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Validating a Sustainable, Smart, and Circular City Architecture Through Urban Living Lab Experiments

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Abstract

Rapid urbanization and climate change pressure cities to integrate sustainability, digitalization, and circular economy principles. Yet most existing approaches treat these agendas separately, leaving gaps in how urban infrastructures, governance, and data systems can jointly support circular transformations. This paper addresses this challenge by proposing and validating a Sustainable, Smart, and Circular City (SSCC) architecture that operationalizes the waste–energy–information nexus. The architecture is structured into seven interconnected layers—Physical, Digital, Analytical, Participatory Governance, Data Strategy, Innovation Management, and Assessment—and is tested through two integrated experiments in the Fenicia Urban Living Lab, Bogotá: (i) an AI- and drone-based system for waste detection and community reporting and (ii) a solar-powered IoT urban garden for environmental monitoring. These experiments demonstrate how digital twins, participatory governance, and multi-actor collaboration can activate circular strategies while enabling evaluation against international standards (ISO 37106, U4SSC, LEED). The results confirm that the SSCC model can transform siloed services into integrated, circular functions that enhance quality of life, productivity, and ICT-based sustainability. The originality of this study lies in validating an SSCC architecture that incorporates the waste–energy–information nexus across seven layers and demonstrates, through Urban Living Lab experimentation, how such an architecture can guide the transition from Smart Sustainable Cities to Circular Cities.

Keywords: sustainable smart circular cities (SSCCs); urban living lab (ULL); waste–energy–information nexus; circular economy; smart city architecture; digital twin; internet of things (IoT); artificial intelligence (AI)

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1. Introduction

The increasing challenges of climate change, urbanization, and resource scarcity have led cities to adopt sustainable development. The smart sustainable city (SSC) model seeks to use digital technology to improve urban operations, reduce environmental impact, and boost quality of life [1,2]. While it has enhanced urban services, it is criticized for emphasizing technology, often ignoring systemic integration with circular resource flows and citizen participation [3,4].

In this context, the circular city has recently gained traction as an emerging urban typology that goes beyond efficiency to promote regenerative urban systems. A circular

city aims to incorporate the principles of the circular economy—such as reuse, recycling, regeneration, and value retention—into the urban metabolism, for example, by reusing building materials, recycling plastics and metals, or converting organic waste into compost, thus enabling cities to function not only as consumers but also as producers of resources through closed-loop systems [5,6]. These principles closely align with those of the 2030 Agenda and Sustainable Development Goal 11, which call for inclusive, safe, resilient, and sustainable cities [3].

According to the United for Smart Sustainable Cities (U4SSC) initiative, this transition requires reconfiguring the SSC model by integrating circularity in urban assets, services, and governance frameworks. The U4SSC guide to circular cities proposes a four-step implementation framework: establishing a circularity baseline, assessing the potential of circular actions, applying enablers to catalyze change, and evaluating impacts [7]. This approach moves beyond abstract principles by providing tools and templates to identify actionable circular strategies within specific city infrastructures, supported by enabling conditions such as data governance, stakeholder engagement, and innovation ecosystems [7].

This paper uses the following working definition of a circular city: "*A circular city is an urban system that integrates circular economy principles into its physical infrastructure, services, and governance mechanisms, aiming to decouple urban growth from resource consumption and environmental degradation.*" This definition aligns with the perspective of the U4SSC initiative, which highlights that circular cities encourage the regeneration of natural systems, the preservation of material value, and the implementation of closed-loop processes across urban assets and functions. Achieving this vision requires rethinking how cities produce, consume, and manage resources through circular economy strategies. It also involves leveraging enabling technologies and participatory governance to promote cross-sectoral circular practices [1,3,4].

Global initiatives have repeatedly highlighted the importance of aligning smart city innovation with sustainable urban development. The UN-Habitat World Cities Report emphasizes that digital transformation must go hand in hand with environmental and social progress to avoid increasing urban inequalities [8]. Similarly, the World Smart Cities Outlook 2024 points out that smart performance should be evaluated alongside sustainability outcomes, highlighting the need for integrated frameworks [9]. Comparative analyses, such as the multidimensional assessments of Taipei and Almaty, reveal an ongoing gap between smart indicators and actual sustainability performance [10]. Additionally, Shmeleva and Shmelev suggest multidimensional frameworks for assessing Smart Sustainable Cities, showing that integrated approaches are essential for capturing the complexity of urban transitions [11]. These insights highlight that, although considerable progress has been made in evaluating smart and sustainable cities separately, bridging the two remains a critical research challenge, which this paper seeks to address.

1.1. Problem Statement and Research Gaps

Despite the conceptual maturity in the literature, the practical implementation of circularity within smart sustainable city (SSC) architectures remains underdeveloped. This constitutes a fundamental problem facing cities: circular strategies are often disjointed, evaluation methods are limited, and comprehensive frameworks that connect the circular economy, digital infrastructure, and participatory governance are missing [1,3,4]. Addressing this problem motivates the purpose of this paper, which is to propose and validate an architectural model for a Sustainable, Smart, and Circular City (SSCC) that explicitly incorporates the waste–energy–information nexus.

Within this broader problem, three specific research gaps can be identified. First, the integration of circularity into the SSC paradigm remains unclear, as much of the lit-

erature treats circularity as a separate rather than an essential part of smart sustainable cities [1,3,5,6]. Second, the alignment between digitalization, circularity, and the energy transition is limited. While IoT, AI, and data analytics are recognized as enablers, their roles in actively supporting circular flows and resource regeneration are rarely incorporated into governance or design practices [1–4]. Third, systemic and measurable urban architectures are missing. Current models often focus on digital platforms or sector-specific solutions but fail to explain the interconnections between infrastructure, governance, and innovation ecosystems. Although the U4SSC framework provides a foundation, it still needs adaptation and validation through real-world testing, especially in Global South contexts [3,7]. These gaps highlight the core challenge that the SSCC architecture aims to address.

Despite these global efforts, studies still reveal a disconnect between smart and sustainable performance. The comparison between Taipei and Almaty shows how cities can improve smart infrastructure while falling short in sustainability outcomes, highlighting the absence of unified performance metrics [10]. Likewise, Shmeleva and Shmelev contend that only multidimensional frameworks can adequately capture the interaction among technological innovation, environmental sustainability, and social well-being [11]. These findings confirm that the lack of integrated approaches remains a key gap, emphasizing the need for models like the SSCC that explicitly link smart and sustainable dimensions.

1.2. Objectives

Building on the gaps identified above, this paper addresses the need to structurally embed circularity within the frameworks of sustainable and smart cities. It explores how cities can move beyond isolated technological or environmental interventions and adopt systemic architectures that support innovation and evaluation in the context of circular urban transitions. This objective is addressed through this specific research question:

> *How can a smart sustainable city architecture integrate the circular city components that enable innovation and evaluation in real urban contexts?*

To address this question, this paper proposes and validates a Sustainable, Smart, and Circular City (SSCC) architecture that explicitly incorporates the waste–energy–information nexus. The architecture consists of seven interconnected functional layers—Physical, Digital, Analytical, Participatory Governance, Data Strategy, Innovation Management, and Assessment—and is tested in the Urban Living Lab of Fenicia, Bogotá. This case study demonstrates how circular strategies can be activated through digital twins, urban experimentation, and collaboration among multiple actors. The originality of this research lies in validating an SSCC architecture that not only operationalizes the waste–energy–information nexus across these seven layers but also provides empirical evidence of how such an architecture can support the transition from Smart Sustainable Cities to Circular Cities.

2. Materials and Methods

This research uses a qualitative and design-oriented methodology to examine how sustainable, smart, and circular city architectures can incorporate the cycles of waste, energy, and information through physical, digital, and social elements. The study is divided into two main phases: a conceptual overview based on literature and reference models, and an empirical validation through an urban living lab (ULL) case study.

The conceptual synthesis of the SSCC architecture was achieved through a structured review of international standards and academic reference models, highlighting commonalities and gaps in integrating smart and circular city dimensions. These insights were incorporated into a seven-layer architecture explicitly designed to include the waste–energy–information nexus. To ensure the design's validity, the architecture was repeatedly tested against empirical requirements from the Fenicia ULL, where multi-actor workshops, partic-

ipatory feedback, and real-world constraints informed its operational feasibility. Internal validity was supported by aligning each layer with established frameworks and KPIs, while external validity was confirmed through two integrated experiments, demonstrating both the system's functionality and its adaptability to different contexts.

Figure 1 shows the method used in this study. It starts with creating a conceptual framework that combines parts from current sustainable, smart, and circular city models. Then, an empirical case study at Fenicia ULL is performed to test the proposed architecture. Data collection included two participatory experiments: (i) community- and drone-based waste reporting and (ii) IoT sensor monitoring in the urban garden for environmental factors. Although the dataset was limited, it was enough for initial testing, allowing AI-supported analysis, integration into a digital twin, and a readiness assessment. System behavior was also examined using participatory causal loop diagrams (CLDs), with evaluation metrics adapted from frameworks like LEED for Communities, focusing on waste, energy, and quality of life. This method enabled a systematic evaluation across different layers and a focus on the waste–energy–information nexus.

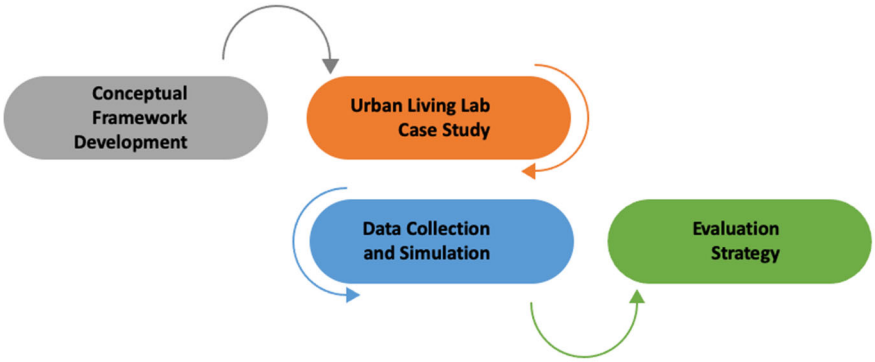

Figure 1. Methodological approach followed in this study.

3. Conceptual Framework Development

The first stage involved a structured review and synthesis of existing architecture models from smart, sustainable, and circular city paradigms. Key documents included international standards (e.g., ISO 37106:2021 [12]), technology integration frameworks (e.g., FIWARE, CPS/IoT architectures), and academic reference models. These models were compared and contrasted with the proposed SSCC architecture, highlighting complementarities, gaps, and opportunities for integration across physical infrastructure, sensor and data layers, digital modeling, governance, and assessment mechanisms.

3.1. Standards Based Foundations for Urban Architecture

The development of the SSCC architecture is based on international standardization efforts that aim to guide urban innovation toward sustainability, efficiency, and resilience. Two key references—the U4SSC initiative and the ISO 37106:2021 standard—provide structured pathways and operational models for the design and governance of smart sustainable cities.

The U4SSC initiative, coordinated by ITU, UNECE, and UN-Habitat, offers a four-step framework for implementing circular cities. This approach emphasizes: (1) establishing a baseline for urban circularity, (2) identifying and prioritizing circular actions across city assets and products, (3) deploying enablers to catalyze change, and (4) evaluating impacts using context-specific key performance indicators [7]. These steps are supported by tools and templates to streamline the assessment of urban circularity, covering areas such as energy, water, mobility, and waste.

