolution description through GPS and other technologies, but its focus is monitoring the current state, and it remains in the diagnosis area of Quadrant I, which is quantitative and micro-scale. Rhythmopolis proposed in this study is a theoretical framework for converting high density data into concrete interventions in this Quadrant I and develops the prescription area at a quantitative and micro-scale. These technological advances have laid the foundation for discussing qualitative differences in urban rhythms. However, urban rhythms are not a uniform phenomenon; each city is expected to have its own distinctive rhythms shaped by infrastructure and culture. The following section reviews research based on such data to clarify the regional characteristics of urban rhythms.

III. REGIONAL CHARACTERISTICS OF URBAN RHYTHMS

This section examines how urban rhythms are determined by mobility infrastructure and cultural practices. Newman and Kenworthy [30] classified major world cities from the viewpoint of transportation infrastructure and urban density into rail-dependent, automobile-dependent, and mixed types. This section theoretically examines characteristics that each mobility infrastructure gives to urban rhythms, referring to this classification.

A. Discrete Rhythms in Rail-Dependent Cities

In cities with developed rail networks, urban rhythms tend to synchronize with train schedules. Rail mode share in central Tokyo is about 50.3%, and similar trends are confirmed in Paris, Hong Kong, and other cities [31]. Rail is a system that transports large numbers of people at scheduled times, and the higher the rail dependency, the more discrete the wave pattern of human flows is expected to be.

Batty [32] called this characteristic temporal bundling and pointed out that periodic density changes occur when many individuals' movements are bundled at specific times. As a characteristic of rail systems, delays propagate throughout the network. Tan et al. [33] demonstrated through simulations of London's rail network that without recovery measures, secondary delays would increase by 151.33% compared to when countermeasures were implemented.

In rail cities, Transit Oriented Development (TOD) centered on stations progresses, concentrating commercial and business functions around stations. Calthorpe [34] systematized the TOD concept and argued that high-density, mixed-use development centered on public transit nodes reduces automobile dependency and achieves sustainable urban forms. In such cities, station boarding and alighting rhythms are considered to synchronize directly with activity rhythms in surrounding areas.

B. Continuous Rhythms in Car-Dependent Cities

In North American cities, such as Los Angeles and Houston, and Middle Eastern cities, such as Dubai and Riyadh, automobile mode share is high. Automobile commuting mode share in the Los Angeles metropolitan area is about 88%, and public transit use is 6%. In these cities, departure times are largely left to individual discretion [35].

Mokhtarian and Chen [36] showed that commuting time distribution in automobile-dependent cities approximates a normal distribution and demonstrated that peak sharpening as in rail cities is less likely to occur. Characteristics of automobile cities include prolonged congestion and flattened peaks. According to Daganzo [37], when road networks reach saturation, temporal demand spreads and peak periods extend.

Parking infrastructure is also involved in the formation of such continuous rhythms, not just road infrastructure. Shoup [38] showed that cruising for parking can account for about 30% of downtown traffic and pointed out the influence of parking policy on urban rhythms. Parking location, capacity, and pricing structures are factors that indirectly determine urban rhythms through spreading arrival times at destinations and adjusting stay durations.

C. Modal Interaction in Mixed Cities

Many large cities have mixed structures where multiple transport modes coexist. New York, Chicago, Berlin, and Seoul fall into this category. Banister [39] proposed modal shift from automobile dependency to public transit, walking, and cycling as a sustainable urban transport paradigm. In cities in transition, however, multiple rhythms interfere in layered ways.

In mixed cities, pulse-like rail rhythms and continuous automobile rhythms intersect spatially and temporally, forming complex polyrhythms. Mobility as a Service (MaaS), which has spreading in recent years, is a platform that promotes integrated use of multiple modes and may bring flexibility to urban rhythms [40].

D. Cultural Modulation of Rhythms

Cultural and social practices specific to cities and regions are also elements that determine urban rhythms. Zerubavel [41] presented the concept of social construction of time and argued that time divisions, such as working hours, rest periods, and holidays are culturally determined.

In Spain, southern Italy, Greece, and other places where siesta culture is established, distinct rhythms are formed from about 1pm to 4pm. In southern European countries like Spain, lunch breaks last around 50 minutes, with over half of workers eating with family. In contrast, other European countries average less than 30 minutes, and some nations rarely eat with family at all [42]. In Islamic regions, Friday is important as a day of worship, and many countries have Friday and Saturday as holidays. According to Wang et al. [43], traffic volume on highways during China's major holidays has been found to reach up to 1.88 times that of adjacent weekdays.

The influence of seasonal changes on urban rhythms is closely related to cultural interpretation. Kato [44] pointed out time consciousness based on four season cycles as a characteristic of Japanese culture and discussed relationships where natural cycles and social activities mutually determine each other. More generally, in monsoon climate cities, wet and dry season rhythms, and in high latitude regions, midnight sun and polar night rhythms are considered to influence urban activity patterns.

E. *Factors Determining Urban Rhythms*

Based on the above discussion, main factors determining urban rhythms can be organized as follows. First, infrastructure factors include rail network development, road capacity, and public transit service frequency and hours. Second, spatial structure factors include urban density, job housing relationships, and commercial facility location patterns. Third, institutional factors include working hour regulations, store hour regulations, and school start times. Fourth, cultural factors include mealtime practices, work values, and religious time norms. Fifth, climate factors include temperature, daylight hours, and seasonal changes. Rhythm characteristics specific to each city are formed by the combined action of these factors.

However, in the 21st century where sustainability is demanded, spatial resources have reached their limits of expansion. The approach of adapting life to space can no longer be sustained. Instead, a shift to an approach that adapts space to target life rhythms is now required. How can we reverse the causal relationship between space and rhythm that has been taken for granted in traditional planning? The following section proposes Rhythmopolis as a theoretical framework to address this question.

IV. THEORETICAL FRAMEWORK: RHYTHMOPOLIS

This section integrates the discussions in previous sections and proposes Rhythmopolis as a theoretical framework for quantitatively evaluating urban rhythms and developing them into planning theory.

