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Smart Sustainable Cities as Digital Ecosystems: Concept and Framework Description

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ABSTRACT

Cities are increasingly understood as complex adaptive systems composed of interdependent social, economic, environmental, and technological subsystems. Traditional smart city models—focused on isolated technologies—fail to address this complexity. This study introduces a conceptual and technical framework that redefines the smart city as a digital ecosystem, where autonomous agents represent urban actors—including citizens, infrastructures, services, and industrial entities. These agents operate within shared data spaces, common ontologies, and negotiation protocols, enabling distributed decision-making, adaptive coordination, and continuous cross-domain co-evolution.

The framework was examined through three practical cases: (1) a multi-agent traffic management system in Taipei that improves flow efficiency and reduces emissions; (2) an adaptive multi-resource smart-grid model demonstrating self-organizing balancing of electricity, gas, and heat; and (3) a cross-domain integration scenario linking Smart City (SC) and Industry 4.0 ecosystems through semantic mediation and multi-agent negotiation.

Results show that ecosystem-based urban management enables real-time optimization, interoperability, sustainability and resilience across sectors. The paper further introduces the Digital Ecosystem Sustainability Evaluation System (DESES)—a method for assessing sustainability as an emergent, adaptive property rather than a static collection of KPIs.

The study shows that digital ecosystems shift sustainability and resilience from predefined policy targets to emergent outcomes of system design. This paradigm enables cities to self-organize, co-evolve with their environment, and respond adaptively to disruptions. The proposed framework offers a foundation for next-generation urban management systems that integrate people, technologies and governance within a unified, living digital ecosystem.

KEYWORDS: smart city; digital ecosystem; sustainability; resilience; multi-agent systems; ontologies; urban governance.

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ABBREVIATIONS

AI, Artificial Intelligence; API, Application Programming Interface; CTU, Czech Technical University; DESES, Digital Ecosystem Sustainability Evaluation System; DNA, Deoxyribonucleic Acid; DT, Digital Twin; ICT, Information and Communication Technology; IoT, Internet of Things; ISO, International Organization for Standardization; ITS, Intelligent Transport System; KPI, Key Performance Indicator; MAS, Multi-Agent System; NTUST, National Taiwan University of Science and Technology; RL, Reinforcement Learning; SC, Smart City; SDG, Sustainable Development Goal; SG, Smart Grid; SUMO, Simulation of Urban Mobility; UMS, Utility Management System; UN, United Nations.

INTRODUCTION

The concept of the sustainable city is closely intertwined with the evolution of the Smart City. Originally, SC initiatives in the 1990s and early 2000s were ICT-centric, focusing on efficiency through the deployment of sensors, Smart Grid (SG), e-government platforms, and intelligent transport pilots. These early projects were predominantly technology-driven, prioritizing operational efficiency over sustainability [1].

In the 2010s, the rise of global climate agendas—such as the Paris Agreement and the UN Sustainable Development Goals (SDGs)—shifted the discourse toward sustainable smart cities [2,3]. SC frameworks increasingly integrated energy efficiency, mobility, and environmental protection, repositioning technology as a tool for advancing sustainability targets [4].

By the late 2010s and early 2020s, the concept further evolved into citizen-centric and resilient smart cities. While still focusing on sustainable programs and environmental goals such as the European Green Deal [5], the COVID-19 pandemic and subsequent economic and political disruptions highlighted the need to prioritize systemic resilience [6,7].

These concepts (sustainability and resilience) are complementary—sustainability ensures long-term balance by reducing resource consumption, protecting ecosystems, promoting social equity, and strengthening governance [8]. Resilience ensures adaptive capacity—the ability of the city to withstand shocks such as natural disasters, blackouts, or pandemics, and to recover quickly while maintaining core function [9]. For example, a sustainable city minimizes energy use and emissions, while a resilient city can reroute energy, water, or mobility flows during disruptions. Together, sustainability and resilience form the twin pillars of adaptive and future-proof urban development.

Today, the SC sustainability refers to the ability of cities to adopt smart technologies, managerial practices, and conceptual approaches to simultaneously achieve environmental goals (reducing emissions, improving energy efficiency, enabling circular resource flows), social goals (inclusivity, accessibility, improved health, and education), economic goals (innovation, competitiveness, and efficient resource allocation), and governance goals (transparency, participation, and adaptive decision-making).

For the purposes of this paper, we define the SC concept as a human-centered, adaptive, resilient, and sustainable urban ecosystem capable of autonomous self-adjustment and continuous co-evolution, designed to ensure high-quality living conditions. SC Sustainability is defined as the integration of digital innovations with sustainable development principles, ensuring that urban growth meets present needs without compromising the needs of future generations [3,10].

Research Gap

Developing sustainable smart cities remains a difficult scientific problem because it combines multiple, interdependent dimensions. First, it requires balancing environmental, social, economic, and governance objectives, where progress in one area often creates trade-offs in another (for example, economic growth versus emissions, or digital efficiency versus privacy) [1,2].

Second, measurement of sustainability remains fragmented. Standards such as ISO 37120, the UN SDGs, and the European SC model provide useful benchmarks but mostly measure independent indicators [3]. However, these frameworks typically treat indicators as isolated and static, rather than as components of a dynamic and interconnected urban system. McManners argues that sustainability research itself must evolve—shifting from passive assessment toward proactive design for desired outcomes [11].

Third, cities must integrate heterogeneous data sources: from IoT sensors and satellites to administrative records and citizen apps—across diverse standards and governance models. Ensuring interoperability, trust, and security across these layers remains one of the central technical and organizational challenges [4].

The fourth issue is the strong interdisciplinary nature of the topic. Bridging all domains into a coherent framework remains a major research task [6].

Finally, sustainability must incorporate resilience and governance. Cities face deep uncertainty from climate change, pandemics, and geopolitical shocks [7]. SC systems must be adaptive and resilient, while also embedding participation, fairness, and ethical safeguards—without which even highly advanced technological solutions risk underperformance or failure [10].

SC Sustainability is not a purely technological issue but a complex, interdisciplinary challenge. The main difficulty of achieving SC Sustainability arises from the complexity of urban systems, which makes it nearly impossible to predict outcomes with linear models. In this context, sustainability becomes not a fixed target but an emergent property of continuously interacting and co-evolving urban subsystems.

Complexity of Smart Cities

Cities are widely recognized as complex adaptive systems [6,8], composed of heterogeneous actors—citizens, businesses, institutions, and infrastructures—that interact across multiple scales. Urban processes are nonlinear, path-dependent, and characterized by feedback loops that generate emergent behaviors not reducible to individual components [1]. Interventions in one domain, such as transport, often cascade into others, such as energy or environment [12]. This interconnectedness explains why many smart city projects struggle when focusing narrowly on isolated domains: the interdependence between mobility, energy, health, and governance create systemic effects that extend beyond individual interventions [2,4].