Complementing this, ISO 37106:2021 introduces an operational model for digitally enabled smart cities, structured around four layers: (1) Leadership and governance, (2) Service and process integration (customer delivery), (3) Data and information management, and (4) ICT infrastructure. This operational model supports horizontal integration across urban services and vertical coordination among governance, data strategy, and infrastructure. ISO 37106 encourages cities to move from siloed operations toward a "digital by default" service model, ensuring that urban processes are interoperable, citizen-centered, and responsive [12]. In practice, this shift enables urban services like integrated waste and water management platforms, mobility-as-a-service systems that combine different transport modes, energy efficiency initiatives linked to real-time consumption data, and participatory governance portals for citizen feedback. These services show how the model goes beyond simply applying technology to existing structures: it redefines how urban services are delivered, making them cross-sectoral, adaptable, and accountable. Figure 2 illustrates this transition, highlighting how siloed urban services are reorganized through governance changes that emphasize transparency, stakeholder collaboration, and integration of internal city systems.

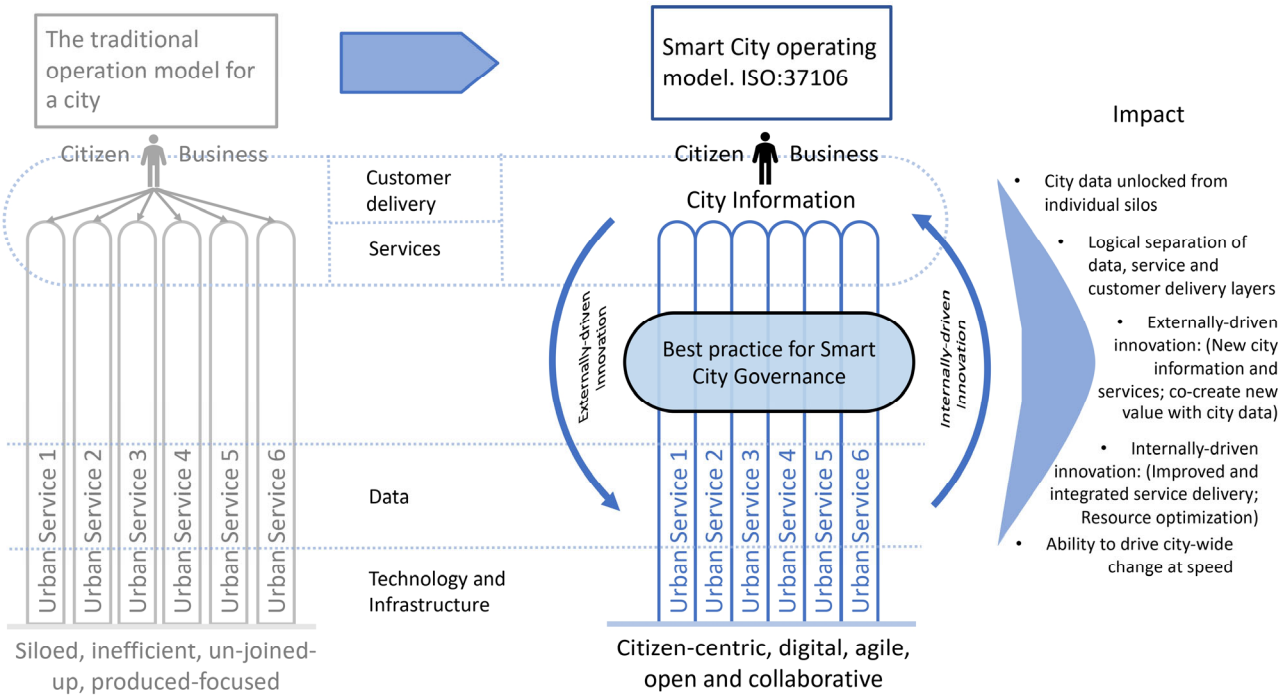

Figure 2. Transforming the city's operation model based on ISO 37106:2021.

Together, these frameworks outline both a strategic roadmap (U4SSC) and an operational architecture (ISO 37106) for implementing sustainable and smart urban systems. While U4SSC emphasizes sustainability transitions through circular actions, ISO 37106 concentrates on institutional transformation through digital capabilities. Their integration provides valuable guidance for constructing architectures that connect physical infrastructure, digital systems, and governance mechanisms—a foundational perspective for the SSCC model proposed in this study.

3.2. Academic Reference Models and Urban Architecture Definitions

The concept of smart city architecture in academic literature reflects a growing effort to organize urban complexity using clear frameworks. According to Anthopoulos [13], smart city architecture refers to "*the structured arrangement of digital and non-digital components that interact through services, data, and processes to support urban functionality*". This

definition highlights that architecture is not just a technological plan but a systemic setup of interconnected layers—physical, digital, social, and institutional—aligned with strategic urban goals.

Anthopoulos emphasizes two key roles of smart city architectures:

1. Operational integration, which ensures smooth interaction across physical infrastructure, data platforms, and user interfaces;
2. Strategic alignment, which connects technological deployments with urban priorities like resilience, inclusivity, and sustainability.

From an academic perspective, several reference models have been proposed to conceptualize smart city architectures. Anthopoulos' n-tier architecture model is one of the most influential, emphasizing a layered approach that includes data, infrastructure, interconnection, business, services, and user layers. This structure enables a modular and scalable design that supports both technological integration and governance needs [14].

Building on this vision, the Smart City Reference Architecture Model (SCRAM) proposed by Zygiaris [15] highlights the importance of planning ecosystems composed of green infrastructure, interconnected systems, instrumented platforms, applications, innovation layers, and governance. To integrate these two perspectives within our SSCC architecture, we adopt a layered approach where shared elements—such as data and infrastructure management, interconnection mechanisms, and governance functions—are aligned across both models. Key factors guiding this integration include interoperability standards (e.g., open APIs and data models), cross-cutting governance mechanisms that coordinate innovation and service delivery, and modular design principles allowing different layers to be adapted without disrupting the entire system. This approach ensures that both technological and governance aspects are incorporated while maintaining flexibility for validation through ULL experimentation.

Another perspective comes from enterprise architecture, as reviewed by Mamkaitis et al. [16], which applies the TOGAF Architecture Development Method (ADM) to classify smart city concerns into "why," "what," and "how." This framework helps organize technological and organizational processes in cities as enterprise-like systems, providing a structured approach for incremental development and integration [16].

Furthermore, the IDEAL-CITIES platform offers a trustworthy and secure framework designed for circular smart cities. Its architecture combines IoT, data security, resilience, and citizen participation into an operational backend made up of communication middleware, security mechanisms, and an application manager. It exemplifies how urban platforms can structurally embed circular economy and sustainability goals within smart city frameworks [17].

Additionally, there are some technical references like the FIWARE Reference Architecture, which proposes a modular, open-source model based on a Context Broker and the NGSI-LD data interface. It enables interoperability across domains—such as energy, mobility, and waste—by integrating IoT devices, open APIs, and semantic data structures [18]. In the SSCC architecture, energy is obtained from renewable sources at the community scale (e.g., solar modules in the urban garden), monitored through IoT sensors, and linked to demand management services. Waste is managed through participatory detection (community and drone imagery), classification using AI, and integration with municipal collection systems. These services are designed to be compatible with community needs by addressing daily concerns such as cleaner public spaces, efficient irrigation in the urban garden, and real-time feedback on service performance. Linking is achieved through the Context Broker, which enables waste, energy, and mobility data to flow across domains, supporting composite services like waste-to-alert systems or energy-to-irrigation control. Participation is integrated through Urban Living Labs (ULLs), where individuals contribute data, vali-

date system outputs, and influence service design. Meanwhile, the Cyber–Physical System (CPS)/IoT Architecture outlined by NIST emphasizes the coordination between sensing, actuation, computation, and communication [19], providing the foundational layers that support this physical-digital integration in real-time.

Together, these models highlight a common goal: to develop layered, interoperable, and adaptable architectures that handle urban complexity. However, they differ in emphasis. Some models focus on technical integration (e.g., FIWARE, CPS), while others prioritize institutional coordination (e.g., enterprise architecture, SCRAM) or normative principles (e.g., Ideal Cities). These models also lay the groundwork for analyzing and designing smart city architectures that are adaptable, inclusive, and capable of evaluation.

The SSCC architecture discussed in this paper extends these traditions by explicitly incorporating circularity as an urban function, evaluation, and innovation management. The next section explains the structure and reasoning behind the SSCC model in detail.

3.3. Proposed Architecture for Sustainable, Smart, and Circular Cities (SSCCs)

The proposed SSCC architecture responds to the limitations and biases identified in existing smart city models. While useful, most current frameworks either focus on technological management without fully incorporating circularity and sustainability principles or emphasize governance without the operational mechanisms needed for systemic change.

Additionally, SSCC architecture responds to the fragmentation and siloed implementation often seen in urban technology strategies.

The model's structure was developed through a synthesis process involving the following:

- An analysis of international standards like ISO 37106 and the U4SSC implementation pathway.
- A critical review of academic models focusing on interoperability, adaptability, and governance alignment.
- The identification of three interconnected systemic components of a nexus: waste, energy, and information, which define the metabolic, energetic, and informational cycles that a circular smart city must manage.

In operational terms, the SSCC architecture addresses the three identified nexuses with specific mechanisms. Clean energy is produced from distributed renewable sources, such as solar panels in community facilities and microgrids, which are monitored through IoT sensors to ensure pollutant-free supply and efficient distribution. Different types of waste are managed through complementary flows: organic waste is processed into compost for urban agriculture, recyclable materials are redirected into municipal and community recycling streams, and residual waste is tracked for collection through participatory detection and AI-supported classification. Information generated across these processes—such as energy production, waste detection, and service usage—is collected via IoT devices and citizen reports, standardized through open APIs, and integrated into the digital twin (a *digital twin* is a virtual replica of urban systems that mirrors their physical, social, and environmental dynamics in real-time to enable monitoring, simulation, and decision support). This ensures that data not only documents performance but also actively supports decision-making and ongoing adaptation across the different layers of the architecture.

This resulted in organizing the SSCC architecture into four core functional layers called Urban Functions, supported by cross-cutting layers that ensure strategic alignment and assessability, as shown in Figure 3.

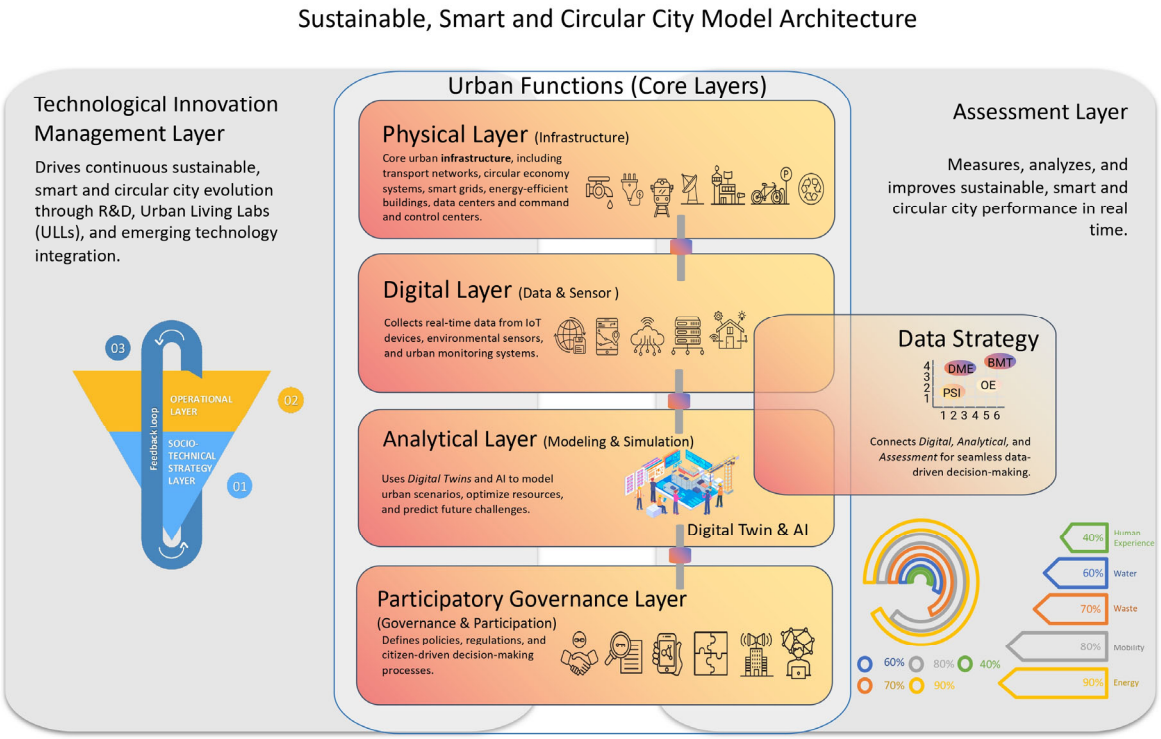

Figure 3. Sustainable, Smart and Circular City Model Architecture.