A. *The Concept of Rhythmopolis and the Inverse Problem Approach*

Rhythmopolis is a theoretical framework that views cities not as collections of static spaces but as collections of dynamic temporal structures and reconstructs the direction of causality in planning. Figure 2 illustrates this conceptual evolution by comparing three urban paradigms. In the early 20th century, Metropolis conceptualized by Geddes aimed at organic development of single cities through spatial expansion. Later, Megalopolis introduced by Gottmann extended this to inter-city connection through regional infrastructure. These 20th century concepts were models that maintained and developed urban functions through spatial expansion, driven by population growth and economic development. In contrast, Rhythmopolis proposed in this study aims at autonomous growth at the district level through optimization of temporal structure in mature cities where physical spatial expansion has reached saturation. Section II clarified the relationship between technological development and time concepts in urban planning, and Section III organized factors that shape rhythms based on existing research in each city. The theoretical framework proposed in this section attempts to tune existing urban stock along the time axis. This represents a paradigm shift from spatial expansion to temporal intensification.

The core of this framework is transforming urban planning from setting space and observing results (forward problem) to

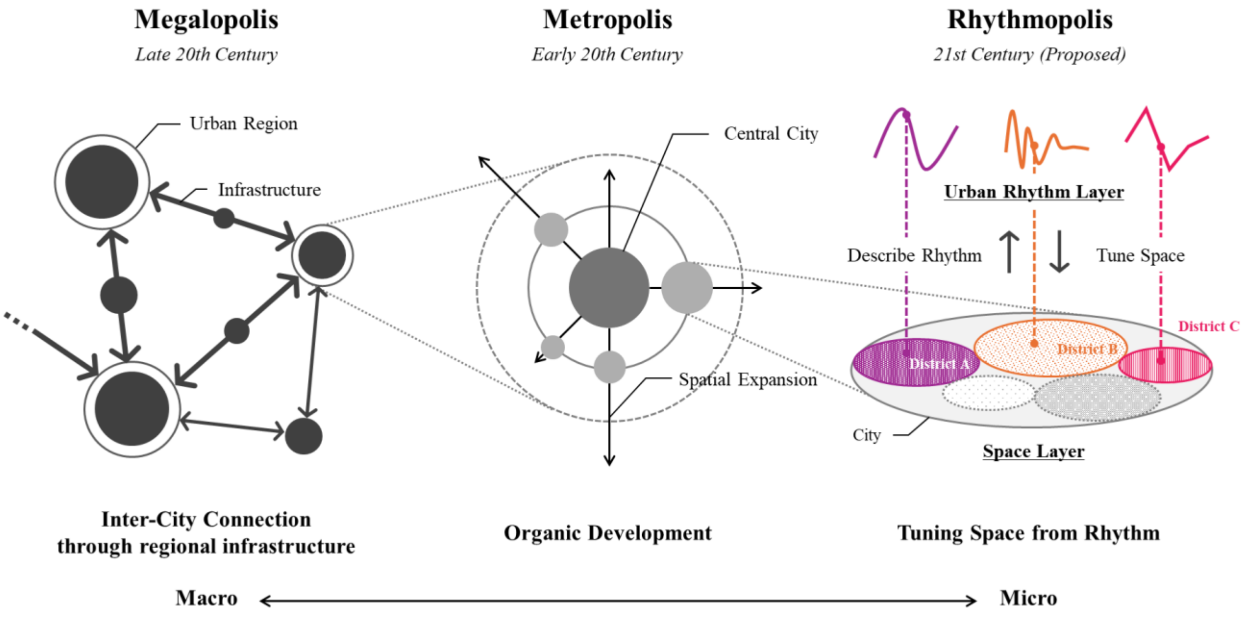

Figure 2. Conceptual Comparison of Metropolis, Megalopolis, and Rhythmopolis.

tuning space based on target rhythms (inverse problem). Traditional urban planning was a forward problem approach that tried to control activity R (Rhythm) by determining space S (Space). This can be expressed mathematically as:

$$R = f(S) + \varepsilon \tag{1}$$

Here f is a mapping representing physical constraints that space places on activity, and ε is an unpredictable error term. In traditional zoning methods, while the state of space input S could be understood, it was difficult to understand how the resulting rhythm R interferes. Arrhythmia criticized by Lefebvre can be interpreted as a state where the error term ε increases due to the rigidity of space S, causing urban life rhythms to malfunction.

Rhythmopolis reconstructs this as an inverse problem that sets target rhythm R_{target} and searches for spatial configurations S that minimize error from the actual output:

$$S^{*} = \arg\ \min{}_{S}\, \mathcal{L}(f(S), R_{\text{target}}) + \lambda \cdot R(S) \tag{2}$$

Here $\mathcal{L}$ is a loss function (degree of rhythm deviation), R is a regularization term (feasibility of spatial configuration), and λ is a regularization parameter.

B. *Structuring the Error Term: Introducing Signal Processing*

The biggest barrier to solving this inverse problem is the multi-dimensional nature of activity rhythm R and the error term ε that has been treated as unpredictable noise. In urban analysis so far, attempts have been made to extract periodicity of urban activities using Fourier transforms [45][46]. Fourier transform is a method for decomposing time series signals into frequency components and has succeeded in extracting basic periodicities, such as daily (24 hour) and weekly (168 hour) cycles.

However, Fourier transform assumes stationarity, making it difficult to capture nonstationary changes, such as cultural and seasonal modulation seen in Section III. Rhythm quality pointed out by Lefebvre refers to dynamism where multiple rhythms interfere while producing urban space, but such qualitative aspects are discarded in conventional methods.

Therefore, this study introduces the theoretical framework of Music Information Retrieval (MIR) [47][48]. MIR is an interdisciplinary research field that has developed since the late 1990s, aiming to automatically extract and analyze meaningful information from music signals. The feature of MIR is that it converts physical signals into perceptually meaningful higher-order features, such as timbre, tempo, and harmony.