From this perspective, a smart sustainable city cannot be managed as a deterministic machine. Instead, it must be understood as a dynamic ecosystem where adaptation, diversity, and learning are central to long-term sustainability [9]. Natural ecosystems embody these qualities: their stability arises not by resisting change but by adapting through change. Resilience and sustainability are thus not external targets but emergent properties of system [9,13].

This insight suggests that cities should adopt the self-management principles of natural ecosystems. Research in network science reinforces this point: resilience depends not only on connectivity but on appropriate topologies [14]. Many infrastructures are not strictly scale-free; robustness emerges from redundancy, modular hierarchies, and polycentric governance, rather than centralized hub-and-spoke designs [10].

Based on this conceptual hypothesis—that viewing a city as a digital ecosystem enhances its capacity to coordinate services across domains and to achieve sustainability objectives—we formulate the central research question: How can the SC be conceptualized as a digital ecosystem to enable sustainability and resilience across interconnected urban domains?

MATERIALS AND METHODS

The implication is clear: if cities are designed as ecosystems—embedding diversity, redundancy, modularity, adaptive feedback, and distributed governance—then sustainability and resilience become intrinsic properties rather than afterthoughts. A city conceived in this way is not a static machine but a living, adaptive system. Just as a forest survives through diversity, interdependence, and resilience, a city ecosystem thrives when services, data, and actors interact fluidly, adapt to shocks, and co-evolve with citizen needs [15].

Analogy: Forest vs. City Ecosystems

Insights from natural ecosystems provide a useful lens for conceptualizing urban ecosystems. A forest sustains itself through diversity, interdependence, and continuous adaptation [15]; cities can be designed and governed in an analogous way:

1. Basic Elements (actors):

- Species ↔ Actors. Forest ecosystems include trees, pollinators, fungi, and predators, each occupying ecological niches. In cities, citizens, firms, government bodies, and artificial agents (IoT devices, digital twins, AI services) occupy functional roles that together shape urban outcomes [1].
- Keystone Species ↔ Critical Services. Certain species, like wolves or bees, act as keystones whose loss destabilizes the ecosystem [16]. Similarly, critical services such as electricity, water, and digital connectivity function as keystones in cities: their failure can cascade across domains and trigger systemic breakdowns [17].
- Genetics (DNA) ↔ Ontologies. Ontologies are the formal vocabulary, relationships, and rules that make heterogeneous actors and services interoperable. They function as the "genetic code" of the city, defining what entities exist, how they relate, what actions they can perform, and how they negotiate.

2. Processes:

- Energy & Nutrient Flows ↔ Data & Service Flows. In forests, energy from sunlight cascades through food webs, recycling nutrients. In smart cities, data collected by sensors flows through models and services, structuring urban functions [4].
- Continuous Interaction (the "metabolism") ↔ Service Provision. The city operates as a continuous market-of-services where various actors discover, negotiate, agree, execute, and learn—24/7. Adaptive cooperation replaces static schedules, just as in natural ecosystems.

3. Properties of the system:

- Symbiosis & Cooperation ↔ Interoperability. Mycorrhizal networks in forests enhance nutrient absorption and mutual resilience. In cities, interoperability between domains such as transport, energy, and environment enables integrated services with greater collective benefit [4].
- Resilience and sustainability. Natural ecosystems absorb shocks (f.e., fire, storms) and reorganize while retaining function. Likewise, city ecosystems can reallocate resources and learn from disruptions—rerouting mobility flows during outages or rebalancing grids during peak demand [13].
- Evolution & Co-Adaptation. Forest species evolve together, adapting to climate, soil, and interspecies dynamics. In cities, AI-driven services evolve, governance adapts, and citizen behavior shifts—co-evolving toward sustainability.

Natural ecosystems are often described in terms of species occupying niches and energy and nutrient flows that circulate among them. As Surie notes, city, industrial, and renewable energy ecosystems can be understood in similar terms: firms, entrepreneurs, NGOs, and government bodies act as “species”; energy, materials, knowledge, and waste circulate among them [18].

A city is not a static machine to be optimized once; it is a living, adaptive system whose sustainability depends on diversity, feedback, and cooperation, just as in natural systems [9].

The SC Digital Ecosystem

A Smart Sustainable City should not be viewed as a collection of isolated technological solutions but as a living digital ecosystem—an environment where diverse actors, services, and data systems interact continuously, adapt, and co-evolve, much like species in a natural ecosystem.

A SC Digital Ecosystem is a socio-technical environment where diverse urban actors—citizens, institutions, businesses, and artificial agents—interact through interconnected digital services, shared data, and adaptive governance mechanisms. It integrates technological infrastructures (IoT, AI, digital twins), managerial practices, and conceptual frameworks to support interoperability, cooperation, and continuous co-evolution across city domains.

To support this, the ecosystem requires a new framework: an extensible network of intelligent systems that facilitates collective decision-making, standardized data exchange, negotiation protocols, dynamic data storage, event response, and secure information transfer while ensuring user protection.

DIGITAL ECOSYSTEM CONCEPTUAL FRAMEWORK

The SC Digital Ecosystem can be described through five core elements: actors, services, data and models lakes, knowledge, interactions. Together, these elements transform the city from a set of fragmented infrastructures into an adaptive, co-evolving environment.

1. Actors as Digital Agents.

All actors in the ecosystem—citizens, institutions (government, businesses), artificial agents (AI services, IoT devices), and infrastructure components—are represented by digital agents. These agents embody the roles, preferences, and constraints of their real-world counterparts. For example, a traffic-light agent manages intersection flows, a household energy agent balances demand with tariffs, and a governance agent aligns local actions with policy objectives.

2. Services as Agent Functions.

Urban services—mobility, energy, water, waste, health, safety, governance—function as the “species” of the ecosystem. Agents both provide and consume these services within a virtual market. As in natural ecosystems, each service consumes resources (data, capacity) and produces outputs (e.g., traffic optimization, energy balancing, emergency response).

3. Data and Model lakes.

Data serves as the nutrient flow of the digital ecosystem. Data lakes store raw, real-time streams from IoT sensors, participatory apps, and industrial platforms, while model lakes contain AI models, digital twins, and simulation modules that convert data into actionable insights. Data reflects the current system state and supply inputs for decision-making, forecasting, and event triggers.

4. Knowledge and ontologies.

Above the data and model layers sits the knowledge layer, which defines meaning and ensures interoperability. Domain-specific ontologies describe areas such as transport, energy, or health, while a global smart city ontology binds them into a coherent semantic framework. This layer acts as the "genetic code" of the city, ensuring that agents communicate effectively and evolve without fragmentation.

Ontologies support several critical functions:

- Semantic unification: harmonize terminology across domains (e.g., Vehicle, Intersection, CO_2, Budget).
- Capability modeling: specifying what an agent can do (e.g., TrafficSignal hasCapability: switchPhase).
- Policy includes embedding rules, constraints, and compliance requirements.
- Negotiation protocols: formalize priorities and fairness constraints (e.g., hospital corridor priority).
- Federation: aligning domain ontologies into a shared conceptual layer.

Their genetic analogy is deliberate: ontologies enable inheritance (class hierarchies), expression (context-dependent policy activation), mutation (rule updates), and recombination (cross-domain semantic integration).