3.3.1. Urban Functions (Core Layers)

The SSCC model organizes the operational aspect of the city into four core layers, collectively known as Urban Functions. Each layer represents a key urban capability that supports the city's metabolism, manages urban services, and advances its transition toward sustainability and circularity. These functions are designed to be interoperable, not isolated, in line with the architectural principles outlined in ISO 37106 [12]. These layers form the structure of the city's operational dimension:

1. Physical Layer (Infrastructure Function):
   This layer encompasses the urban infrastructure systems that support the city's physical operations. It includes networks for energy, water, transportation, sanitation, and waste management, as well as essential digital infrastructure such as data centers and command-and-control centers. In the SSCC architecture, clean energy mainly originates from distributed renewable sources like solar panels on community facilities and microgrids, reducing dependence on fossil fuels and supplying pollution-free energy. Waste is managed through multiple streams: solid waste is reported via participatory methods and classified using AI; organic waste is composted in urban gardens; and recyclable materials (plastics, glass, metals) are diverted into municipal and community recycling processes. Data collected in this layer—such as real-time energy production, waste detection, and service usage—is made interoperable through IoT devices and open APIs, supporting higher layers of the architecture for monitoring, decision-making, and service enhancements. The Physical Layer serves as the tangible backbone of urban functionality and resilience, integrating civil and digital assets into a cohesive operational environment. Its inclusion addresses the need for physical–digital convergence and incorporates lessons from CPS and FIWARE architectures [13,16–18]. Unlike traditional urban infrastructure, which is often linear and resource-intensive, the Physical Layer in a circular smart city features regenerative and interconnected systems. Energy networks prioritize renewable sources like solar microgrids, reducing dependence on pollutants. Waste management shifts from end-of-pipe collection

to infrastructure that supports sorting, recycling, and composting at various scales. Transportation is improved not only by roads and transit lines but also through shared electric fleets and smart charging stations. Additionally, digital infrastructure is designed to seamlessly integrate with physical assets, enabling real-time monitoring and optimization via IoT and digital twins. This redesign distinguishes circular smart cities from conventional urban areas by embedding circularity and intelligence directly into their infrastructure's design and operation.

2. Digital Layer (Sensing and Data Acquisition Function):
The digital layer allows the city to perceive and record its state and processes. It includes IoT sensors, edge devices, user-reporting platforms, and telemetry systems that monitor key urban metrics like air quality, traffic flow, energy use, and public safety. Using standardized interfaces and real-time protocols (e.g., NGSI-LD), this layer gathers detailed data from the physical environment, ensuring observability and supporting situational awareness. Importantly, this online feature specifically applies to the Digital Layer and not the entire SSCC model. To prevent system failures, the layer has redundancy features such as distributed edge processing, local data buffering, and fallback procedures that enable services to keep running in degraded mode until connectivity is restored. Additionally, participatory reporting platforms provide an offline backup, ensuring critical information can still be gathered through community input. This design helps maintain system resilience even if parts of the digital infrastructure are temporarily offline. It thus serves as the essential input system for analysis and decision-support tools.
3. Analytical Layer (Modeling and Simulation Function):
This layer defines the city's ability to model, simulate, and predict outcomes using real-time and historical data. It combines digital twin environments, AI-based analytics, scenario simulators, and system dynamics models to assess impacts, forecast demands, and evaluate urban policy options. By turning raw data into strategic insights, this layer supports evidence-based planning, operational improvements, and adaptive governance. It functions as the intelligence core of the SSCC architecture.
4. Participatory Governance Layer (Coordination and Co-decision Function):
This layer organizes the institutional and collaborative processes through which the city involves stakeholders in co-design, oversight, and collective decision-making. It includes digital participation platforms, stakeholder engagement mechanisms, governance protocols, and interfaces for citizen science (e.g., ULLs) and deliberation. Its goal is to embed democratic legitimacy and local knowledge into the operation of all other layers, ensuring that the SSCC develops in a socially inclusive, accountable, and context-aware way.

These four layers interact dynamically, supported by the Innovation Management Layer, the Assessment Layer, and the Data Strategy.

3.3.2. Transversal Strategic Layers

Three more layers enhance strategic and operational consistency within the architecture:

1. Technological Innovation Management Layer:
This layer acts as the engine of ongoing urban development. Operated through Urban Living Labs (ULLs), this layer supports experimentation, evaluation, and scaling of socio-technical innovations. It encourages collaboration among academia, public agencies, communities, and startups, and connects innovation directly to urban value creation.
2. Assessment Layer:
This layer supports dynamic monitoring and assessment of performance at all lev-

els. It implements real-time and lagging KPIs within sustainable, smart, and circular city frameworks. In practice, evaluation combines live monitoring (through IoT data streams and dashboards) with structured self-assessments and progress reports created by various actors involved in service delivery. These reports may include institutional reviews, operator records, or participatory inputs when available, ensuring that information reflects both quantitative metrics and qualitative validation. Evaluation thus has a hybrid nature: automated indicators (e.g., ISO and LEED-based KPIs) are supplemented by reporting and review cycles from multiple stakeholders to ensure accuracy, transparency, and alignment with local priorities. The Assessment Layer facilitates adaptive governance by closing the loop between data collection, simulation, action, and learning. It primarily relies on KPIs for Sustainable Cities [20] and the Leadership in Energy and Environmental Design (LEED) rating systems [21], which measure improvements in urban services such as energy, water, waste, transportation, and human experience, in line with the UN Sustainable Development Goals.

3. Data Strategy Layer:
   This transversal layer acts as a strategic enabler throughout the entire SSCC architecture. Instead of being merely a technical component, the data strategy is viewed as a socio-technical planning tool that guides how urban data is collected, integrated, managed, and used to create value across different domains. This layer defines three primary functions:
   (i) Data acquisition: ensuring participatory and interoperable data flows from three main sources—sensor and IoT networks capturing environmental, energy, and mobility data; citizen inputs via reporting platforms and mobile apps; and institutional records like municipal databases or operator reports. The collection process uses open standards (e.g., NGSI-LD), APIs, and interoperability protocols to ensure consistency and comparability;
   (ii) Data processing: supporting structured analytics through AI pipelines, edge–cloud architectures, and semantic alignment. This includes anomaly detection, combining diverse datasets, and preparing real-time inputs for the digital twin, ensuring data streams are reliable and usable across layers;
   (iii) Data application: converting insights into informed decisions, operational improvements, and co-creating public services. Examples include dynamic waste collection routes, adaptive urban garden irrigation, and citizen dashboards that foster transparency and participation.

   Within the SSCC model, the data strategy layer supports four value creation mechanisms: Decision-Making Enhancement (DME), Operational Efficiency (OE), Product and Service Innovation (PSI), and Business Model Transformation (BMT). It connects the digital, analytical, and assessment layers while also incorporating principles of inclusivity, ethics, and data justice [22]. This placement ensures that data does not just support city functions but actively drives urban transformation, linking sensing, modeling, participation, and evaluation within a unified and adaptable governance framework.

3.3.3. Comparative Positioning Within the Smart City Architecture Landscape

To evaluate the uniqueness and added benefits of the SSCC architecture, a comparative analysis was performed against a selection of leading smart city models. These include academic frameworks, institutional and enterprise models, and technology-centric platforms. Each of these models provides valuable insights in areas such as interoperability, system integration, innovation support, or trust and security management.

However, the comparative review also highlights important gaps: most models lack built-in mechanisms for circularity, do not institutionalize innovation management, or treat evaluation as an external or ad hoc process. In contrast, the SSCC model positions sustainability, circularity, innovation, and evaluation as core architectural elements, implemented through clearly defined layers and interdependencies.

Table 1 summarizes the main differences and complementarities among these models, highlighting how the SSCC architecture builds on existing paradigms while addressing their structural limitations. This comparison supports the argument that the SSCC model provides a strong and scalable framework for managing complex urban transitions in a clear, participatory, and measurable way.

Table 1. Comparative positioning with key differences across models.

Model/ Framework	Main Focus	Key Layers/ Components	Circularity Integration	Evaluation Mechanisms
Anthopoulos n-tier	Layered architecture for ICT-enabled urban services and governance	Data, infrastructure, interconnection, business, services, users	Implied via sustainability, not explicit	Not central to model
Smart City Reference Architecture Model (SCRAM)	Innovation ecosystems and planning layers for smart cities	Green infrastructure, systems, platforms, apps, innovation, governance	Partially considered under sustainability goals	Implied via case studies and planning metrics
Enterprise Architecture (TOGAF-based)	Enterprise system modeling for incremental integration and governance	Business, application, data, technology (TOGAF ADM phases)	Not directly addressed	Enterprise KPIs and structured development phases
IDEAL-CITIES Framework	Secure and circular smart city architecture with IoT and citizen trust	Middleware, security layer, application manager, IoT/citizen interface	Explicit integration of circular economy principles	Security, trust, resilience metrics
FIWARE Architecture	Open-source, interoperable platform for smart cities with context data management	IoT agents, Context Broker (NGSI-LD), data/API management, digital twin integration	Dependent on use case; enables integration with circular services but not built-in	No inherent evaluation layer; depends on external dashboards or KPIs
NIST CPS/IoT Framework	Integration of cyber–physical systems with IoT for responsive, real-time city operations	Sensing, control, computation, communication, actuation	Not explicitly included; focus is on functional system interoperability and reliability	Focus on system performance, safety, and operational metrics; not sustainability KPIs
SSCC Architecture (Proposed)	Integration of sustainability, circularity, innovation and evaluation in urban systems	Physical infrastructure, Digital (sensors), Analytical (modeling/simulation), participatory governance, innovation management, data strategy, assessment	Core principle; waste-energy-information nexus articulated	Explicit assessment layer with sustainability and circular KPIs

4. Conceptual Framework for Transversal Layers: Integrating Innovation Management and Evaluation into the SSCC Architecture

The design of a Sustainable, Smart, and Circular City (SSCC) architecture requires cross-cutting components that support both innovation management and strong assessment mechanisms. While the core urban functions address the technological and participatory aspects of the system, these cross-cutting layers provide essential support for ongoing improvement and strategic alignment. In this section, we discuss two key cross-cutting layers: the Technological Innovation Management Layer and the Assessment Layer. Both layers build on our previous work on the Technological Innovation Model [23] and the multidimensional approach for assessing smart cities in developing countries [24].