The reason MIR is considered applicable to urban rhythm analysis is the structural similarity between the two. Just as multiple instruments in music play different rhythms while forming overall harmony, in cities different rhythms, such as rail, automobiles, pedestrians, and commercial activities interfere in layers while forming the overall temporal structure of the city. In recent years, the descriptive capability of MIR has been applied to fields other than music analysis, including machine anomaly detection [49], heart sound classification in medicine [50], and ecosystem monitoring in bioacoustics [51], expanding its application range as a general signal processing framework for diagnosing the state of complex systems.

By treating urban human mobility data as signals and applying the MIR framework, rhythm R can be described for the first time as a multi-dimensional vector:

$$R(t,x) = [timbre(t,x), tempo(t,x), harmony(t,x)]^{\mathsf{T}} \tag{3}$$

Here t is time and x is location. Table 2 shows conceptual correspondences between music attributes and urban rhythms.

TABLE II. CORRESPONDENCE BETWEEN MUSIC ATTRIBUTES AND URBAN RHYTHM

Music Attribute	***Urban Rhythm Correspondence***	***Structural Components***
Timbre	Micro-structure and dynamic texture of stay behavior	Statistical shape of stay duration distribution and dynamic fluidity (turnover and flux)
Tempo	Periodic fluctuations in aggregate population	Intensity and phase of daily and weekly periodic cycles in aggregate population
Harmony	Layering and composition of diverse activity types	Quantity and composition of everyone’s type of life rhythm

By defining such multi-dimensional features, qualitative concepts discussed in Section III, such as discrete rhythms of rail cities, continuous rhythms of automobile cities, and cultural modulation can be operated as quantitative and comparable variables. By structuring rhythm quality that was discarded as error term ε, the foundation for setting objective functions for the inverse problem is established.

C. *Expanding Control Variables and Planning Implications*

By vectorizing rhythm R through the MIR framework, variables that could not be operated in space-centric models become defined as new control variables.

For temporal interventions, flextime policies and staggered commutes and school times are effective for rhythm periodicity. Pedestrian space design and signal control tuning contribute to tempo adjustment, and demand spreading policies, dynamic pricing, and distributed operating hours are considered for compressing dynamic range.

For spatial interventions, spatial and temporal arrangement of mixed uses is important to increase polyrhythm harmony. Specifically, this includes multipurpose facility use through time sharing, placement of flexible public spaces, and promotion of mixed land use around nodes.

For institutional interventions, promotion of flextime policies, telework support, and distributed school start times apply. These policies are expected to reduce the sharpness of city-wide rhythms by expanding individual discretion over activity start times. By combining these temporal, spatial, and institutional measures, it becomes possible to tune urban rhythms toward target states.

Rhythmopolis does not reject existing zoning. It is an approach that dynamically optimizes space S as a solution to achieve target rhythm R_{target}, rather than treating it as a fixed premise. Normative approaches, such as the 15-Minute City can also be positioned within the Rhythmopolis framework. The goal of daily life being completed within a 15-minute walk can be interpreted as one example of target rhythm R_{target} defined from an accessibility viewpoint, and Rhythmopolis provides a framework for generalizing and treating this quantitatively.

D. Future Prospects and Challenges

Implementation of the Rhythmopolis theoretical framework requires addressing the following technical and social challenges. First, development of methods for identifying the mapping f. The mapping from space S to rhythm R is nonlinear and high dimensional, but recent advances in technologies, such as deep learning can be effective means for approximating and estimating these complex dependencies. Modeling the mapping f based on observation data is key to evolving this framework from descriptive to predictive.

Second, building consensus formation processes for target rhythm R_{target}. Defining desirable rhythms involves not only technical optimization but also social value judgments. Rhythmopolis has the potential to function as an evidence-based platform supporting consensus formation among various stakeholders by using rhythm as a quantitative common language.

Third, preparing verification environments for intervention effects. For spatial interventions that are difficult to experiment with in actual cities, approaches that estimate causal effects through simulation in environments, such as digital twins are considered effective.

This paper focused on the conceptual definition of Rhythmopolis. Specific feature extraction using MIR and verification of relationships with urban space using actual data are outside the scope of this study, but these are important challenges to address for connecting the proposed theoretical framework to urban planning practice.

V. CONCLUSION

This study organized the theoretical history of how time concepts have been treated in urban planning from the viewpoint of how measurement technologies have changed and attempted to reinterpret Lefebvre's rhythmanalysis in the context of current urban informatics. Based on this, this study proposed Rhythmopolis as a theoretical framework that enables quantitative analysis of urban rhythms based on human mobility data and development into planning theory.

This study makes three primary contributions. First, by organizing the development of time concepts in urban planning along two axes of spatiotemporal granularity and description mode, this study showed that the area of setting targets and tuning interventions based on micro-scale quantitative data from dense sensing remains undeveloped. Second, this study proposed Rhythmopolis as a theoretical framework to address this gap. In the history of urban concepts, Metropolis aimed at organic development of single cities, and Megalopolis aimed at inter-city connection through regional infrastructure. Rhythmopolis is positioned as a third concept aiming at autonomous district level operation through temporal structure optimization. Third, this study presented a viewpoint for transforming the logic of planning from the forward problem of predicting activity from space to the inverse problem of tuning space from target activities. To solve this inverse problem, the theoretical framework of MIR was introduced as a means for structuring rhythm quality that was discarded as error.

In future research, the first stage will be collecting human mobility data from multiple cities, extracting rhythm features, and evaluating the accuracy of inter-city comparison and arrhythmia detection. The next stage will be estimating causal relationships between spatial interventions and rhythm changes and developing inverse problem solution methods.