5. Optimization Through Continuous Interaction.

At the top layer, agents optimize system behavior through continuous negotiation, cooperation, and adaptation. The city operates as a perpetual marketplace of services where agents discover, negotiate, execute, and learn in real time—replacing rigid schedules with adaptive coordination.

This interaction is enabled by:

- Multi-agent coordination: consensus building, coalition formation, conflict resolution.
- Virtual markets: resource trading (e.g., energy, capacity, bandwidth) through pricing, credits, or auctions.
- Adaptive learning: updating strategies through reinforcement learning (RL) or federated learning.

This distributed optimization model avoids dependence on a fragile central controller. Agents optimize locally within global ecosystem constraints, enabling transparency, trust, and continuous improvement. The conceptual schema of the framework is shown in Figure 1.

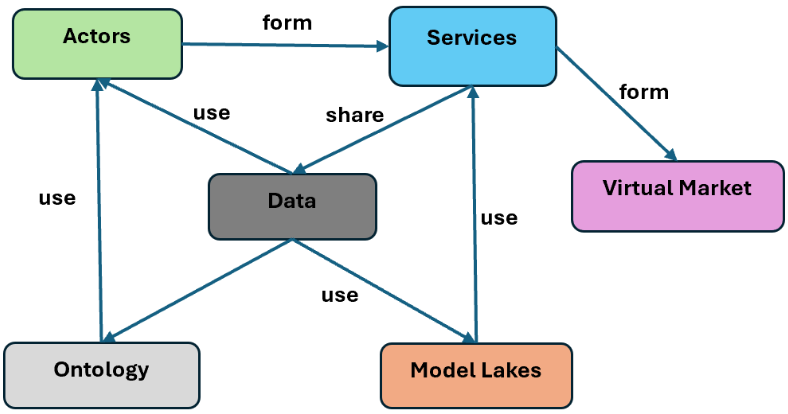


Figure 1. Conseptual framework schema.

Systemic Properties

When developed on these principles, the digital ecosystem exhibits several essential properties for long-term urban sustainability:

- Interoperability, ensuring that actors communicate through shared standards and ontologies.
- Resilience, enabling the system to absorb, withstand, and adapt to shocks such as floods, blackouts, or cyber incidents.
- Openness, allowing new services or actors to integrate without disrupting the whole system.
- Co-evolution, in which citizens, technologies, and governance evolve together.
- Circularity, promoting resource efficiency and regenerative flows.

These properties parallel the dynamics of natural ecosystems. By embedding diverse actors, functional services, nutrient-like data flows, adaptive interactions, and systemic behaviors, smart cities can evolve into living digital ecosystems where sustainability and resilience emerge naturally from system design rather than being imposed as external targets.

In summary, the SC Digital Ecosystem can be envisioned as a living city brain.

- Agents function as neurons, providing and coordinating services.
- Data lakes act as the bloodstream, circulating information across domains.
- Ontologies serve as DNA, encoding knowledge, semantics, and governance rules.
- Multi-agent interactions operate as synapses, enabling negotiation, cooperation, and continuous learning.

Together, these elements allow the city to sense, decide, and adapt dynamically, making sustainability and resilient emergent outcomes rather than static objectives.

Implementation Strategy

The transition from a conceptual framework to operational reality requires structured implementation strategies tailored to each city's context. Depending on local priorities, resource availability, and governance maturity, SC Digital Ecosystems can be realized through several complementary approaches.

Domain-Based Approach

Domain-specific digital ecosystems are developed independently, each with its own ontology, agents, and service portfolio. Typical domains include Intelligent Transport System (ITS), SG, Industry 4.0.

Agents operate and negotiate within their respective domains, optimizing local objectives such as mobility efficiency or energy balancing. However, they can also request or consume services from other domains through well-defined interfaces. The domains themselves remain unaware of each other's internal logic or ontologies. This ensures functional interoperability without requiring full semantic or structural integration.

Steps:

1. Identify priority domains (e.g., mobility, energy, healthcare).
2. Define domain ontologies and agent roles.
3. Develop and test services in simulations or digital twins (e.g., traffic optimization, grid balancing).
4. Validate performance against KPIs such as efficiency, emissions, and resilience.

Strengths: practical and incremental—easier to fund, govern, and deploy.

Limitations: Interoperability remains limited to API-level exchanges; the absence of a unified semantic layer restricts deeper cross-domain coordination unless integrated later.

Integration of Domain Ecosystems into a Unified Framework

Based on the domain approach, the next step involves federation, where domain-based ecosystems interconnect through a common interoperability layer such as a federated data lake, shared ontologies, and multi-agent negotiation protocols.

Steps:

1. Define a federation ontology that links domain ontologies while preserving their autonomy.
2. Establish interoperability standards and APIs.
3. Deploy cross-domain negotiation protocols (e.g., transport ↔ energy ↔ environment agents).
4. Implement governance dashboards and citizen participation platforms.

Strengths: scalable, compatible with legacy systems, and suitable for progressive evolution.

Limitations: it requires careful harmonization of standards and strong governance to avoid the creation of new “federation silos.”

General Approach

In this approach, the city is designed as a holistic digital ecosystem from the outset, supported by a unified architecture, shared ontology, and interoperable services spanning all domains.

Steps:

1. Develop a core ontology and reference architecture.
2. Deploy foundational infrastructures (IoT, open data hubs, federated learning systems).
3. Build cross-domain services (e.g., mobility, energy, governance, health) as interconnected modules.
4. Integrate feedback loops and adaptive governance mechanisms.

Strengths: provides a coherent, city-wide ecosystem from the beginning.

Limitations: high complexity, cost, and institutional barriers; best suited for newly planned smart cities or major redevelopment programs.

These approaches are not mutually exclusive. New cities may adopt the general strategy from the start, while established cities often begin with domain-specific pilots and gradually transition toward federated integration. In all cases, ontologies and negotiation protocols serve as the ecosystem’s “genetic code,” ensuring long-term adaptability, interoperability, and sustainability across domains.

PRACTICAL CASES

To demonstrate the feasibility of the proposed framework, a set of progressively detailed practical cases was developed. The first case focuses on fundamental elements—agents, negotiation mechanisms, and basic optimization. The second case demonstrates the Domain-Based Approach, showing how all core components (actors, services, data flows, and ontologies) operate within a real-world domain. The third, ongoing case presented in the discussion section explores cross-domain integration into a Unified Framework, illustrating how SC and Industry 4.0 ecosystems may be semantically and operationally merged.

Case 1: Smart Transport and AI-Driven Traffic (Prague, Taipei)

The project, developed through collaboration between the Czech Technical University (CTU) and the National Taiwan University of Science and Technology (NTUST), aims to enhance traffic efficiency in Taipei and Prague. Consistent with Rothengatter’s view of transportation as a complex adaptive system characterized by feedback loops, tipping points, and cross-domain interactions [12], vehicles and traffic lights were modeled as autonomous agents capable of negotiation to optimize throughput, reduce congestion, and improve safety.