4.1. Technological Innovation Management: Key Approaches

This layer provides the strategic and operational foundation for innovation management within the SSCC model. Based on the principles of Urban Living Labs (ULLs), it promotes collaborative, context-aware, and measurable urban innovation, addressing systemic urban challenges through co-creation, testing, and ongoing learning. The management of this layer is influenced by factors such as stakeholder engagement, institutional alignment, resource availability, and the maturity of tested solutions. Potential gaps—such as limited participation, weak institutional adoption, or barriers to scaling—are addressed through cycles of experimentation, feedback, and co-creation.

The innovation management model, as shown in Figure 4, integrated into this SSCC model layer, is structured around two interrelated domains.

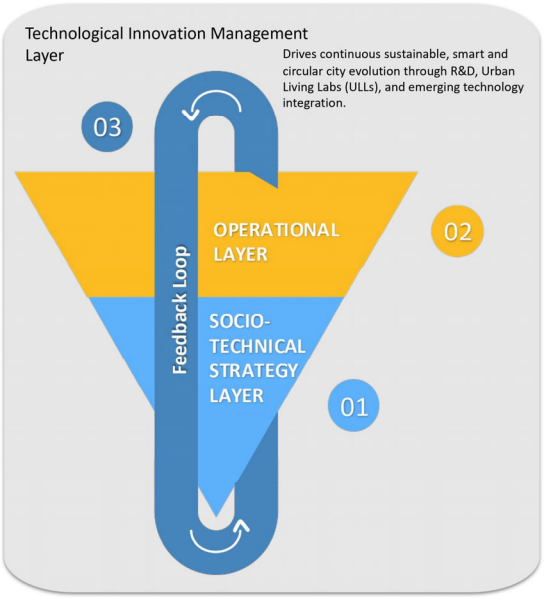

Figure 4. Technological Innovation Management Layer.

Strategic Layer: Establishes the vision and governance structures for urban experimentation. It aligns technological interventions with sustainability goals, encourages stakeholder participation, and institutionalizes ongoing evaluation. It incorporates five socio-technical strategies [25]:

1. Enhancing civic engagement through digital and analog co-design mechanisms;
2. Facilitating physical and virtual testing environments;
3. Establishing adaptive governance for collaborative coordination;
4. Linking technologies with the dynamics of real urban life;
5. Ensuring integration of scalable, smart solutions grounded in local realities.

Operational Layer: Implements strategies through designated roles (coordinators, creators, enablers, providers, users) and feedback systems that link experimentation with measurable results. It uses platforms like digital twins to facilitate real-time learning and establishes KPIs for quality of life, productivity, and ICT-driven sustainability.

The layer is informed by empirical insights from the Fenicia ULL in Bogotá, a pilot that exemplifies urban innovation amid institutional fragmentation, limited digital infrastructure, and social complexity. In this context, the innovation model supports adaptive processes, stakeholder alignment, and the integration of smart solutions—especially around the waste–energy–information nexus.

Furthermore, the Technological Innovation Management Layer turns the SSCC into a dynamic innovation ecosystem, ensuring that urban transformation remains not only technological but also inclusive, participatory, and sustainable over time.

Orchestrating the SSCC Model Through the Technological Innovation Management Layer

The Technological Innovation Management (TIM) Layer is essential for orchestrating the SSCC model, acting as the catalyst for systemic change. Instead of viewing innovation as an external or spontaneous force, the SSCC framework treats it as a controlled and coordinated process that connects experimentation, stakeholder involvement, and iterative learning with urban planning and service design.

This orchestration aligns with and strengthens the implementation guidance of both ISO 37106 and the U4SSC framework in the following ways:

Alignment with ISO 37106: ISO 37106 defines an operational model that facilitates the shift from siloed, analog systems to integrated, data-driven, and citizen-centered cities. The SSCC's innovation layer addresses several key components of this transformation:

- "Leadership and governance" by establishing adaptive, multistakeholder governance through ULLs;
- "Service and process integration" by enabling testbeds that align services and innovation with community needs and local infrastructure;
- "Data and information management" through the use of platforms like digital twins, which enable real-time monitoring, traceability, and collaborative simulation;
- "ICT infrastructure" involves using participatory technologies to involve users in the innovation process, turning infrastructure into a civic asset.

Alignment with U4SSC Framework: The U4SSC methodology outlines four steps: (i) establishing baselines, (ii) identifying and prioritizing circular actions, (iii) deploying enablers, and (iv) evaluating impacts. The SSCC's innovation layer directly supports this pathway.

- As a platform for experimentation, it supports Step 2, which involves identifying circular actions that are locally feasible and impactful (e.g., waste-to-energy pilots);
- Through Urban Living Labs, it functions as a city enabler (Step 3), speeding up innovation adoption and local adaptation;
- By incorporating monitoring and assessment mechanisms, it lays the groundwork for Step 4, where urban impacts are evaluated and strategies are improved.

Regarding evaluation, the TIM Layer supports a phased and iterative process that begins with preparation (designing pilots and assessing readiness), moves through experimentation (ULL-based testing), and advances into operational deployment and scaling. Evaluation is guided by indicators from international standards (ISO 37120, LEED for Cities/Communities) and readiness frameworks (TRL, SRL, ORL), ensuring comprehensive coverage of technological, social, and organizational components. In this way, the TIM Layer coordinates innovation processes and aligns them with governance frame-

works, while the Assessment Layer ensures that monitoring and validation are carried out systematically.

4.2. Smart Cities Assessment: Key Approaches

In developing countries, the assessment of smart cities has become increasingly important as cities adopt digital technologies to address major challenges like rapid urbanization, socio-economic inequalities, and sustainability. Implementing smart technologies in these regions holds the potential to greatly improve the quality of life and the efficiency of urban services, though it also presents unique challenges related to infrastructure and governance. According to Esashika [26], the evaluation of smart cities can be approached through several key frameworks. One approach focuses on ranking, comparing the performance of different cities using standardized indicators, while another assesses the maturity of smart cities by evaluating their level of technological adoption and public policy development. Additionally, the data-driven management approach emphasizes real-time management using big data, and the innovation ecosystem approach highlights collaboration among governments, academia, industry, and civil society to foster urban innovation.

These approaches, widely used worldwide, provide a solid foundation for evaluating the progress of smart cities. However, in developing countries, where social inequalities are greater and resources are scarcer, it is crucial to supplement these methods with an additional approach: Conscious and Inclusive Communities. This framework ensures that urban development is not only technologically advanced but also fair and participatory, focusing on the needs and realities of local communities as the core of the transformation process. Table 2 outlines the main features of each approach.

Table 2. Smart Cities Assessment.

Key Approach	Generalities
Ranking Approach	Based on rankings which compare the performance of cities based on standardized indicators such as mobility, governance, sustainability, and quality of life.
Maturity Approach	It classifies cities into stages, from early technology implementation to advanced integration of smart solutions.
Data-Driven Management Approach	Leverages technologies such as big data, IoT, and sensors to collect and analyze real-time data, optimizing urban services like mobility, waste management, and energy consumption.
Innovation Ecosystem Approach	Emphasizes collaboration between government, industry, and academia to drive urban innovation.
Conscious and Inclusive Communities Approach	Focused on ensuring that smart city development does not exacerbate social inequalities but instead promotes inclusion and equity.

The following section outlines these five key approaches, tailored to evaluating smart cities in developing countries, each providing a vital perspective for understanding and enhancing the urban transformation process in these areas.

4.2.1. Ranking Approach

The classification approach to smart city evaluation relies on the use of rankings, which compare the performance of cities based on standardized indicators such as mobility, governance, sustainability, and quality of life [27]. These rankings provide a quantitative snapshot of how cities perform in key areas of urban development, offering governments, policymakers, and stakeholders a clear view of where their cities stand in comparison to others. By identifying strengths and weaknesses in urban systems, this approach helps to pinpoint specific areas that require improvement, fostering more targeted policy interventions [28].

Several contemporary rankings evaluate smart cities, each with specific regional focuses and criteria. In Europe, the European Smart Cities Ranking by Giffinger et al. [29] continues to be influential, alongside the CITYkeys initiative, which prioritizes sustainability and innovation metrics [30]. Globally, the IMD Smart City Index (2023) and the Networked Society City Index by Ericsson [31] focus on holistic smart city metrics, including connectivity and citizen engagement. Other indices, such as the Smart City Index [32] and the IESE Cities in Motion Index 2023 [33], assess a city's performance across dimensions like mobility, governance, and quality of life, offering a comprehensive view of urban development.

In the context of developing countries, where cities often face significant disparities in infrastructure, technological capabilities, and governance, the classification approach serves as a particularly useful tool for benchmarking progress [28,34]. It allows cities to set clear, measurable goals and track their development over time relative to international standards. This is important for cities striving to enhance their global competitiveness while addressing critical challenges such as poverty, transportation inefficiencies, and energy shortages. Rankings also provide a means to promote transparency and accountability, as they allow citizens and stakeholders to assess the effectiveness of local governance based on visible, standardized criteria.

However, while the classification approach offers substantial benefits, it is not without challenges. In developing countries, there is often a lack of reliable and consistent data, which can undermine the accuracy and usefulness of rankings. Cities in these regions may struggle to collect the high-quality data necessary to measure performance across various indicators due to financial constraints, technical limitations, or insufficient administrative capacity. This data gap can lead to skewed or incomplete evaluations, potentially misrepresenting a city's actual progress or needs. Furthermore, the focus on measurable indicators can sometimes overlook critical qualitative aspects of urban life, such as social inclusion and community engagement, which are harder to quantify but equally essential to the success of smart city initiatives [35].

Despite these challenges, the classification approach remains a powerful tool for urban development in developing countries. It provides a structured, comparative framework that enables cities to benchmark their progress and set ambitious yet achievable targets. For governments, these rankings offer a roadmap to prioritize investments and reforms in areas where cities are lagging behind. Additionally, rankings serve as an important motivational tool, encouraging cities to improve their standing by implementing new policies, technologies, and governance strategies that address their specific shortcomings. The competitive nature of rankings can drive innovation, as cities seek to enhance their performance and visibility on a global stage [36].

In summary, the classification approach is highly valuable in promoting smart city development, especially in developing countries where the need for clear, actionable metrics is crucial. However, it must be adapted to the local context, with efforts made to improve data collection processes and account for qualitative dimensions of urban life. Despite its limitations, the visibility and accountability that rankings provide make them an indispensable tool for cities aiming to enhance their sustainability, governance, and overall quality of life.

4.2.2. Maturity Approach

The maturity approach evaluates a smart city's development by examining factors such as technological infrastructure, the adoption of public policies, and social engagement [37,38]. It classifies cities into stages, from early technology implementation to advanced integration of smart solutions. In developing countries, this approach helps

cities identify strategic priorities, focusing on infrastructure and regulatory frameworks to advance towards higher levels of smart city development [35,39].

By assessing a city's technological readiness and governance capacity, the maturity approach provides a roadmap for policy and infrastructure improvements. Early-stage cities might prioritize basic infrastructure such as internet access and urban sensors, while more advanced cities could focus on smart transportation systems and real-time data analytics [40].

This approach is particularly valuable for developing countries, as it highlights developmental gaps and enables cities to set incremental goals aligned with their current capabilities. Policymakers can use this framework to understand which policies or interventions are needed to transition from one stage to the next, such as strengthening governance structures or enhancing public–private partnerships.

Despite its benefits, the maturity approach faces challenges, particularly in developing regions, where financial and resource constraints, along with political instability, can slow progress. For this reason, the approach advocates a phased, long-term strategy, ensuring cities gradually build the foundations for a more advanced smart city ecosystem.

Ultimately, the maturity approach remains an essential tool for guiding sustainable and inclusive urban growth. By understanding where a city stands in its development cycle, urban managers can make more informed decisions, allowing for targeted interventions and tailored strategies that address both technological and social needs.