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Development of Urban Dashboard for Smart District Planning and Management

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***Abstract*—District planning and management are gaining renewed attention, while urban digital dashboards have expanded with open data and smart city initiatives. Yet, most dashboards remain descriptive and provide limited support for district diagnosis and strategy-making. This paper synthesizes prior research and leading practices in urban dashboards and district planning to propose design principles for the urban dashboard that supports smart district planning and management. Based on a review of district planning theory, assessment methods, and global dashboard practices, the study develops an integrated framework consisting of (1) a fine-grained smallest spatial unit database, (2) Application Programming Interface (API) -based automated data acquisition, (3) analytics combining Geographic Information System (GIS) indicators and generative Artificial Intelligence (AI) for comparative diagnosis and action exploration, and (4) an interactive interface with visualization and natural-language dialogue. The framework is positioned as planning-oriented digital infrastructure supporting both top-down policy prioritization and bottom-up place management.**

Keywords- urban dashboard; district; neighborhood; BID.

I. INTRODUCTION

In recent years, urban policy has increasingly emphasized the importance of spatial reconfiguration and management at the district scale. Districts represent a walkable spatial unit and serve as a fundamental planning scale rooted in residents' daily life. They also function as a community unit and, in many contexts, constitute the smallest scale of local self-governance beneath prefectures, municipalities, and wards.

Internationally, institutional models, such as Business Improvement Districts (BIDs) have established a framework in which local businesses secure funding at the area scale and autonomously implement cleaning, safety measures, publicity, and events [1]. In addition, within urban design and transport policy, the concept of the X-minute city—which promotes pedestrian-oriented urban form, improved local accessibility, and the reorganization of public services at the district scale—has rapidly gained traction worldwide [2]. In Japan, and particularly in Tokyo, district-based urban initiatives, such as Area Management have expanded in redevelopment areas and central districts. In these initiatives, private firms and landowners increasingly take responsibility for maintaining and operating public spaces, promoting pedestrian circulation, shaping urban landscapes, and enhancing local attractiveness [3]. This trend aligns with a broader international shift toward understanding districts not only as "spatial units," but also as "managerial units" for urban governance and place management.

In parallel with the expansion of district-based urban governance, global momentum toward urban digitalization (smart cities) and data-driven policymaking has accelerated. Technological developments—including the improvement of open data infrastructures, the establishment of urban operating systems, and the spread of IoT and sensing technologies—have made it increasingly feasible to visualize and monitor urban conditions. In particular, cities, such as London [4], New York [5], and Paris [6] have begun to publish digital dashboards (hereafter, urban dashboards) that aggregate city-scale data and present them at district-scale spatial units, enabling residents and local organizations to access and utilize urban information. Yet, compared to these global cities, Tokyo lacks an urban dashboard that visualizes urban conditions at the district scale. Although the Tokyo Metropolitan Government has released dashboards related to policy evaluation [7], there remains no comprehensive mechanism that assesses urban space itself and provides data in a form that can be reorganized and interpreted at the district scale. As a result, despite the growing number of district-scale planning and management initiatives across cities, a digital infrastructure that connects city-scale data with district-scale practice remains missing.

Focusing on this gap, this paper aims to propose design principles for an urban dashboard that reorganizes city-scale data into district-based units and visualizes districts' relative characteristics. Such an urban dashboard should be positioned not only as a tool for public authorities to identify priority districts and target interventions from the perspective of urban publicness, but also as a foundational infrastructure for smart district planning and management—enabling district management organizations and citizens to understand the distinctive features of their own area and to advance policy formation and consensus-building.

The paper is structured as follows. Section II outlines the review methodology. Section III reviews research on urban dashboards and compares dashboard practices in major cities to clarify their design rationales and limitations, as well as the gap in Tokyo. Section IV summarizes the theoretical development of district planning, institutional frameworks,

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and the evolution of district assessment methods, and presents an analytic perspective for district diagnosis to inform dashboard design. Section V integrates the discussions in Sections III and IV to propose a conceptual model and design framework for an urban dashboard that supports smart district planning and management. Section VI concludes.

II. METHODOLOGY

This study is positioned as a review-based research project that systematically organizes existing literature, policy documents, and practical reports in the fields of urban planning and smart cities, with the aim of developing an integrated understanding of district planning theory and urban dashboards. This study is positioned as a review that bridges two strands of scholarship that have not been sufficiently connected to date: research on urban dashboards and research on district-scale planning and assessment. To ensure transparency and reproducibility, this Section presents the literature search process and selection criteria.

The primary search was conducted using Web of Science, a major academic database for urban planning and smart city research. The review targeted literature published from 1970 onward. The following English keyword combinations were used: "urban dashboard", "city dashboard", "district planning", "neighborhood planning", "Business Improvement District", "15-minute city". In addition, administrative reports, open data portals, and technical documentation related to urban dashboards were collected for major cities (e.g., London, New York, Paris, and Tokyo) in order to supplement academic findings with practice-oriented insights.

Among the collected materials, those meeting the following criteria were selected for review: Research on urban dashboards, open data, and smart city analytics, Studies on district-scale planning and governance, Literature on district diagnosis and assessment methods (both subjective and objective), Studies on the 15-minute city and accessibility analysis, and Implementation cases in specific cities (New York, London, Paris, and Tokyo).

III. URBAN DASHBOARDS: CONCEPTS AND GLOBAL PRACTICE

A. *Conceptualizing Urban Dashboards*

The urban dashboard is an information platform that integrates diverse urban indicators and visualizes them on a single interface through maps, charts, and related tools. Since the 2010s, urban dashboards have been increasingly introduced in major cities worldwide as platforms providing evidence for decision-making, driven by the expansion of open data, the rise of Evidence-Based Policy Making (EBPM), and the diffusion of business intelligence tools [8]. By visualizing urban processes and performance through data, dashboards support rapid situational awareness and Key Performance Indicator (KPI) management within administrations, while also offering an intuitive means for communicating urban conditions to the public [9].

Existing research includes studies on UI design based on comprehensive reviews of global dashboard practices [8], [10], as well as studies focused on user experience [11], [12]. Regarding use contexts, research has examined both administrative applications—such as leveraging dashboards for policy design and operational improvement through case studies [13]—and citizen participation perspectives. In the latter stream, dashboards are discussed as mechanisms through which local governments present publishable data in accessible formats, thereby enhancing transparency and accountability, while enabling citizens and businesses to use data for their own decisions and analyses [11], [14]. At the same time, some studies have pointed to the insufficient interactive and dialogical capacities of many existing urban dashboards [10].