The simulation was carried out using the SUMO platform, replicating the real infrastructure and traffic conditions of two major intersections—Gongguan and Keelung–Xinhai. Empirical traffic data, including vehicle types, flow volumes, and signal phase timings, were collected to calibrate the model. Two control strategies were evaluated:

- Multi-agent negotiation algorithm: traffic lights adjust signal plans through local interactions.
- RL algorithm (Q-learning): traffic lights dynamically adapt based on accumulated data and reward optimization.

A weighted reward system was designed to balance objectives such as minimizing waiting times, reducing trip durations, and maximizing throughput, while also considering vehicle types and lane density.

Basic System Entities in the Taipei Case

- Actors (species): vehicles and traffic lights were modeled as agents with distinct roles. Vehicles attempt to minimize delays, while traffic lights negotiate phase changes to balance system-wide flows.
- Ontologies (genetics): negotiation rules and adaptation mechanisms were encoded as reward functions and decision protocols. These ontological structures governed how agents interpreted data, prioritized objectives (e.g., throughput vs. fairness), and adjusted behavior in real time.

The Agent communication diagram is shown in Figure 2.

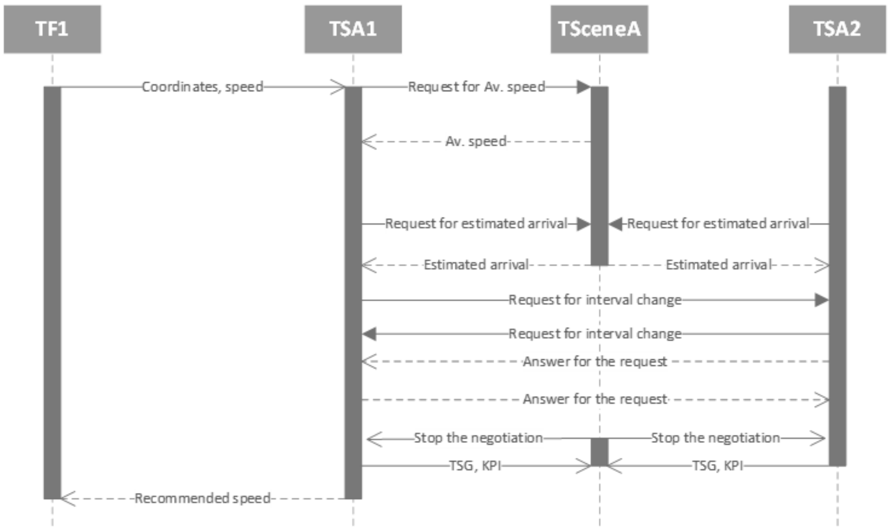


Figure 2. Agent communication diagram for Smart Transport and AI-driven Traffic.

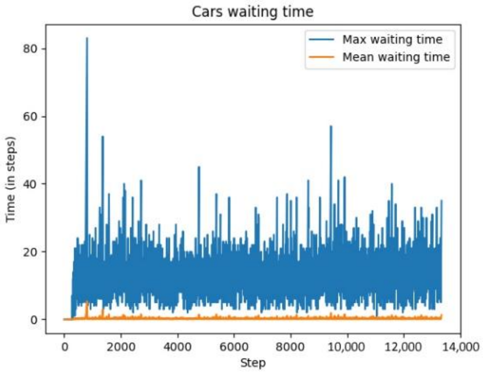
Key Findings

- Non-peak hours: trip durations decreased by 29–39%, median waiting times by up to 44%, and throughput improved by 7.9%.
- Peak hours: trip durations improved by 12–33%, with up to 25% reduction in average travel time.
- Environmental impact: significant reductions in CO_2 emissions, particularly for common vehicle types (e.g., Euro-4 petrol vehicles).

Algorithm Comparison

- The RL algorithm operated faster and distributed waiting times more evenly.
- The multi-agent algorithm achieved comparable throughput optimization but required minimum signal durations to remain effective.
- Both approaches processed updates below real-time thresholds (<30,000 μs per simulated second), showing feasibility for deployment.

The comparison of multi-agent algorithm and RL algorithm is presented in Figure 3.



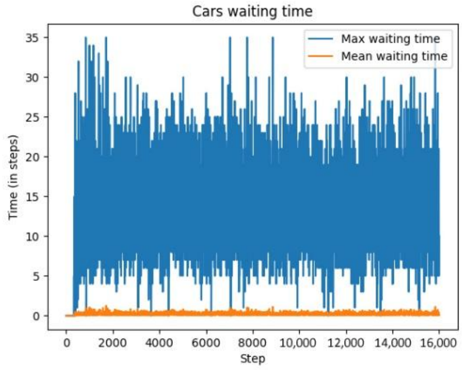


Figure 3. Results of multi-agent algorithm (**left**) and RL algorithm (**right**).

Both algorithms demonstrate sufficient processing speed for real-time operation; however, their approaches differ fundamentally:

- The multi-agent algorithm follows an event-driven recalculation model, where each newly introduced object (e.g., a vehicle) can trigger a chain reaction that modifies the traffic light schedule. However, this approach lacks predictive capabilities, as it responds only to immediate conditions.
- The RL algorithm, on the other hand, operates based on data accumulation. While recalculations are rapid, the model incorporates historical data, which sometimes leads to decisions that do not fully reflect current road conditions.

This case illustrates how core ecosystem elements—actors, services, and ontologies—manifest in practice. System performance arises from their interactions: vehicles and lights (actors) negotiate actions according to shared rules (ontologies), while intersections (keystone services) determine emergent system behavior. By embedding adaptive capabilities into each entity, traffic management evolves from static scheduling to a resilient, learning ecosystem capable of responding to real-world variability and advancing sustainability goals.

Case 2: Smart Utility Management Solution (UMS) in Prague

To extend the ecosystem concept beyond transport, a UMS based on the SG paradigm was developed. The system models gas, heat, and electricity networks as an adaptive peer-to-peer digital ecosystem where consumers, producers, and operators interact in real time. Its primary objective is to balance fluctuating energy, gas, and water demands while maintaining reliability, efficiency, and sustainability in resource distribution. The interface of the UMS system presented in Figure 4.

The UMS supports key functions such as configurable network setup, adaptive real-time planning, predictive "what-if" scenario analysis, performance analytics, and scalable deployment—from nano-grids to city-wide infrastructures. A multi-agent engine generates agents for each network component, coordinating negotiations and dynamically adjusting supply–demand balances. If consensus is not reached, a dispatcher agent restarts the process or proposes compromises (e.g., temporary household demand reduction with compensation) [19].