4.2.3. Data-Driven Management Approach

The data-driven management approach leverages technologies such as big data, IoT, and sensors to collect and analyze real-time data, optimizing urban services like mobility, waste management, and energy consumption [41]. This approach enables cities to make informed and efficient decisions, adjusting operations dynamically to improve both service delivery and urban quality of life. In developing countries, data-driven systems present significant opportunities to enhance efficiency and transparency, addressing challenges such as congestion, pollution, and resource management [42].

By integrating real-time technologies, cities can optimize systems like traffic flow and energy use, becoming more responsive and adaptable [43]. This approach allows cities to bypass traditional urban management methods, streamlining processes and reducing inefficiencies. For example, real-time data on waste collection can optimize routes, lowering fuel costs, while smart meters can help reduce energy waste.

Despite its potential, technological infrastructure remains a key challenge in developing countries. The installation of sensors and data platforms requires substantial investment, and even where infrastructure exists, data processing capacity and skills gaps may limit effectiveness. Data privacy and security concerns also arise, particularly in regions with weak regulations, where there is a risk of data misuse or dependency on large technology firms.

Nevertheless, the benefits of data-driven management for improving urban efficiency, cost savings, and citizen engagement are substantial. It offers cities the ability to monitor and adjust their operations in real-time, fostering sustainable urban growth and better meeting the needs of the population [44]. While challenges remain, data-driven approaches represent a crucial step toward smarter, more responsive cities, especially in developing countries.

4.2.4. Innovation Ecosystem Approach

The innovation ecosystem approach, based on the Triple Helix model, emphasizes collaboration between government, industry, and academia to drive urban innovation. Over time, this model evolved into the Quadruple Helix, adding civil society as a crucial pillar, recognizing the role that citizens play in shaping city development [45]. By involving

a broad spectrum of stakeholders, the model ensures that smart city solutions are not only technologically advanced but also aligned with the needs of the local population [46].

In developing countries, where technological and socio-economic barriers often exist, this approach is particularly important. Collaboration between sectors helps cities overcome challenges related to infrastructure, governance, and economic development. Governments provide regulatory support, industries offer technologies, academia supplies research, and civil society ensures inclusivity. Urban Living Labs (ULLs) exemplify this approach by engaging stakeholders—including citizens—in the testing and implementation of smart technologies, ensuring that innovations benefit all segments of the population, particularly the marginalized [47].

The innovation ecosystem approach operates on the principle that no single sector can address urban challenges alone. By fostering collaboration, it offers a holistic framework where each actor contributes unique capabilities to create sustainable and innovative solutions [48]. It also promotes the democratization of innovation, ensuring that citizens actively participate in the development of technologies that shape their cities.

However, the approach's success depends on effective coordination among stakeholders, which can be hindered by institutional silos, misaligned incentives, or a lack of trust. Cities must therefore promote inclusive governance frameworks that encourage open communication and shared accountability.

This approach is justified by its ability to create locally relevant and adaptable solutions, ensuring that smart city initiatives in developing countries become catalysts for broader transformation, not isolated experiments. The emphasis on collaborative learning ensures that smart city technologies are not only cutting-edge but also socially relevant and scalable to diverse urban contexts.

The innovation ecosystem approach is vital for developing smart cities, particularly in developing regions where challenges demand a collective effort. By fostering cooperation between government, industry, academia, and civil society, cities can co-create solutions that are inclusive, innovative, and sustainable, ensuring that technologies address the real needs of the communities they serve.

4.2.5. Conscious and Inclusive Communities Approach

The Conscious and Inclusive Communities approach, proposed as an original contribution of this study, focuses on ensuring that smart city development does not exacerbate social inequalities but instead promotes inclusion and equity [49–51]. This approach emphasizes the importance of involving local communities in all phases of smart city projects, from planning and implementation to governance. In developing countries, where inequalities are often deeper, this approach ensures that smart technologies address the real needs of marginalized populations, fostering urban development that is inclusive, culturally aware, and socially sustainable [50–52].

While other approaches prioritize technology, innovation, and institutional maturity, the Conscious and Inclusive Communities framework centers on people and communities as the core of the urban development process. The premise is that technology alone cannot solve urban problems unless the needs, active participation, and inclusion of citizens are considered [53,54]. The approach aims to mitigate urban inequalities, particularly in developing contexts, where smart city solutions, if not designed inclusively, risk worsening social divides. This approach ensures that the benefits of smart development reach all sectors of the population, especially the most vulnerable communities, which are often ignored in urban transformation processes [53,55].

The Conscious and Inclusive Communities framework promotes equitable and participatory development by fostering platforms where citizens are not only recipients of

technology but co-creators of solutions [51]. Conscious inclusion ensures that residents can express their needs, participate in decision-making, and ensure that urban development respects their interests, identities, and cultures [53,56]. Moreover, cities that empower their communities through active and conscious participation are more resilient to challenges such as social, economic, or environmental crises. This approach highlights the importance of aligning urban development with local realities, drawing on the knowledge and adaptability of communities to create solutions that truly reflect their needs [51,56].

The justification for this approach is grounded in the need to overcome criticisms of traditional smart cities, which often prioritize technological infrastructure and economic efficiency over social contexts or the needs of the population [57]. As noted by scholars, one of the key criticisms of traditional smart city projects is their tendency to focus on technology without addressing the human element of urban life [57]. The Conscious and Inclusive Communities approach responds to these critiques by ensuring that technological solutions promote equitable and participatory development, rather than exacerbating social inequalities.

In developing countries, where inclusion and equity are not optional but essential for the success of any smart city project [28], this approach ensures that smart cities improve quality of life not just for the wealthiest or most connected sectors but for all citizens. This is particularly important for the disadvantaged communities, which are often the most affected by technological changes if they are not involved in the process from the start. By embedding inclusion and equity as central pillars of smart city development, the Conscious and Inclusive Communities framework ensures that cities become more just and resilient.

Furthermore, this approach complements the other evaluation frameworks—Classification, Maturity, Data-Driven Management, and Innovation Ecosystems—by ensuring that smart city assessments also measure their social impact and their capacity to include all citizens, regardless of socio-economic status. While the other approaches offer useful models for measuring and managing smart cities, they do not explicitly address the critical issues of social equity and participation. The Conscious and Inclusive Communities framework fills this gap, providing a more holistic view of urban development that goes beyond technological innovation to focus on social well-being.

Finally, the Conscious and Inclusive Communities approach promotes a broader vision of smart cities. True urban intelligence does not only lie in technological efficiency but in a city's ability to create a just, inclusive, and resilient society. The success of a smart city should not be measured solely by its ability to innovate, but by its capacity to improve the lives of all its citizens, ensuring that no one is left behind. This approach calls for a more inclusive evaluation of smart city initiatives, where success is defined not just by innovation metrics but by the social, economic, and cultural progress of the entire population.

4.2.6. Multidimensional Evaluation Framework

To effectively evaluate smart city initiatives, especially in the context of developing countries, a multidimensional framework is necessary. Such a framework must be attuned to local specificities and capable of supporting both strategic alignment and operational performance. The assessment model must, therefore, be flexible enough to accommodate diverse urban realities while enabling decision-makers to understand how digital, participatory, and innovative elements influence sustainable development outcomes.

The Assessment Layer is designed to align with the strategic objectives previously used in evaluating urban experiments within the ULL framework, specifically: quality of life, productivity, and ICT sustainability. These objectives ensure continuity and coherence across the SSCC evaluation structure and support the comparability of performance results over time and among initiatives. Consistent with the guiding principles of the SSCC

model, this layer also emphasizes the interconnectedness of waste, energy, and information, positioning performance assessment not as a final step but as a dynamic process that both reflects and guides the city's transition pathways.

The evaluation approach used is organized around three primary strategic perspectives, each corresponding to particular layers in the SSCC architecture.

(a) Data-Driven Management Approach: This emphasizes how cities utilize digital technologies to enhance decision-making and improve services. It aligns with the SSCC model in the Digital Layer, Analytical Layer, and Data Strategy.
Data-Driven Management enables cities to create dashboards and simulations that inform policy development.

(b) Innovation Ecosystem Approach: This perspective focuses on how smart city projects create environments that support socio-technical innovation, collaboration, and entrepreneurship. It aligns with the SSCC model in the Technological Innovation Management Layer.
Innovation Ecosystem supports experimentation and rapid prototyping in ULLs.

(c) Conscious and Inclusive Communities Approach: This perspective highlights community participation, equity, and stakeholder engagement. It directly connects to the Participatory Governance Layer. Inclusive Communities helps identify barriers to participation and guides the development of fair governance frameworks.

These three approaches create a comprehensive framework for assessing smart city performance. They help in developing KPIs that are not only technical or operational but also social and inclusive.

The assessment framework proposes a multidimensional and inclusive approach that combines both quantitative tools—such as KPIs based on available data like energy usage, waste generation, or transportation efficiency—and qualitative tools, including participatory methods like focus groups, interviews, and co-design workshops that capture citizens' perceptions and experiences.

This structure supports ex ante assessment (e.g., before deploying a digital platform or service), ongoing assessment (e.g., tracking the adoption and impact of a smart waste management system), and ex-post assessment (e.g., measuring social inclusion outcomes after a participatory mobility planning process).

The adapted model highlights the following attributes:

- Inclusivity: Tools that capture diverse voices and community perspectives.
- Adaptability: Suitability for different urban settings and scalable from pilot projects to city-wide programs.
- Co-creation: A focus on KPIs created through participatory processes.
- Digital transparency: Utilization of open data and digital platforms to foster trust and promote accountability.
- Learning and iteration: Feedback loops that allow cities to evolve through evidence and citizen input.

This Assessment Layer is further enhanced by incorporating evaluation methodologies and indicators from complementary sources. The Arc and LEED for Cities and Communities frameworks provide a strong structure for measuring performance through quantifiable scores in areas like energy, water, waste, transportation, and human experience. These are especially useful for benchmarking environmental and livability performance across urban systems [58]. Additionally, the Sustainable Cities Handbook [20] introduces context-sensitive KPIs relevant to the Global South, especially for waste management and energy use, which closely align with the SSCC model's focus on circularity and transition.

Furthermore, the Data Strategy Layer highlights the importance of aligning data collection and management processes with evaluative goals, enabling the strategic use of urban data to inform both the simulation (Analytical Layer) and participation (Governance Layer). Together, these sources help operationalize the Assessment Layer as a dynamic, evidence-based, and participatory tool, connecting strategic urban goals to concrete metrics for sustainable, smart, and circular city performance. Table 3 presents the proposed multidimensional evaluation KPIs. These KPIs are indicative and can be adjusted according to the requirements of each urban service.

Table 3. Multidimensional Evaluation KPIs.

Dimension/Layer	KPIs [1]		
Technological Innovation Management Layer	Number of ULL experiments conducted per year	Rate of innovation adoption in urban services	Socio—Technical Innovation Readiness (Technological—TRL, Social—SRL, Organizational—ORL, Scalability—ScR)
Physical Layer	Energy use intensity (kWh/m^2/year) [LEED]	Solid waste diverted from landfill (%) [LEED]	Access to public transportation within 800m (%) [Arc]
Digital Layer	Real-time sensor coverage (% urban space)	Open data availability index	IoT data quality compliance rate
Analytical Layer	Simulation-to-decision integration rate	Predictive modeling accuracy (by urban service)	Use of scenario planning tools in policy design
Participatory Governance Layer	Citizen engagement rate in decision-making (%)	Inclusion index (gender, age, income representation)	Co-creation sessions held per year
Data Strategy	Data governance maturity score	KPI alignment with strategic objectives	Stakeholder accessibility to performance dashboards
Assessment Layer	Overall SSCC performance score	Cross-dimensional KPI dashboard coverage (%)	Number of domains monitored in real-time (Energy, Water, Waste, Transportation, Human Experience)

[1] These KPIs are indicative and can be modified based on the requirements of each urban service.