B. *International Comparison of Dashboard Practices*

Major global cities have developed urban dashboards that reflect distinct urban strategies and administrative cultures. The dashboards of London, New York, and Paris are representative examples. Table 1 summarizes their key characteristics and Figure 1 shows their user interfaces. Tokyo's 23 wards constitute a megacity comparable in population scale to London and New York, while the wider metropolitan region is comparable to Greater Paris. Moreover, Tokyo's chōchōmoku (smallest neighborhood block units) are among the finest-grained spatial units used internationally and function as a base unit for statistical analysis, similar to London's Lower Layer Super Output Areas (LSOAs) and New York's Neighborhood Tabulation Areas (NTAs). For these reasons, comparing Tokyo's potential dashboard development with established practices in London, New York, and Paris is academically justifiable.

In London, the Greater London Authority provides the London Area Profiles [4], which visualize census-based statistics on society, population, housing, and related dimensions at borough and ward scales, in a format close to raw data.

In New York City, the nonprofit organization Measure of America develops and publishes DATA2GO.NYC [5]. It visualizes over 400 indicators across three spatial scales—from boroughs to neighborhoods. Compared to London's dashboard, it places stronger emphasis on composite indices that are easier for the public to interpret, such as the Human Development Index (HDI). Its interface also enables exploratory analysis, such as examining correlations among indicators, supporting users' independent analytic engagement.

In Paris, the urban planning agency APUR provides the Portail des mobilités / Mobility Portal Greater Paris [6], a mobility-focused dashboard specialized in geospatial analysis that aligns with the 15-minute city concept. It supports analyses of accessibility to daily services via transport systems, as well as relationships between travel modes and environmental impacts. Notably, it includes future projections (e.g., 2030 forecasts for travel demand and air pollution), highlighting its function as a planning support tool for encouraging environmentally sustainable behavioral change.

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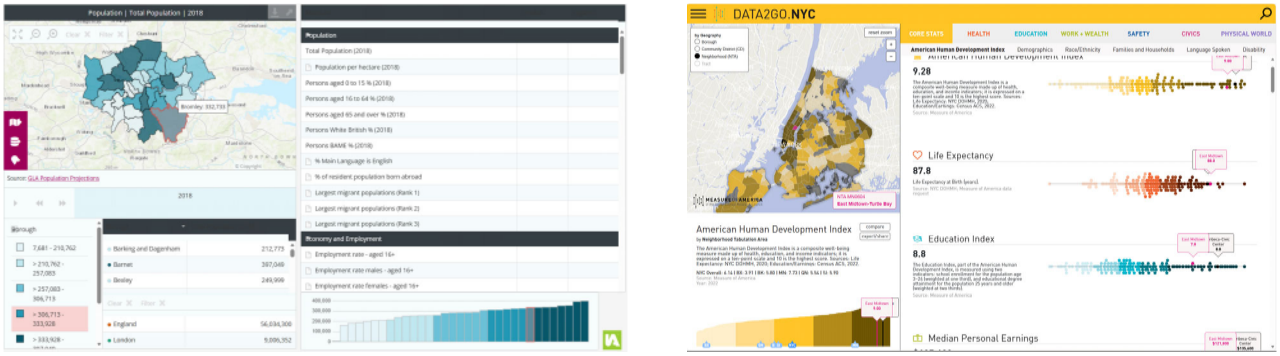
These dashboards are useful for diagnosis and comparison at the district scale; however, they were not developed as dashboards specifically intended for district planning and management. Relatedly, the urban dashboards in all three cities remain largely limited to data visualization and descriptive statistics, and they offer little in the way of Artificial Intelligence (AI) -based automated diagnosis or policy recommendation functions. Such AI-enabled capabilities are needed because enabling citizens to diagnose district-level issues and explore policy options in natural language through generative AI can improve civic literacy regarding district management and urban policy and, in turn, encourage more proactive civic participation.

In Tokyo today, open data is widely provided through the Tokyo Metropolitan Government Open Data Catalog [15] and the Tokyo Data Platform [16]. The metropolitan government also publishes policy-evaluation dashboards [7] that visualize progress on long-term strategies and policy measures. However, the primary focus of these dashboards is KPI management. Additional dashboards exist in domains, such as fiscal management [17], Small and Medium-sized Enterprise business sentiment [18], and administrative process digitalization [19], yet Tokyo still lacks an urban dashboard capable of diagnosing the structure of urban space and district characteristics. This gap is particularly salient given the growing prevalence of district-based urban

TABLE I. CHARACTERISTICS OF URBAN DASHBOARDS IN LONDON, NEW YORK AND PARIS

City	London	New York (NYC)	Paris
Urban dashboard	London Area Profiles [4]	DATA2GO.NYC [5]	Portail des mobilités [6]
Spatial units for data aggregation	32 boroughs within Greater London	5 boroughs / 59 community districts / approx. 200 neighborhoods (NTAs) within NYC	131 communes / 12 territories within the Greater Paris region
Indicators	89 indicators on population, economy and employment, public safety, housing, environment, transport, education, and health	Approximately 400 indicators on the Human Development Index (HDI), demographic diversity, health, education, economy, public safety, civic/political participation, housing and living conditions, etc.	More than 50 indicators on walkability-based accessibility to public transport hubs and everyday services, commuting distance and travel modes, air pollution, etc. In addition, forecasts for transport demand and air pollution in 2030 are also provided.
Visualization features	a. Visualizes the spatial patterns of each indicator by linking maps and histograms (main screen) b. Enables district-scale profile reports	a. Visualizes the spatial patterns of each indicator by linking maps, histograms, and scatter plots (main screen) b. Enables district-scale profile reports c. Displays results of correlation analysis between indicators	The main interface consists of three types: a. Visualizes district characteristics using charts b. Visualizes the spatial patterns of key indicators on maps and provides corresponding excerpts from research reports c. Visualizes transport accessibility on maps from any user-selected location



London Area Profiles (London) [4]

DATA2GO.NYC (New York City) [5]

Portail des mobilités (Paris) [6]

Future Tokyo: Tokyo's Long-Term Strategy Policy Dashboard (Tokyo) [7]

Figure 1. User interface of urban dashboards in London, New York, Paris and Tokyo.

governance and Area Management across the city. In short, Tokyo faces a challenge in the absence of a digital infrastructure that connects city-scale data to district-scale planning and management.