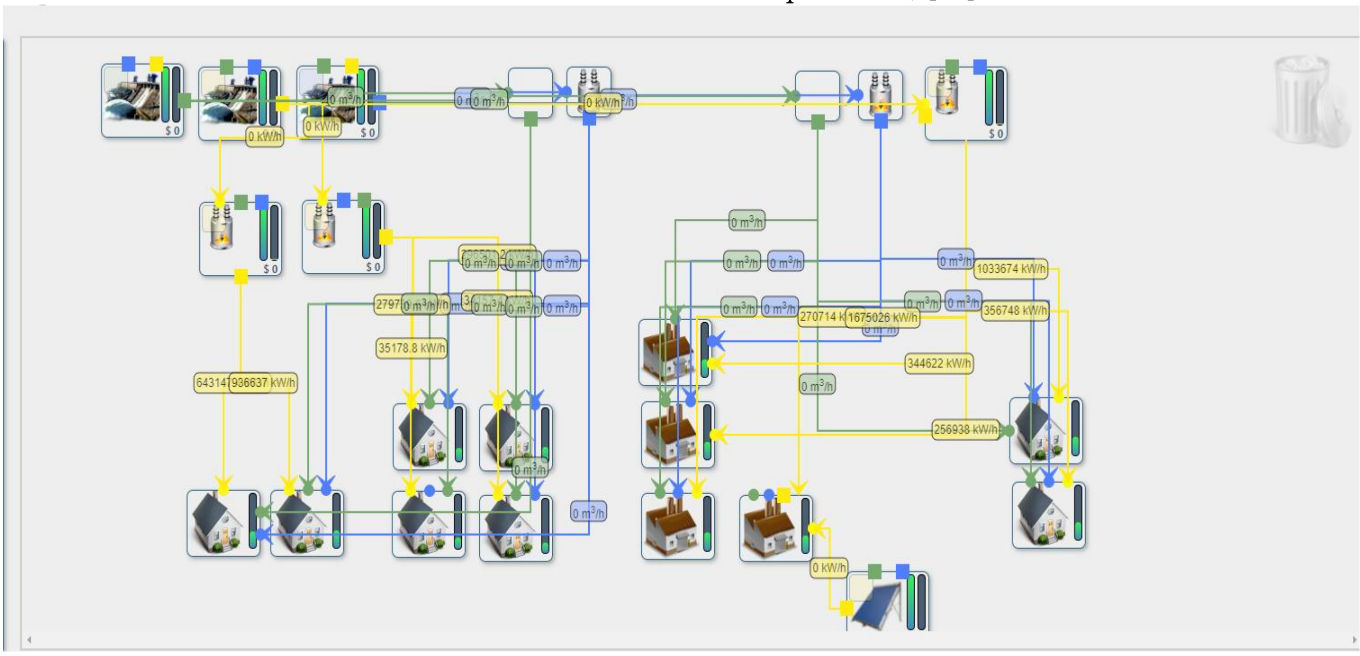


Figure 4. Interface of the UMS system.

Basic System Entities

- Actors (species): households, factories, commercial consumers, network providers, and suppliers act as agents with distinct roles. Demand-side agents define consumption plans, while suppliers generate and distribute resources.
- Ontologies (genetics): the UMS integrates an ontology-based knowledge base describing all consumers, suppliers, and network elements, enabling semantic interoperability and negotiation rules across multiple resource domains (Figure 5).
- Data and Model Lakes (nutrient and cognitive layers).

The ecosystem continuously collects telemetry from smart meters, sensors, and industrial controllers, feeding a federated data lake that stores multimodal data (loads, prices, weather conditions, consumption forecasts). These inputs support predictive analytics, optimization, and scenario testing.

- Interactions (metabolism).

Agents engage in continuous negotiation and coordination to maintain equilibrium among supply, demand, and cost. Interaction mechanisms include:

a. Multi-agent negotiation protocols (Contract-Net, auction-based).
b. Virtual markets where agents trade energy quotas or flexibility credits.
c. Event-driven updates when certain conditions (weather, demand spikes) trigger adaptive planning.

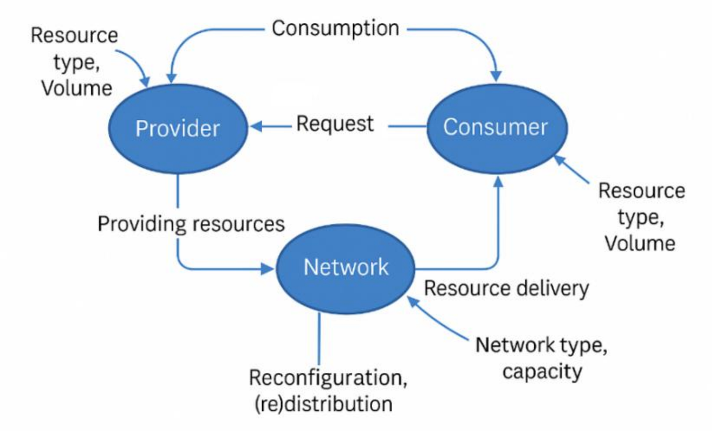


Figure 5. Ontology of UMS.

Illustrative Scenario

A factory requested additional electricity beyond its typical operational load. Initially, suppliers rejected the request due to residential demand constraints. Supplier agents then negotiated with household agents to temporarily reduce consumption, offering incentives such as discounts or special tariffs. When insufficient, the factory agent searched for alternative providers. One supplier offered electricity by activating a gas-powered generator, triggering further negotiation between electricity and gas providers over production cost and conversion efficiency. Through iterative negotiation, the system converged on an optimal configuration that met industrial requirements while preserving network stability. The agent communication diagram is shown in Figure 6.

Key Findings

- System balancing: UMS dynamically balanced supply and demand across multiple energy carriers.
- Economic efficiency: Adaptive reallocation reduced household utility costs by 12%.
- Environmental impact:
    a. CO_2 emissions were reduced by shifting demand to renewable or hybrid sources (solar, hydro, gas–electric).
    b. Peak shaving lowered the need for carbon-intensive emergency generation.

c. Integration of local renewables (e.g., solar panels) reduced dependency on fossil-based supply.

The Prague SG case demonstrates how digital ecosystem principles strengthen resilience in utility management. Instead of relying on static supply–demand schedules, UMS adapted to fluctuations, balanced competing needs, and ensured sustainability through self-organization and negotiation-based planning.