While international frameworks like LEED and Arc offer a common structure for evaluation, their direct application in developing countries is often limited by regional factors such as data access, institutional capacity, and infrastructure gaps. To address this, the SSCC model adds more context-specific KPIs, especially from the Sustainable Cities Handbook, which focus on waste and energy metrics tailored to the Global South. As a result, the evaluation follows the same general framework as in developed countries but includes adjustments to account for local constraints and opportunities. Furthermore, the innovation ecosystem perspective is operationalized by connecting data on multi-actor collaboration (e.g., participation records, institutional partnerships, co-created services) with performance indicators. This approach ensures the evaluation not only measures infrastructure or environmental results but also explores how governance, community, and innovation ecosystems interact to support sustainable, smart, and circular transitions.

4.2.7. Operationalizing the SSCC Model Through the Assessment Layer

The Assessment Layer is a vital component that enables the operationalization of the SSCC model by turning its conceptual framework into a results-oriented system. This is accomplished through a set of multidimensional KPIs that facilitate ongoing monitoring, benchmarking, and strategic alignment. Its design aligns with major international standards and frameworks that support the development of smart, sustainable cities.

This layer aligns with and supports the implementation guidance of both ISO 37106 and the U4SSC framework in the following ways:

Alignment with ISO 37106: ISO 37106 provides a framework for local governments to develop smart city operating models that are agile, transparent, and citizen-focused. The SSCC Assessment Layer helps implement this in the following ways:

- Performance-based management: The layer creates a clear system of indicators linked to city goals (e.g., quality of life, sustainability), allowing municipalities to shift from reactive to data-driven decision-making.
- Evidence-based evaluation cycles: These support ongoing improvement loops, as required in ISO 37106, allowing for iterative assessment of pilots and programs, especially in ULLs.
- Stakeholder participation: Using qualitative methods (e.g., co-design sessions, inclusive metrics) ensures the integration of user feedback, supporting the standard's call for inclusive and transparent governance.
- Cross-silo integration: KPIs are connected to various SSCC layers (e.g., digital infrastructure, innovation management), encouraging interdepartmental alignment and shared accountability related to different urban services—key principles of ISO 37106.

Alignment with U4SSC Implementation Framework: The U4SSC initiative offers a circular city implementation guide based on a four-step approach: (i) establishing baselines, (ii) identifying and prioritizing circular actions, (iii) deploying enablers, and (iv) evaluating impacts. The SSCC Assessment Layer aligns accordingly.

- Baseline establishment: Using multidimensional KPIs enables cities to evaluate their current status in areas such as waste, energy, water, and mobility—reflecting U4SSC's Step 1.
- Action prioritization: By mapping indicators to strategic objectives (e.g., productivity, sustainability), this layer enables informed prioritization of circular and digital actions.
- Enabler integration: The Assessment Layer uses tools like data governance protocols and open dashboards, which are defined in U4SSC as enablers for scaling action.
- Impact measurement: It offers a framework for continuous outcome evaluation using internationally benchmarked indicators (LEED, Arc), directly addressing Step 4 of the U4SSC model.

The Assessment Layer not only adheres to the guidelines of ISO 37106 and U4SSC, but also acts as a bridge between the strategic vision of the SSCC model and its practical application, making urban innovation cycles measurable, repeatable, and adaptable to different urban contexts.

5. Results

This section outlines the main empirical findings from implementing the SSCC model in the Fenicia ULL. A key insight from the research is that experimenting in isolation—focused on just one urban service—would not be enough to confirm the integrated vision proposed by the SSCC architecture.

Instead of trying to optimize waste management, energy systems, or information flows separately, the SSCC model aims to show how these elements connect through physical, digital, and social infrastructure. As a result, two coordinated experiments were created and implemented to put into practice and test the waste–energy–information nexus in real urban environments.

- Experiment 1 focused on AI-driven waste management in the neighborhood, using drone imagery, smartphone data, and community reports to locate, classify, and address waste. In this pilot, the AI model was trained and validated specifically to

detect plastic bottles, which served as a representative category of recyclable waste. Community members submitted geotagged photos via a mobile platform, along with brief descriptions to report waste observations. Reports were verified by cross-checking submissions with drone imagery and manual validation by researchers in the Urban Living Lab. Although limited to one waste type, this process showed how AI detection, participatory reporting, and verification can be combined to support urban waste management, while also emphasizing the need to expand classification to other categories in future iterations.

- Experiment 2 assessed the socio-technical innovation of an urban garden equipped with solar-powered IoT sensors to monitor irrigation needs and explore ways toward energy self-sufficiency. The sensors tracked soil moisture, air temperature, and solar radiation, sending data to a cloud platform for real-time monitoring. Community members participated in the system through workshops and demonstrations, providing feedback on usability and the relevance of the information produced. Sensor data verification involved comparing automated readings with manual soil checks conducted by researchers. Although the pilot did not advance to a fully automated irrigation system, it showed how IoT and renewable energy can support participatory monitoring and raise community awareness of sustainable practices.

While each experiment has individual value, it is only when they are considered together—sharing data infrastructure, involving the same communities, and feeding into a common digital twin—that the model's transformative capacity becomes clear. The shift from siloed urban services to an integrated, circular ecosystem, as proposed by the SSCC architecture, requires this cross-experiment coordination. This section examines how each experiment helps validate specific layers of the SSCC model and how their integration supports systemic urban transformation.

Following this reasoning, the connection between both experiments was intentionally designed to prevent fragmentation and instead show how different urban interventions can work together as parts of an integrated sustainable system. This integration was organized according to the layered structure of the SSCC model, allowing a thorough validation of the waste–energy–information relationship through five main dimensions.

1. Shared physical infrastructure: Both experiments operate within the same urban area—the Fenicia neighborhood—and are connected via a common digital twin platform that spatially integrates waste reporting data, sensor-based monitoring, and geolocated intervention results. The neighborhood thus serves as a central point for multiple urban functions.
2. Common technological innovation layer: The two experiments use complementary emerging technologies. The waste management pilot applies AI for image classification and geolocation, while the urban garden incorporates IoT sensors powered by solar panels to monitor irrigation cycles. Both are integrated into the digital twin and designed to feed real-time data into participatory decision-making workflows.
3. Participation and governance layer: Residents and local actors (government, academia, civic organizations, and startups) are involved in both initiatives. Community members report waste via mobile platforms and take part in workshops to co-design and evaluate the urban garden sensor system. This shared participation not only boosts legitimacy but also supports the model's focus on inclusive governance.
4. Assessment layer: Key performance indicators (KPIs) from both experiments were designed to follow international standards like ISO 37106, U4SSC, and LEED for Communities. Metrics such as energy self-sufficiency, quality of life, waste reduction, and citizen engagement were used to track progress and evaluate replicability.

5. Scalability and replication potential: The modular design of both pilots enables them to be adapted to other urban settings. More importantly, their integration within the SSCC framework shows how cities can move from isolated pilots to scalable, system-wide solutions that connect environmental, technological, and social areas.

Together, these elements strongly support the SSCC model's main idea: that sustainable urban change needs not just new technologies, but also their coordination within a shared system that can connect services, infrastructure, and governance. In practice, this means sustainable transformation happens through specific services—like AI-assisted waste detection, IoT-based environmental monitoring, and participatory reporting—that turn abstract ideas of circularity into practical improvements for communities. Artificial intelligence helps these services by enabling automated classification, geolocation, and real-time feedback, thus linking digital abilities with real service delivery.

The validation of the SSCC model does not depend on testing each architectural layer separately, but instead on observing how these layers work together and support each other in real urban settings.

Table 4 explains how each SSCC model layer was implemented through the integrated experiments. It shows how the Physical and Digital Layers supported data collection, the Analytical Layer turned data into insights, the Participatory Governance Layer connected communities, the Data Strategy Layer ensured data compatibility, the Technological Innovation Management Layer coordinated experimentation, and the Assessment Layer carried out evaluations.

Table 4. Empirical evidence from Integrated Experiments.

SSCC Model Layer	Empirical Evidence from Integrated Experiments	Evaluation Ratio
Technological Innovation Management Layer	Application of the ULL based socio-technical innovation model in both experiments, using iterative design, multi-actor coordination, and testing in real-life settings.	High. (Social Readiness) SRL 7/(Organizational Readiness Level) ORL 5—Strong socio-technical engagement, moderate institutional uptake. Validated through continuous feedback loops and alignment with ISO 37106 operational guidance.
Physical Layer	Infrastructure of the Fenicia neighborhood used for both experiments; urban garden equipped with solar-powered IoT sensors; drones for photogrammetry-based 3D modeling.	Moderate. Tested in limited urban assets; infrastructure performance assessed mainly via pilot IoT and drone applications. Technological Readiness Level (TRL 6–7)—IoT prototypes tested in real context; drones validated for 3D mapping.
Digital Layer	Citizen-generated images (via smartphones and drones); sensor data from humidity, temperature, and solar radiation modules; data structured via FIWARE Smart Data Models.	High. Real-time acquisition validated; TRL 7—Validated in operational environment; interoperability tested through FIWARE standards.
Analytical Layer	Digital twins developed for both experiments: one for spatial waste accumulation simulation, another for agro-environmental monitoring and energy analysis in the urban garden	Moderate–High. Functionality of digital twins validated for visualization and analysis; predictive capacities still limited due to small datasets.
Participatory Governance Layer	Co-design sessions, structured feedback loops, and community sensing strategies; ongoing involvement of citizens in reporting, validation, and scenario planning.	High. (Social Readiness) SRL 7; Active community participation and validation; alignment with U4SSC inclusivity.

Table 4. *Cont.*

SSCC Model Layer	Empirical Evidence from Integrated Experiments	Evaluation Ratio
Data Strategy	Operationalized across acquisition, processing, and application domains; integration via Orion Context Broker, QuantumLeap, CrateDB; value created through mechanisms: Decision-Making Enhancement (DME), Operational Efficiency (OE), Product and Service Innovation (PSI), and Business Model Transformation (BMT).	Moderate. Interoperability validated; value creation mechanisms partially demonstrated in pilots; comprehensive integration still pending scaling.
Assessment Layer	KPI tracking aligned with ISO 37106, U4SSC, LEED for Communities; measuring Quality of Life, Productivity, and ICT-based Sustainability.	Moderate–High. KPIs defined and applied; coverage of sustainability dimensions validated, though benchmarking limited to pilot scale.

Note: Evaluation ratios combine quantitative results (e.g., TRL, SRL, ORL) with qualitative scales (Low, Moderate, High) derived from readiness frameworks and empirical validation in the Fenicia ULL. They are intended to be indicative rather than definitive, reflecting the pilot nature of the experiments.

The coordinated implementation of waste management and urban garden experiments thus shows the shift from isolated urban services to interconnected, circular city functions.

5.1. Waste Management Experiment: Validating Integrated Urban Intelligence

This section introduces the first experiment conducted at Fenicia ULL, which focused on developing a cyber–physical system (CPS) for participatory urban waste management over a one-month period from May to June 2025. The CPS integrated three types of data sources: (i) drone imagery for aerial identification of waste hotspots, (ii) photos uploaded by community members via a mobile platform, and (iii) geotagged annotations by researchers. The AI module was specifically trained to detect plastic bottles as a representative recyclable waste category. The CPS utilized multiple SSCC layers by combining physical sensing (Digital Layer), AI-based classification (Analytical Layer), participatory reporting (Governance Layer), and iterative validation through the ULL (Innovation and Assessment Layers). In this way, the CPS enabled not only automated waste detection but also verification and feedback from multiple stakeholders, demonstrating the feasibility of integrating cyber systems into circular waste management practices.