IV. THE HISTORY OF DISTRICT PLANNING THEORY

As confirmed in Section III, urban dashboards are useful for comparing districts, yet they offer only limited functionality for the diagnosis and decision-support required for district planning and management. This Section therefore organizes the evolution of district-scale planning theory and the shifts in approaches to district assessment as the theoretical foundation for bridging this gap. On this basis, it extracts the key requirements for a dashboard that can support smart district planning and management, and links the discussion to the design proposal in Section V.

A. Evolution of Theoretical Foundations

Theories and practices of district-scale planning have transformed gradually alongside shifts in twentieth-century planning thought. In early modernist and functionalist planning, Clarence Perry's neighborhood unit concept [20] served as a representative model, proposing a district spatial structure organized around elementary school catchments and prioritizing the distribution of daily functions and the exclusion of through traffic. This model became widely institutionalized as a guiding principle for residential development. However, the large-scale redevelopment projects promoted during the 1950s and 1960s were increasingly criticized for producing uniform spatial environments and undermining community cohesion, leading planners to reconsider approaches grounded in everyday lived experience [21].

Responding to these critiques, Jane Jacobs [22] emphasized that mixed land uses, diversity, and pedestrian-oriented environments generate urban vitality, articulating a vision of the city that foregrounded social dynamics at the district scale. From the 1960s onward, advocacy planning and collaborative planning gained prominence, reframing planning not as a purely expert-driven technical exercise but as a dialogical process involving citizen participation and interest mediation [23]. In the 1970s, the importance of local resources and human-scale environments was reaffirmed, and historic district preservation and community design became central themes of district planning theory [24]. In the 1980s and 1990s, New Urbanism emerged in the United States, promoting walkable streets, mixed use, and traditional block design [25]. During the same period, Transit-Oriented Development (TOD) evolved as a planning and development paradigm, strengthening arguments for concentrating residential and employment functions around transit stations and integrating district form with mobility systems [26]. By the 1990s, these urban design and development theories became embedded in institutional frameworks and guidelines across countries, consolidating districts as policy units where urban regeneration, transport policy, and community planning intersect [27].

In the twenty-first century, district-scale planning entered a new phase centered on sustainability, mobility optimization, and the reorganization of everyday living areas. Districts have increasingly been positioned as strategic units for reshaping metropolitan structures [28]. Building on these trends, planning agendas have once again strongly foregrounded walkable, human-centered public space as a key international direction [29]. Barcelona's Superblocks (Superilles) exemplify this shift: by restricting car traffic at the block scale and reallocating space toward pedestrians and cyclists, the project has become a globally recognized model of district-scale public space transformation [30]. Similarly, Paris's "15-minute city" strategy and the "X-minute city" initiatives in places, such as Milan and Portland propose urban structures in which daily functions can be completed within the district, encouraging optimized everyday mobility and a reconfiguration of living areas [28].

More recently, comprehensive district models have expanded further, including eco-districts [31] designed for climate change mitigation and innovation districts [32] aimed at fostering startup ecosystems. These approaches integrate environmental, economic, and social values, redefining districts not merely as spatial units but as sites of layered value creation and as foundations for sustainable, multifunctional urban structures.

B. International Comparison of Institutional Frameworks

District-scale planning institutions vary widely across countries, but many are positioned within hierarchical planning systems. They range from statutory instruments defining land use policies and building rules, to more flexible frameworks implemented as guidelines. In addition to formal planning instruments, private and community-led district management has become an increasingly important element of contemporary district governance.

In the United Kingdom, the 2011 Localism Act established Neighbourhood Development Plans (NDPs) as statutory plans, enabling community organizations to influence land use decisions [33]. While more than 2,600 areas have advanced plan-making, shortages of local capacity—especially in urban contexts—remain a persistent challenge [34].

In the United States, many cities adopt Neighborhood Plans as subordinate components of comprehensive plans, and their flexible operation often connects with redevelopment and historic preservation policies [35]. Moreover, BIDs are widely adopted as practical governance mechanisms that improve district environments through additional contributions from businesses, supporting functions, such as events, cleaning and safety measures [1].

In Japan, the district plan system introduced in 1980 provides a foundational planning framework. It enables municipalities to designate rules on building form and landscape through formal urban planning decisions, and resident-based organizations, such as local planning councils often participate in plan formulation and implementation [36]. In addition, Area Management has expanded in central districts of major cities, with private actors engaging in public space management and event programming to form business communities and enhance district value [3]. In Tokyo, in contrast to BIDs that are funded through additional levies on area businesses, developer-led Area Management has become common, particularly where major office developments serve as anchors. Such initiatives operate alongside large-scale redevelopment and aim to differentiate districts from competing urban areas [3].

Other institutional frameworks, such as Germany's B-Plan which regulates detailed land use under administrative leadership [37], also play important roles. Across these diverse systems, a shared challenge lies in balancing alignment with higher-scale plans and the flexibility required to reflect district-specific needs.

C. *Approaches to District Assessment*

Methods for evaluating districts have evolved alongside the history of urban planning. Early neighborhood unit models relied primarily on physical criteria, such as facility placement. From the 1960s and 1970s, as citizen participation expanded, social evaluation approaches emphasizing lived experience and community issues gained prominence [20]. Since the 1990s, the spread of Geographic Information System (GIS) has made quantitative assessments more common, including analyses of accessibility, facility distribution, and walking catchments, forming the foundation of contemporary living-area analytics [38].