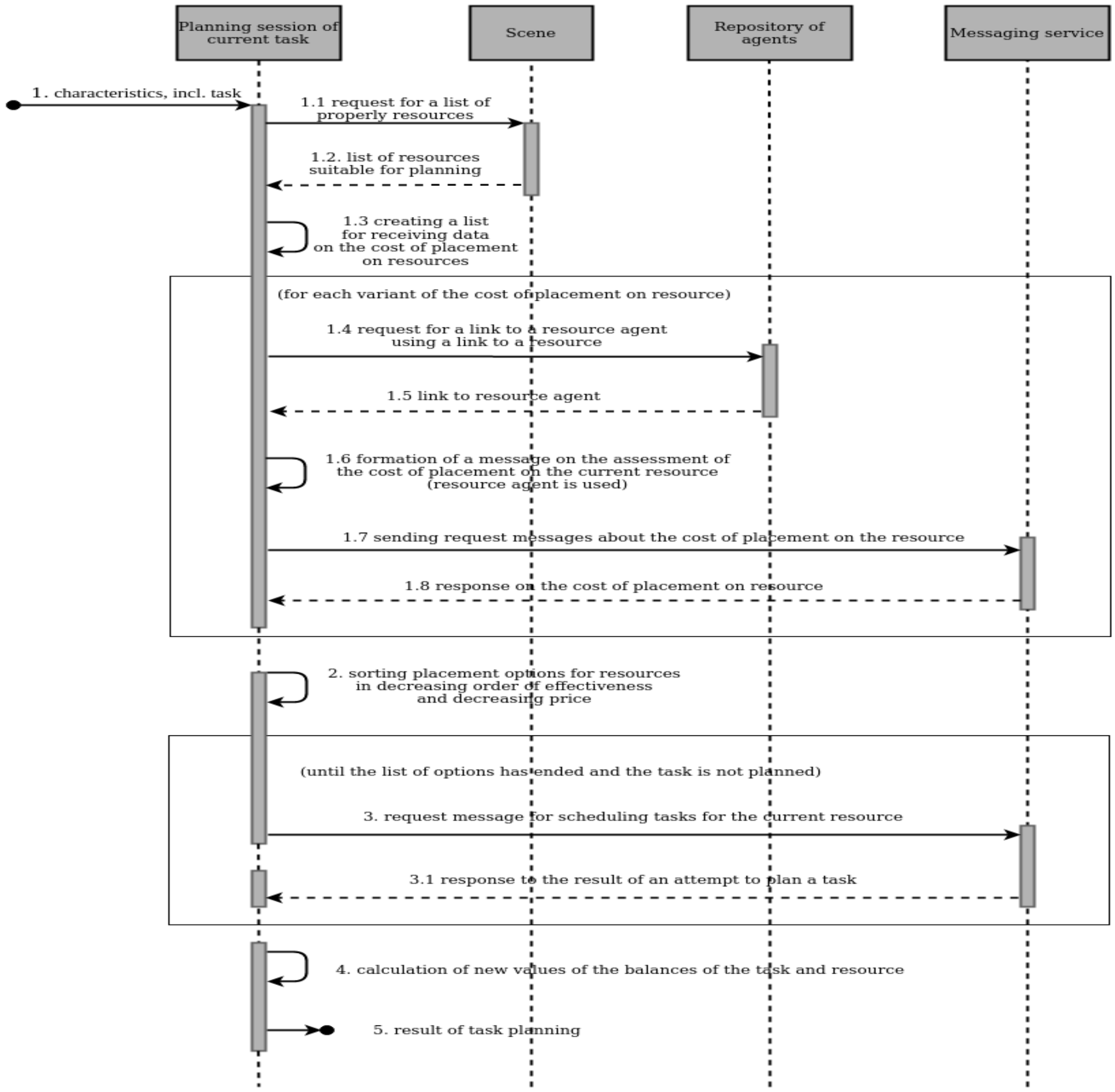


Figure 6. Agent communication diagram for Smart Utility Management solution.

Case 3: SC and Industry 4.0 (Ongoing)

Recent studies show that innovation ecosystems mobilize resources across business, finance, and governance, emphasizing the need for multi-actor, multi-service digital infrastructures in urban systems [20]. Given the strong technological overlap between Industry 4.0 and SC domains, their integration was selected as the focus of the third case study.

This ongoing research examines how these two distinct, yet interdependent ecosystems can operate cooperatively within a unified digital framework. Building on the Implementation Strategy described earlier, it investigates how urban and industrial platforms can interconnect through shared ontologies, interoperable services, and agent-based negotiation processes.

In Case 2, Industry and City actors interacted through service-based resource exchanges without deep semantic coupling. At this level, mutual resource optimization is achieved through direct, contract-based negotiation.

More generally, the two ecosystems remain logically independent yet physically overlapping, since factories operate within city limits and depend on urban infrastructures such as transport, energy, and public services.

Illustrative Scenario

A factory is initiating a sudden production surge and requesting additional working shifts and resources from the city. This triggers a chain of adaptive interactions across multiple domains:

1. Grid agents detect increased industrial demand and forecast potential stress on electricity and water networks.
2. Environmental agents assess the impact of additional generation on CO_2 emissions and regulatory thresholds.
3. Transport agents evaluate potential increases in workforce mobility demand based on new working shifts.
4. Energy agents explore resource substitute options.
5. Governance dashboards present decision-makers with trade-offs between industrial productivity and sustainability targets.
6. Decision: production schedules are adjusted, renewables are activated, demand-response measures are applied, and citizens are informed of temporary adaptations.

This scenario demonstrates how adaptive coordination among energy, environment, mobility, and governance domains can transform a potential stressor into a negotiated balance between economic growth, environmental performance, and citizen well-being.

Strategic Integration Approach

Merging SC and Industry 4.0 ecosystems does not require collapsing them into one system (Figure 7). The main idea is to use bridge ontologies for semantics, shared scenes for context and mechanism that enables goal-based negotiation:

1. Bridge Ontology Layer (Meta-Ontology): aligns shared concepts such as enabling cross-ontology reasoning without merging entire schemas.
2. Scene Interoperability: creates translation zones where agents register goals, exchange offers, and synchronize events (e.g., "Urban Factory Mobility Scene" for coordinating factory deliveries).
3. Shared Context Events: both ecosystems subscribe to a common message bus distributing events such as "Factory surge in energy

demand" or "Emissions threshold exceeded." This enables reactive integration without tight coupling.

4. Inter-Agent Negotiation Protocols: define shared goal templates (f.e., reserveEnergy, scheduleDelivery) and message structures based on bridge ontologies, allowing direct communication between, for example, FactoryEnergyAgent and CityGridAgent.

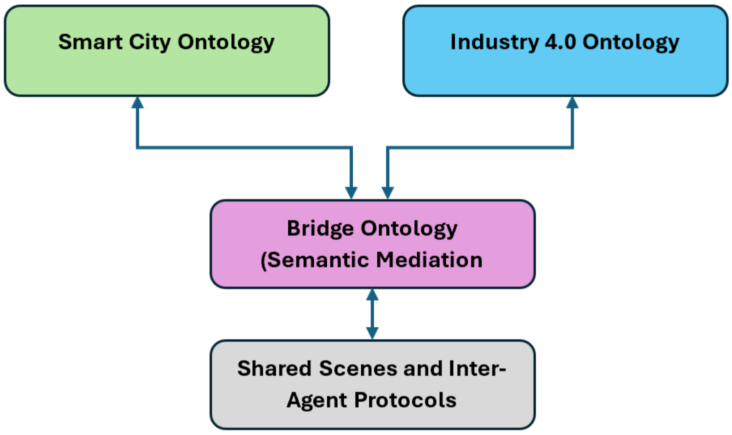


Figure 7. Schema of strategic integration approach.

The Bridge Ontology developed using the Ontology Editor (Figure 8), functions as a meta-ontology connecting the SC and Industry 4.0 ecosystems. It follows several principles to ensure semantic interoperability and scalability.