Figure 5 depicts the digital twin architecture developed for the Fenicia ULL waste management experiment, which, as shown in Figure 6, includes spatial data generation, citizen input, artificial intelligence, and geovisualization to enable the detection, simulation, and strategic planning of street-level waste.

5.1.1. Objectives of the Waste Experiment

The main objective of this experiment was to design, deploy, and validate a participatory CPS capable of identifying, classifying, and responding to solid waste accumulation in urban public spaces. The system aimed to achieve the following:

- Integrate citizen-generated and drone-acquired imagery.
- Process visual data using an AI model for waste classification and localization.
- Input data into a digital twin for real-time spatial visualization.
- Establish feedback and response systems at the institutional and community levels.

This directly supports the SSCC model's goal of moving from isolated public services to integrated, data-driven urban functions.

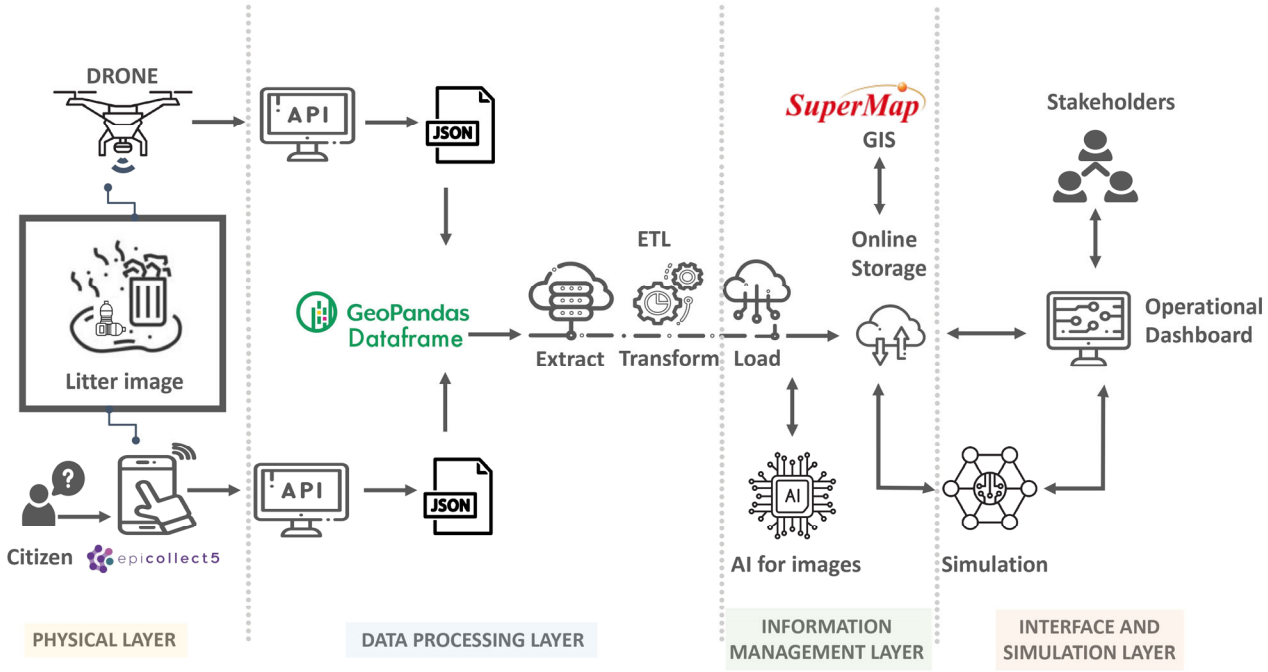

Figure 5. Digital Twin Architecture.



Figure 6. A neighbor taking a picture of litter using Epicollect 5, processed with AI, and visualized with a digital twin.

5.1.2. Methods and Implementation of the Waste Experiment

The system architecture consisted of the following:

1. A data collection interface through Epicollect5 v 86.2.1 for community members to geolocate and photograph waste incidents.
2. Drone flights to capture high-resolution aerial images.
3. A YOLOv5-based AI model trained to accurately detect different waste categories (100% precision; 81.1% recall).
4. A digital twin platform built with SuperMap GIS to visualize waste hotspots and aggregate temporal data.
5. A dashboard built with Grafana and FIWARE components (Orion Context Broker, QuantumLeap, CrateDB) to facilitate monitoring and data analysis.

Participation was encouraged through co-design sessions with residents, workshops with local government officials, and the incorporation of institutional responses from the UAESP (Bogotá's waste management authority).

5.1.3. Key Findings of the Waste Experiment

The main key findings are as follows:

- The system demonstrated low-latency information flows (<10 min) between data collection and visualization;
- Over 30 georeferenced reports were gathered from local residents using Epicollect5 v 86.2.1.
- The digital twin enabled multi-scalar decision-making, supporting both neighborhood-level response and institutional planning;
- The experiment confirmed the potential of open-source, low-cost architectures for smart waste systems in the Global South.

5.1.4. Validation and Contribution of the Waste Experiment

Table 5 presents the validation of the components in the experiment related to the SSCC model.

Table 5. Validation of SSCC Layers for Waste Experiment.

SSCC Model Layer	Validated Component in the Waste Experiment	Integration in Validation
Technological Innovation Management Layer	Iterative design under ULL principles; integration of academic, public, and community actors; real-environment testing of socio-technical system.	Integrated—Multi-actor coordination and iterative cycles connected to CPS deployment.
Physical Layer	Infrastructure of the Fenicia neighborhood used for experiment.	Non-integrated—Contextual infrastructure was used but not part of system-to-system integration.
Digital Layer	Image classification using YOLOv5 (100% precision, 81.1% recall); community sensing via smartphones; drone-based image acquisition.	Integrated—All digital inputs (AI, drones, smartphones) connected through data pipelines.
Analytical Layer	Real-time spatial modeling of waste hotspots; integration into SuperMap-based digital twin; dashboards built with Grafana and FIWARE stack.	Integrated—Outputs directly connected to Digital Layer inputs and governance dashboards.
Participatory Governance Layer	Community-generated data via Epicollect5 v 86.2.1; structured feedback mechanisms; institutional engagement with UAESP.	Integrated—Citizen reports and institutional validation linked to CPS workflows.
Data Strategy	Full data flow from acquisition (drones, smartphones) to processing (YOLOv5, FIWARE stack) and application (dashboard, institutional response); activation of value strategies: DME (waste hotspot detection and response planning), OE (automation of data capture and classification), and BMT (exploration of AI-based waste services as innovation layer for urban sanitation systems).	Integrated—Demonstrated end-to-end pipeline from collection to application.
Assessment Layer	KPIs aligned with ISO 37106, U4SSC, and LEED: improved cleanliness perception, reduced time-to-response, increased citizen engagement.	Partially Integrated—KPI tracking applied to outputs of Digital and Governance Layers, but limited to pilot scale.

The experiment's results clearly demonstrate progress toward the three strategic objectives outlined in the SSCC model.

1. Quality of Life: Enhancing urban cleanliness and citizen satisfaction through increased visibility of city efforts and community involvement.
2. Productivity: Improving waste collection processes and using spatial intelligence to support more efficient institutional planning.

3. ICT-Based Sustainability: Utilizing scalable, open-source technologies like FIWARE, Grafana, and SuperMap; focusing on interoperability and accessibility in low-resource urban environments.

While further iterations are needed to solidify the results, the pilot confirms the core ability of the SSCC architecture to support integrated, circular, and data-driven public service transformation. Although, the real-time visibility of waste flows combined with geospatial tagging offers key insights for resource planning and potential material recovery strategies.

5.2. Urban Garden Experiment: Enabling Local Circularity and Energy-Aware Sensing

This section examines the second experiment conducted within the Fenicia ULL, which centers on implementing an urban garden as a socio-technical platform for community engagement and assessing a solar-powered IoT system for environmental monitoring. This experiment highlights the integration of information, energy, and community participation.

Figure 7 displays the IoT FIWARE architecture for Fenicia ULL urban garden, including the smart data model. Figure 8 presents a 3D digital twin visualization of the urban garden and the solar-powered IoT system for environmental monitoring.

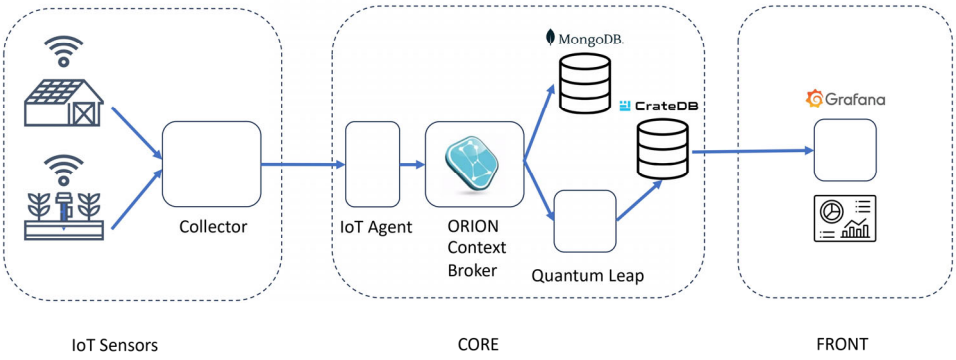

Figure 7. IoT FIWARE Architecture for Fenicia ULL Urban Garden.



Figure 8. Digital Twin 3D Visualization and solar-powered IoT system for Fenicia ULL Urban Garden.

5.2.1. Objectives of the Urban Garden Experiment

The urban garden experiment was designed to achieve the following objectives:

- Implement and verify a low-cost, energy-independent IoT system for environmental sensing (e.g., soil humidity, solar radiation, temperature) in urban agriculture.
- Visualize and control environmental conditions using digital twin technologies integrated with FIWARE and Smart Data Models.

- Evaluate the maturity of innovation across four complementary dimensions: Technological (TRL), Societal (SRL), Organizational (ORL), and Scaling (ScR).
- Facilitate knowledge transfer and community ownership through participatory design, dashboard interaction, and engaging stakeholders.

The pilot acts as a testing platform for integrating energy, information, and community management within a circular urban system.

5.2.2. Methods and Implementation of the Urban Garden Experiment

The experiment was designed using a layered socio-technical model organized into three main phases:

1. Technological Development: Solar-powered IoT sensors measured UV radiation, soil moisture, and temperature. The data were structured via NGSI-LD and processed using Orion Context Broker, QuantumLeap, and CrateDB, with visualization in Grafana and SuperMap digital twin. The FIWARE AgriApp Smart Data Model was adopted for semantic interoperability.
2. Participatory and Co-Design Activities: Workshops facilitated interface adaptation and data interpretation training. Community members proposed new sensor functions and dashboard designs.
3. Readiness Level Evaluation: A TRL-SRL-ORL-ScR framework was applied to assess the innovation's maturity and scalability, serving as a key component of the SSCC model's Assessment Layer.

5.2.3. Key Findings of the Urban Garden Experiment

The main key findings are as follows:

- The system demonstrated stable performance for over 30 days of continuous environmental data collection powered by the energy grid and solar energy;
- Participants showed strong acceptance and interest, especially when able to visualize data on dashboards and maps;
- The use of standardized data models and open-source platforms confirmed the feasibility of replicability and interoperability within smart territory frameworks;
- The project showed potential for future integration with organic waste reuse (e.g., composting) and closed-loop water-energy systems.

5.2.4. Validation and Contribution

Table 6 displays the validation of components in the experiment related to the SSCC model.

Table 6. Validation of SSCC Layers for Urban Garden Experiment.