District assessment methods can be broadly categorized into objective and subjective approaches. Objective approaches are exemplified by the internationally widespread "15-minute city" (and broader "X-minute city") frameworks, which evaluate access to everyday functions through travel time metrics [2]. These methods rely on GIS-based quantitative analysis and are used for inter-area comparison and policy target-setting. Recent progress in the open data availability of urban environmental indicators has further strengthened the quantity and quality of objective district evaluation.

Subjective approaches, by contrast, have a long history in Japan. Since the 1970s, the Community Karte (often translated as Community Profile) has been developed as a participatory tool through which residents examine local living environments, identify problems, and connect analysis to planning proposals—thereby integrating community-based evaluation into administrative policy [39]. This approach incorporates not only measurable conditions but also residents' perceptions, enhancing public involvement and linking directly to contemporary participatory district diagnosis practices. Internationally, similar principles appear in initiatives, such as the UK Parish Plan system and participatory rural appraisal in developing contexts, which enable communities to identify needs and integrate them into planning processes [40]. In this sense, the conceptual foundation of community profiling can be regarded as part of a shared international planning ethos.

Comparing the two approaches, the 15-minute city framework is strong in urban spatial analysis based on objective data, whereas the Community Karte (Community Profile) is strong in identifying issues grounded in lived experience and in facilitating consensus-building. For district assessment to function not merely as description or ranking but as a tool that supports district planning and management, it is necessary to combine participatory evaluation with data-driven evaluation and to enable both a top-down approach—through which public authorities identify priority districts and concentrate support and investment—and a bottom-up approach—through which district management organizations and residents understand the characteristics of their own area and advance policy formulation and consensus-building. Achieving this requires an urban dashboard that can be used by multiple stakeholders, including public authorities, district management organizations, and citizens. Specifically, such a dashboard should restructure diverse datasets collected at the city scale into district-based units, enabling inter-district comparison and time-series monitoring, while also integrating and presenting subjective information, including residents' perceptions and on-the-ground knowledge. In this sense, an urban dashboard of this kind can be positioned as a digital infrastructure for smart district planning and management.

V. DISCUSSION: AN INTEGRATED FRAMEWORK FOR DISTRICT PLANNING AND URBAN DASHBOARDS

A. *Requirements for Urban Dashboards for Smart District Planning and Management*

As discussed in Section III, digital urban dashboards in major global cities reorganize city-scale data—such as population, transportation, environment, land use, and human mobility—into district-based units, enabling inter-district comparison and situational awareness. At the same time, however, many dashboards remain centered on visualization and descriptive statistics and do not sufficiently support the practical needs of district planning and management, including problem identification, priority-setting, and the examination of policy options.

As summarized in Section IV, district planning theory has expanded from viewing districts as "units of everyday living," exemplified by the neighborhood unit concept, to understanding them as "units of management and value creation." Approaches to district assessment have likewise evolved toward integrating subjective, participation-based evaluation with objective evaluation using GIS and related methods, and toward linking diagnosis to concrete improvement strategies. In practice, however, carrying out tasks, such as interpreting districts' relative characteristics from multi-dimensional data, structuring the key issues, and formulating plausible policy options in a sustained and repeatable manner goes beyond what visualization and descriptive statistics alone can support; in this sense, generative AI is essential for performing such work effectively. Accordingly, dashboards that support smart district planning and management must go beyond visualization and incorporate generative AI functions that automatically extract districts' relative characteristics and challenges and propose improvement options, thereby serving as a shared infrastructure usable by both top-down actors (public authorities) and bottom-up actors (local stakeholders). This shift transforms district diagnosis from an expert-dependent practice into a more transparent, data-driven process and constitutes a core element of digital transformation (DX) in urban planning.

B. Design Framework for Urban Dashboards for Smart District Planning and Management

As the proposed dashboard aims to function as a diagnostic instrument that visualizes districts' relative characteristics—strengths, weaknesses, and biases—through AI-based analysis. City-scale data are automatically collected and decomposed into chōchōmoku-scale units, structured into a database, aggregated into districts composed of multiple chōchōmoku, and analyzed. In addition to mapping and graphical visualization, the dashboard incorporates generative AI to propose district issues and potential improvement strategies.

Urban dashboards consist of three layers: a data layer, an analytics layer, and a presentation layer [29]. Building on this model, the dashboard proposed in this study adds a data acquisition layer and consists of four layers, as shown in Figure 2.

1) Data Layer

The data layer comprises two spatial scales. The first is a database at the chōchōmoku-scale, which serves as the minimum unit for data aggregation. The second is a district-scale database, constructed by combining multiple chōchōmoku-units. District boundaries may vary depending on the managerial coverage of Area Management organizations, the spatial extent of developers' assets, or empirically observed living areas derived from mobility data. Therefore, the dashboard interface should allow users to define district boundaries flexibly.

2) Data Acquisition Layer

Data are automatically retrieved via Application Programming Interfaces (APIs) from sources, such as the Tokyo open data catalog, national census results, and commercial statistics, and then organized into chōchōmoku-scale datasets for database construction. A current challenge is the lack of standardized data formats across open data websites and survey sources. To reduce the need for manual preprocessing and enable low-cost, continuous updates of the data layer, the dashboard should incorporate API-based mechanisms for automated data collection and structuring.

3) Analytics Layer

The analytics layer consists of three sub-functions:

(3-1) Aggregation Functions

Some datasets are not available at the chōchōmoku-scale. For such data, spatial analyses—including GIS-based processing of facility distribution datasets—are conducted to generate chōchōmoku-scale aggregates, which are then stored in the database. For social media data, natural language processing and image analysis can be applied to derive district characteristics, which are also stored in the database.