Each agent in both ecosystems can be encapsulated within a wrapper class, enabling standardized interaction and ontology mapping. Two key parent classes define the agent structure:

- BaseDemand—represents the agent's requirements or resource needs.
- CanProvide—represents the agent's capability to deliver or offer services.

An agent may inherit from one or both classes, reflecting its dual role as a consumer and/or provider of services. The "CanProvide" hierarchy is extensible, allowing new agents or resources to be dynamically wrapped into the ontology without altering its core structure. This supports continuous evolution of roles and capabilities within the ecosystem.

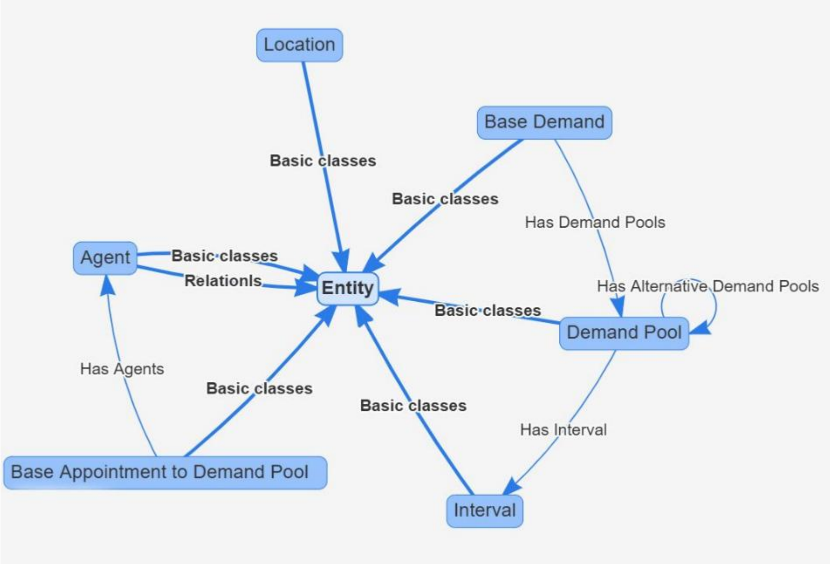


Figure 8. Developed bridge ontology.

Conversely, the "BaseDemand" hierarchy defines specific requirements or "Demand Pools," which are matched with corresponding "CanProvide" entities through semantic reasoning. This alignment enables cross-ecosystem negotiation and resource exchange.

The next development phase includes implementing Scene Interoperability, Shared Context Events, and Inter-Agent Negotiation Protocols to achieve full operational cooperation between the two ecosystems.

Ultimately, integrating SC infrastructures with Industry 4.0 platforms transforms potential competition for resources into mutual reinforcement. This synergy illustrates how cross-domain digital ecosystems can jointly enhance economic productivity, environmental performance, and systemic resilience.

RESULTS AND EVALUATION

Measuring SC Sustainability

Measuring smart city sustainability remains challenging due to the diversity of goals, domains, and stakeholders involved. Over the past decade, numerous frameworks and standards have been introduced to assess urban performance, each offering valuable insights but often constrained by sectoral separation and static evaluation methods.

The most recognized initiatives include the ISO 37120 series [21], which defines indicators for urban services and quality of life across domains such as energy, transport, governance, and safety. ISO 37120 provides a foundation for international benchmarking, while ISO 37122 (smart city indicators) and ISO 37123 (resilience indicators) extend the scope toward digital transformation and adaptive capacity. In parallel, the SDGs apply a global framework at the urban scale [3], emphasizing cross-sectoral objectives such as affordable energy (SDG 7), sustainable cities and communities (SDG 11), and climate action (SDG 13).

Beyond global standards, several projects have advanced holistic, KPI-driven approaches. Huovila et al. compared seven frameworks [4], mapping over 400 indicators across environmental, social, and governance dimensions, while the mySMARTLife project operationalized city-specific KPIs for mobility, environment, and citizen well-being [22]. These initiatives highlight the importance of contextualization and flexibility but also the risk of inconsistency when indicators are not harmonized across domains.

Recent studies call for ecosystem-based evaluation rather than static metrics. Addas (2023) showed how integrating environmental and spatial factors—such as land use, building standards, and mobility flows—enhances governance [23]. Bukhari et al. (2024) further argued that sustainability in smart cities should also encompass entrepreneurship, innovation, and quality of life [24]. Despite such progress, measurement remains largely fragmented and episodic, lacking real-time adaptability and interoperability between cities, which limits comparability and the transfer of best practices.

Evaluation of Practical Cases

Case 1: Smart Transport and AI-Driven Traffic

Relevant KPIs:

- ISO 37120: average travel time, congestion levels, GHG emissions from transport.
- SDG 11.2: access to sustainable transport.
- Project-based: mobility efficiency, citizen satisfaction, safety.

Measured Outcomes:

- Trip durations reduced by 12–39% (efficiency gains).
- Median waiting times fell by up to 44% (accessibility improvement).
- CO_2 emissions significantly reduced (environmental sustainability).
- Throughput increased by ~8% without new infrastructure (resource efficiency).

By treating vehicles and traffic lights as agents, transport sustainability shifts from static KPIs to continuous, adaptive optimization.

Case 2: Smart UMS

Relevant KPIs:

- ISO 37123: resilience of energy and water systems.
- SDG 7: affordable, reliable, and sustainable energy.
- Huovila taxonomy: resource distribution efficiency, system flexibility.

Measured Outcomes:

- Real-time balancing of electricity, heat, and gas prevented blackouts (resilience).

- Demand-response strategies allowed consumers to reduce peak loads by negotiation (participation, governance).
- Adaptive reallocation reduced household utility costs by 12% (economic sustainability).
- “What-if” scenarios increased preparedness for disruptions (resilience metrics).

UMS demonstrates how multi-agent negotiation creates adaptive resilience, embedding sustainability into the grid by design.

Digital Ecosystem Sustainability Evaluation System (DESES)

Traditional sustainability assessments rely on static KPIs applied in isolation, offering valuable benchmarks but failing to capture the complexity and adaptivity of urban systems. The DESES introduces a shift: treating sustainability not as a fixed scorecard, but as an emergent property of flows, interactions, and adaptive behavior across city domains.

The DESES can be described through several aspects:

1. Three Levels of Measurement.

DESES evaluates sustainability across three interconnected levels:

- Micro-level: performance of individual services (e.g., transport efficiency, renewable energy share).
- Meso-level: cross-domain interactions (e.g., balancing transport ↔ energy ↔ environment to minimize emissions).
- Macro-level: systemic resilience and adaptability (e.g., recovery time after floods, blackouts, or pandemics).

This multilevel approach scales from local indicators → ecosystem interactions → systemic resilience.

2. New Evaluation Dimensions (beyond ISO/SDG).

While existing frameworks emphasize environmental, social, economic, and governance dimensions, DESES adds ecosystem-specific properties:

- Interoperability: the degree to which data and services interconnect across domains.
- Adaptivity: speed and effectiveness of feedback loops, assessed via digital twins and real-time KPI updates.
- Co-evolution: alignment between citizen participation, governance responsiveness, and technological evolution.
- Resilience: capacity to absorb shocks while retaining core functions.
- Circularity: extent of resource reuse across domains (energy, water, materials).