SSCC Model Layer	Validated Component in the Waste Experiment	Integration in Validation
Technological Innovation Management Layer	Iterative prototyping within the ULL; validation from TRL 4 to TRL 7; use of open-hardware by startup ORUS.	Integrated—Orchestrated innovation cycles directly linked with TRL evaluation and ULL feedback.
Physical Layer	Urban garden space equipped with environmental sensors and autonomous solar energy system.	Integrated—Physical assets directly connected to digital sensing and analytical layers.
Digital Layer	Real-time sensor data acquisition (humidity, temperature, radiation); structured via Smart Data Models for agriculture.	Integrated—Sensor outputs connected to FIWARE context broker and data strategy workflows.

Table 6. *Cont.*

SSCC Model Layer	Validated Component in the Waste Experiment	Integration in Validation
Analytical Layer	Time-series dashboards (Grafana); data visualized in SuperMap digital twin for simulation of environmental trends.	Integrated—Outputs validated through visualization and simulation linked to Digital Layer inputs.
Participatory Governance Layer	Participatory design of interface; community training; co-creation of KPIs; involvement of Botanical Urban Garden of Bogotá (Jardin Botánico de Bogotá—JBB) and startup ORUS.	Integrated—Direct co-creation and feedback loops with institutional and community actors.
Data Strategy	End-to-end data integration using standardized models (FIWARE, NGSI-LD, AgriApp); activation of value strategies: DME (irrigation decisions), OE (sensor performance optimization), and PSI (co-designed services and visualizations with community and public actors).	Integrated—Demonstrated complete data pipeline from acquisition to application.
Assessment Layer	Full application of TRL, SRL, ORL, and ScR dimensions: TRL 7, SRL 7, ORL 5 (both ORUS and JBB), ScR 4.	Integrated—Multi-dimensional readiness evaluation embedded in the pilot validation.

The pilot confirms meaningful alignment with the SSCC strategic pillars:

1. Quality of Life: Promotes food sovereignty, environmental awareness, and access to green infrastructure.
2. Productivity: Facilitates data-driven irrigation, energy independence, and planning for crop cycles and climate adaptation.
3. ICT-Based Sustainability: Utilizes affordable sensing, solar power, open-source software, and standardized data to promote interoperability and replicability.

5.3. Integrated Validation of the SSCC Architecture: From Silos to Systemic Urban Services

The coordinated implementation of the waste management and urban garden experiments in the Fenicia ULL offers strong empirical support for the SSCC model as a layered and integrative urban framework. Each experiment, while separately addressing a specific issue—waste buildup and sustainable food production—was designed and carried out in a way that aligns with the main hypothesis of the SSCC framework: that sustainable urban transformation requires the integration of physical, digital, social, and data infrastructures to provide circular, intelligent, and participatory public services.

The articulation of both experiments reveals a shift from isolated service delivery to connected urban services.

- Shared Data Infrastructure: Both pilots used a common data ecosystem based on FIWARE standards, allowing interoperability and the creation of a unified digital twin platform that supports multisectoral monitoring.
- Community as a Cross-Cutting Actor: Residents participated in both waste reporting and the co-design of the urban garden sensing platform, demonstrating the potential of community engagement as a unifying element that enhances social legitimacy, responsiveness, and data quality.
- Strategic Alignment of KPIs: The evaluation of both experiments was conducted using KPIs focused on Quality of Life, Productivity, and ICT-based Sustainability, aligned with ISO 37106, LEED for Communities, and U4SSC frameworks. This confirms the feasibility of applying standardized, integrated evaluation tools across various urban functions.

- Operationalization of the Waste–Energy–Information Nexus: While the waste experiment concentrated on information-based planning for sanitation services and the garden experiment focused on decentralized energy and environmental sensing, their combined design envisions a future where waste reuse (such as composting and bioenergy) and energy-efficient irrigation are integrated into a closed urban metabolism.

Through the coordinated deployment of these experiments, all seven layers of the SSCC architecture were operationalized and evaluated, with clear results that demonstrate the feasibility of multisectoral integration; the adaptability of the architecture to local conditions; and the creation of measurable value via the data strategy layer, through DME, OE, PSI, and BMT mechanisms.

The transition from siloed service management to systemic, circular urban innovation is not only conceptually articulated but empirically validated through layered interaction. This positions the SSCC model as a scalable and evaluable framework capable of guiding urban transformations beyond pilot settings.

6. Discussion

The SSCC model introduced in this work provides a response based on both conceptual development and empirical validation. By designing and executing two integrated experiments in the Fenicia Urban Living Lab, we demonstrate how a layered urban architecture can support a systemic shift toward sustainable, smart, and circular cities.

The findings reveal that the SSCC model addresses three gaps identified in the literature. First, it demonstrates the conceptual integration of circularity into the SSC paradigm by embedding the waste–energy–information nexus into urban infrastructures. Second, it achieves operational alignment between digitalization, circularity, and energy transition through the use of AI, IoT, and FIWARE, illustrating how digital tools can strengthen circular strategies. Third, the SSCC architecture is shown to be modular, scalable, and evaluable, with all seven layers activated and validated against international standards (ISO 37106, U4SSC, LEED). Overall, these results highlight the potential of layered architectures to support systemic and measurable circular transformations in real-world settings.

An additional contribution involves integrating readiness frameworks (TRL, SRL, ORL, ScR) with KPI systems (ISO, U4SSC, LEED). This approach not only enables a comprehensive evaluation of the experiments but also enhances the model by aligning technical validation with international benchmarking standards.

While the Fenicia ULL provided a fertile environment to validate the SSCC model, the findings should be approached with caution regarding their generalizability. The layered architecture and its alignment with international standards (ISO 37120, ISO 37106, U4SSC, LEED) indicate that the conceptual framework can be applied across different contexts. However, specific experimental conditions—such as the scale of a neighborhood-level ULL, active participation of a local community, and the technological infrastructure in Bogotá—may limit direct transferability. Therefore, replicating this in other settings will require adjustments to fit the local environment, especially in larger metropolitan areas or cities with different governance structures and resource capacities. The validation presented here should be seen as a case study offering methodological insights and a replicable framework, but it needs further testing before broader use. Future research should replicate this case study in other urban areas to assess scalability and adaptability across various socio-technical and institutional conditions.

7. Conclusions

This study aimed to answer a key research question:

How can a smart sustainable city architecture integrate the circular city components that enable innovation and evaluation in real urban contexts?

This study aimed to validate a Sustainable, Smart, and Circular City (SSCC) model that integrates circularity into the smart sustainable city framework through layered architectures and Urban Living Lab experimentation. The results confirm that the proposed model offers both conceptual and practical benefits, supporting the transition from Smart Sustainable Cities (SSCs) to Circular Cities (CCs).

First, the research shows that the SSCC model provides a validated reference architecture. All seven layers—Physical, Digital, Analytical, Participatory Governance, Data Strategy, Technological Innovation Management, and Assessment—were activated and tested in real-world conditions. This thorough validation confirms the model's robustness and flexibility, demonstrating that layered architectures are effective tools for organizing complex socio-technical systems.

Second, the experiments demonstrate the feasibility of the SSC–CC transition. The waste–energy–information nexus serves as a clear link between the two paradigms, showing how circular practices (waste detection, participatory monitoring, resource optimization) can be incorporated into smart infrastructures supported by AI, IoT, and digital twins. This provides real-world evidence that transitioning to circularity is not just an ideal but also an achievable path when guided by systemic models.

Third, the research highlights the importance of ULLs in supporting sustainable urban transformation. The Fenicia ULL proved to be a productive environment for co-creation, validation, and iterative design, involving academic, government, community, and private stakeholders in experimentation. This demonstrates that ULLs can serve as both innovation testbeds and governance tools, bridging the gap between technological innovation and societal acceptance.

Fourth, the study makes a methodological contribution by integrating readiness frameworks with international KPI systems. This combined approach enables both systemic evaluation with standardized KPIs and context-aware validation through readiness levels, making the SSCC model adaptable to diverse urban settings, especially in developing countries where institutional and infrastructural challenges require flexible assessment methods.

Fifth, the validation confirms that the SSCC model is scalable and can be replicated. Although the experiments were conducted in Fenicia's pilot environment in Bogotá, the layered architecture provides a modular framework that can be adapted to other cities, especially in the Global South. By aligning with international standards and including context-sensitive indicators, the model shows potential to speed up circular transformations in various urban settings.

Finally, the study provides strategic recommendations for policy and practice. Sustainable transformation involves not only deploying digital technologies but also coordinating them across interconnected levels of governance, data, and community engagement. Future research should expand experiments beyond waste and urban gardens to include areas such as mobility, water, and food systems, thereby strengthening the evidence base for circularity across multiple urban sectors. Additionally, scaling the Assessment Layer will be essential to offer comparable, replicable, and actionable insights that can guide policy and planning at city, national, and international levels.

In summary, the SSCC model validated in this study provides both a conceptual breakthrough and a practical tool for guiding the transition from Smart Sustainable Cities to Circular Cities. By integrating innovative technologies, governance mechanisms, and participatory practices within a layered framework, the model shows that sustainable, smart, and circular transformations can be designed, evaluated, and scaled in real urban settings.

Overall, this research provides one of the first empirically validated pathways for progressing from Smart Sustainable Cities to Circular Cities, positioning the SSCC model as both a conceptual framework and a practical tool for systemic urban transformation.

7.1. Contributions to Theory and Practice

Theoretical Contribution: The model advances the conceptual integration of circularity into smart city research by proposing a systemic, architecture-based approach. The articulation of the waste–energy–information nexus introduces a new methodological perspective for analyzing urban metabolism.

Empirical Contribution: Using real-world experiments with ULLs shows that the SSCC model is not just a theoretical idea but also a practical framework. These experiments can be replicated by other cities, especially in the Global South.

Methodological Contribution: Combining ULL methodology with a layered architecture and multidimensional evaluation (TRL, SRL, ORL, ScR) offers a comprehensive approach to assessing the readiness and scalability of socio-technical urban innovations.

7.2. Limitations and Future Work

While the results are promising, several limitations still exist: Integration with waste-to-energy technologies (e.g., pyrolysis) remains in the proposal stage and requires future investment and pilot testing; long-term impacts on institutional decision-making and community behavior have not yet been assessed; and testing in other urban settings with different governance and infrastructure conditions has yet to be conducted.

Additionally, while the current implementation of the SSCC model in Fenicia has concentrated on validating the architecture through information flows, participatory sensing, and low-carbon energy monitoring, future phases will expand into the full operationalization of material circularity. This includes deploying waste-to-energy technologies (e.g., pyrolysis units), integrating composting processes linked to urban agriculture, and developing decentralized microgrids powered by renewable energy. These next steps are already part of the SSCC architecture's design logic and will be gradually implemented in the Fenicia ULL. In doing so, the model will fully meet the objectives of waste reduction, reuse, recycling, transformation, and energy transition outlined in this research.

This study did not measure the annual energy use, CO_2 emissions, or employment impact of the smart components used in the experiments. The devices employed—solar-powered IoT sensors, drones, smartphones, and pilot-scale dashboards—were designed to require minimal additional energy, with most of the monitoring infrastructure in the urban garden powered by autonomous solar systems. Although the potential systemic benefits of adopting circular practices are expected to outweigh the slight increase in the footprint of ICT devices, these assumptions were not tested directly here. Future research should include comparative evaluations of energy consumption, carbon emissions, costs, and employment effects, including possible rebound effects of AI and smart technologies, within the Assessment Layer of the SSCC model.

7.3. Final Reflection

In conclusion, the SSCC model, as validated through the experiments in Fenicia, offers a clear step toward reducing fragmentation in urban innovation. It demonstrates that sustainable, smart, and circular cities are not just ideals but also achievable realities when built on an architecture that combines people, data, and technology to promote collective well-being and planetary sustainability.

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