(3-2) Evaluation Functions

Based on the integrated datasets, the dashboard computes a district-scale well-being score. Similar to the HDI used in New York's dashboard [5], this provides a composite index that summarizes district conditions into an interpretable measure. Using survey results that reveal relationships between residents' subjective well-being and objective urban environmental variables, a function linking environmental indicators to well-being can be constructed, enabling well-being estimation from district-scale urban environment data.

(3-3) Generative AI Functions

Generative AI supports analyses, such as: identifying spatial patterns and distinctive characteristics across indicators, extracting each district's relative features and issues (i.e., which indicators are significantly distinctive

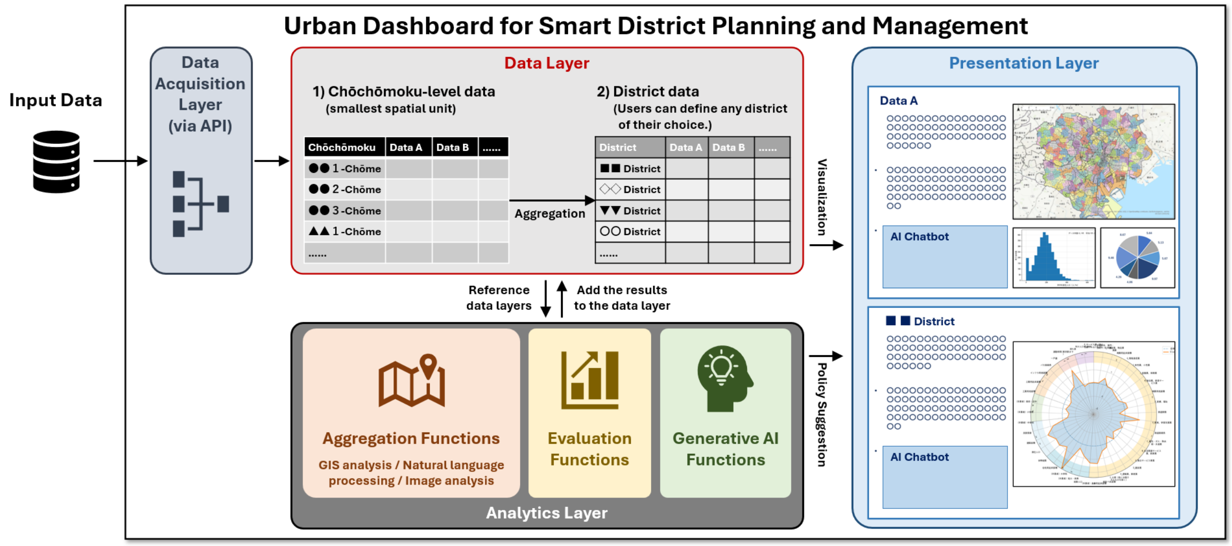


Figure 2. Conceptual image of the urban dashboard for smart district planning and management.

Courtesy of IARIA Board and IARIA Press. Original source: ThinkMind Digital Library https://www.thinkmind.org

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compared with other areas), exploring improvement strategies based on identified challenges, and generating reports synthesizing these analyses.

4) Presentation Layer

The presentation layer integrates visualization and an interactive user interface, comprising multiple switchable screens. The first screen visualizes citywide spatial characteristics through heatmaps, histograms, scatter plots, and similar tools. The second presents district-scale analytical results and interpretations, highlighting each district's relative positioning. The third provides policy and action recommendations generated through the AI functions described above. Through a chatbot interface, users can engage in natural language interaction to identify priority districts and potential solutions from a metropolitan-scale perspective (e.g., development guidance, areas for targeted investment), as well as to develop district-specific intervention strategies from a local perspective (e.g., recommendations for Area Management initiatives based on district characteristics).

VI. CONCLUSION AND FUTURE WORK

Building on the international momentum toward district-scale planning and management and the advancement of urban digitalization and data utilization, this study proposes design principles for a new urban dashboard that restructures city-scale data into district-scale units and visualizes districts' relative characteristics through AI. While existing urban dashboards are useful for inter-district comparison and situational awareness, they are largely centered on visualization and descriptive statistics, and offer limited functionality for addressing practical needs in district planning and Area Management—particularly problem identification and the derivation of improvement strategies. To address this limitation, the study draws on the evolution of district planning theory—from districts as units of everyday living to districts as units of value creation and management—and the shifts in district assessment methods, especially the linkage between participatory evaluation and data-driven evaluation, and on this basis presents an integrated framework that incorporates generative AI functions.

The proposed framework consists of four key elements: (1) establishing a database based on chōchōmoku-scale spatial units; (2) automated data collection and structuring via APIs; (3) analytics using GIS and natural language processing for aggregation, well-being evaluation, AI-based identification of district issues, and exploration of improvement strategies; and (4) an integrated interface combining visualization with interactive, dialogue-based user experiences.

In particular, API-driven automated updating of the data layer and natural-language diagnosis and exploration enabled by generative AI represent critical implementation conditions for treating districts as "managerial units." This design enables administrations to identify disadvantaged districts and spatial inequalities from the perspective of public interest and to prioritize interventions accordingly. At the same time, Area Management organizations and residents can better understand local strengths and weaknesses and use the dashboard to shape strategies for improving pedestrian circulation, activating public spaces, and enhancing district attractiveness. In this sense, the proposed approach can be positioned as a foundation for urban planning digital transformation that supports both governmental and community-driven use and contributes to autonomous district-based place management.

Future research challenges include, first, the need to refine methods for computing well-being. Because appropriate approaches may differ between residential neighborhoods with large nighttime populations and business districts with large daytime working populations, separate well-being modeling frameworks may be required for living environments and working environments. Second, while generative AI-based recommendations offer high usability, they may omit district-specific contexts and consensus-building processes. Generative AI should therefore be positioned not as a substitute for expert and stakeholder decision-making but as a supportive tool for structuring debates and enabling comparative evaluation. Based on these considerations, future empirical work should apply the framework to specific districts in Tokyo, validate indicator systems, evaluate dashboard usability, and test the validity and outcomes of AI recommendations—including policy adoption, behavioral change, and measurable shifts in outcome indicators.

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