3. KPIs and Adaptive Measurement

DESES integrates conventional metrics with dynamic monitoring:

- Environmental KPIs: energy efficiency, renewable share, CO_2 footprint, resource circularity.
- Social KPIs: inclusivity, mobility accessibility, public health, education opportunities.
- Economic KPIs: innovation capacity, competitiveness, efficiency of public–private partnerships.

- Governance KPIs: transparency, participation rates, data openness, trust in digital services.

Unlike static benchmarking (e.g., "Did the city reach 40% renewables last year?"), DESES supports adaptive, ecosystem-based monitoring (e.g., "How do transport, industry, and households dynamically negotiate energy in real time to remain under carbon targets?").

By embedding sustainability assessment into the continuous functioning of the digital ecosystem, DESES shifts evaluation from retrospective checklists toward real-time, adaptive measurement. This approach ensures that sustainability and resilience are not external targets but emergent, continuously maintained properties of the smart city ecosystem.

DISCUSSION

Practical cases represent a natural progression in digital ecosystem maturity: Transactional → Collaborative → Cognitive. Early pilots (transport and energy cases) correspond to Level 1, demonstrating bilateral interactions and basic negotiation. The third, more advanced urban–industrial–environmental case aspires toward Levels 2 and 3—where ecosystems become collaborative and eventually cognitive, functioning as a unified adaptive organism. However, this work is ongoing, and results remain preliminary.

The conceptual framework developed in this paper is rooted primarily in information systems engineering and software architecture. Accordingly, it focuses on digital infrastructures, agent-based coordination, semantic interoperability, and ecosystem-level adaptation. Full validation of the complete digital ecosystem across multiple real-world domains remains outside the current scope. Nevertheless, real-world deployments such as SURTRAC in Pittsburgh [25] and DALI in Texas [26] show that agent-based systems can operate successfully in live urban settings, producing measurable reductions in congestion and emissions. These examples confirm that the foundational principles underlying the proposed Digital Ecosystem—autonomous agents, distributed decision-making, and continuous adaptation—are not only theoretically sound but practically viable.

Implementation Barriers

Full-scale deployment of a SC Digital Ecosystem is constrained by both conceptual and practical limitations. These include restricted access to operational urban data, integration challenges, and varying legal and regulatory frameworks [27], as well as evolving notions of environmental and nature rights [28] and requirements related to administrative law. Issues of security, privacy, and AI ethics present additional challenges. Any operational ecosystem must implement robust cybersecurity, privacy-preserving data processing (e.g., federated learning), transparent agent behavior, and compliance with frameworks such as GDPR. These topics extend beyond the present IT-oriented scope but represent essential directions for future interdisciplinary research.

Practical implementation also faces organizational and social barriers. Cross-department coordination and institutional change may encounter organizational resistance. Many cities face limited technological readiness—legacy infrastructures, insufficient IT capacity, and uneven digital literacy among staff and citizens. Shared data layers and cross-domain ontologies introduce governance challenges concerning interoperability, data ownership, and avoidance of vendor lock-in. Moreover, long-term public acceptance depends on transparency and clear communication about the operation of AI-driven systems. These barriers highlight that successful implementation requires not only technical solutions but also organizational adaptation, capacity-building, and inclusive governance.

Ontologies

Each city functions as a unique socio-technical system, making it impossible to implement a SC Digital Ecosystem through a single universal template. This is particularly evident in ontology development. Although numerous studies propose generic SC ontologies, none can be applied without substantial adaptation. Local infrastructures, administrative procedures, energy systems, mobility patterns, and regulatory conditions all influence how semantic structures must be designed. Ontologies therefore need to be developed iteratively and collaboratively with municipal experts and service providers. Cities require flexible, modular semantic models that evolve with technological maturity and shifting policy priorities, rather than a fixed, one-size-fits-all solution.

In this work, ontologies are treated as the semantic "DNA" of the digital ecosystem, enabling shared meaning, interoperability, and coordinated action across domains. The study concentrates on conceptual alignment—using meta-models, domain ontologies, and a bridge-ontology layer to support communication between SC and Industry 4.0 ecosystems. However, creating standardized vocabularies, governing ontology evolution, and ensuring long-term semantic consistency remain open challenges. Addressing these requires coordinated efforts among domain experts, municipal authorities, and standardization bodies. Existing initiatives such as ISO/IEC smart city vocabularies provide a starting point, but further work is necessary to achieve stable, operational semantic interoperability at the city scale.

Scalability

Scalability is a key consideration for the proposed Digital Ecosystem framework, as cities vary significantly in population, resources, governance capacity, and technological maturity. Although this study emphasizes the conceptual and software-architectural aspects of digital ecosystems, the framework is inherently modular. Individual domains—

transport, energy, utilities, industry—can operate independently while still adhering to the same ecosystem principles. This modularity allows smaller or less technologically advanced cities to adopt only selected components, while larger or more mature cities can integrate multiple domains and gradually evolve toward full ecosystem interoperability. Future research should establish explicit scaling guidelines and maturity levels to support differentiated adoption across cities with varying capacities.

CONCLUSIONS

This paper has argued for reframing smart sustainable cities as digital ecosystems, moving beyond siloed, techno-centric approaches toward integrated, adaptive, and citizen-centric models. Drawing inspiration from natural ecosystems, a conceptual framework where actors, services, data, ontologies, and continuous interactions form a living urban "metabolism." Within this framework, sustainability and resilience are not external benchmarks but emergent properties of ecosystem design.

The study addressed the formulated research questions and conceptual hypothesis by developing a digital ecosystem framework and demonstrating its feasibility through three practical cases. The findings confirm that ecosystem-based coordination, agent negotiation, and shared ontologies can effectively improve sustainability, cross-domain adaptivity, and systemic resilience in smart city contexts.

Through case studies—it is demonstrated how digital ecosystems can operate in practice. Each case highlighted how basic ecosystem entities (actors, keystone services, ontologies) interact to deliver measurable improvements in efficiency, resilience, and environmental performance.

To overcome the limitations of static evaluation frameworks, the paper introduced the DESES. This approach enables continuous, real-time monitoring of sustainability as a dynamic property of the urban ecosystem, aligning the city's evolution with SDGs, ISO standards, and evolving citizen needs.

Future research will focus on expanding cross-domain solutions, developing a more unified urban–industrial ontology, advancing inter-agent negotiation protocols, and conducting real-world pilots to validate the ecosystem-based evaluation approach in operational settings.

Ultimately, cities designed as digital ecosystems will become capable of co-evolving with their environments and societies, embedding sustainability and resilience as intrinsic and continuously maintained properties of urban life.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

Conceptualization, SK; methodology, SK; software, SK; validation, SK and MS; formal analysis, MS; investigation, SK and MS; resources, SK; data curation, SK; writing—original draft preparation, SK; writing—review and editing, SK; visualization, SK; supervision, MS; project administration, SK; funding acquisition, MS. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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