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TOWARDS A SMARTER FUTURE: FRAMEWORK FOR SUSTAINABLE SMART CITY SOLUTIONS

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Abstract: The concept of smart city has emerged as crucial paradigm for developing efficient and intelligent urban solutions aimed at enhancing the quality of life and fostering sustainable environmental management. While realizing this vision often entails significant challenges related to costs, complexity, and connectivity, this paper introduces an innovative four-tier architecture for smart cities. This framework establishes an ICT infrastructure as its foundational layer, integrating collaborative governance, smart services, and end users. The proposed architecture is fundamentally modular and decentralized, explicitly designed to systematically address key challenges such as security, privacy, and interoperability. It supports a gradual, adaptive implementation, leveraging its inherent flexibility for deployment of smart city services. Furthermore, through illustrative scenarios grounded in existing research, the paper demonstrates the significant potential and inherent robustness of this architecture in achieving substantial operational efficiencies, environmental benefits, and overall improvements in urban living.

Keywords: smart city, smart services, smart city architecture

ПАТ КОН ПОПАМЕТНА ИДНИНА: РАМКА НА ОДРЖЛИВИ РЕШЕНИЈА ЗА ПАМЕТНИ ГРАДОВИ

Апстракт: Концептот на паметен град се појави како клучна парадигма која е поврзана со развојот на ефикасни и интелигентни урбани решенија, насочени кон подобрување на квалитетот на животот и поттикнување на одржливо управување со животната средина. За адресирање на значителните предизвици поврзани со трошоците, сложеноста и поврзувањето во остварувањето на оваа визија, овој труд предлага иновативна четирислојна архитектура за паметни градови. Оваа архитектура во својата основа ја има ИКТ инфраструктурата, со интеграција на колаборативно управување, паметни услуги и крајни корисници во единствена целина. Предложената архитектура во основа е модуларна и децентрализирана, експлицитно дизајнирана систематски да ги адресира клучните предизвици како што се безбедност, приватност и интероперабилност. Таа поддржува адаптивна имплементација, искористувајќи го флексибилниот дизајн за постепено распоредување на услугите на паметниот град. Понатаму, преку илустративни сценарија засновани на постоечки истражувања, трудот го демонстрира значајниот потенцијал на оваа архитектура во постигнувањето суштинска оперативна ефикасност, еколошки придобивки и севкупни подобрувања во урбаниот живот.

Клучни зборови: Паметен град, паметни сервиси, паметна градска архитектура

I. INTRODUCTION

IN the last several years, we have been faced with increased level of urbanization. This rapid urban expansion has had negative impacts on the environment, including changes in local and regional climate and loss of biodiversity [1]-[5]. Cities and megacities are faced with new challenges related to effective waste management, lack of resources, air pollution, traffic congestion, lack of parking spaces, inadequate and old infrastructure, etc. [6]-[8]. Higher level of urbanization requires implementation of efficient and smart solutions for transportation and smart solutions for sustainable environmental management with the goal of improving the quality of life within municipalities and cities [9]-[12]. Faced with the challenge that affect the quality of life of the citizens, city authorities made initiatives in direction of implementing a smart city concept [6], [13], [14].

The smart city concept has been actively studied by many researchers, followed by development of several different definitions and frameworks for its implementation. The focus of all these researchers was mainly aimed at identifying challenges associated with the growth of urban population and defining strategy for mitigating problems by using information and communication technology [6], [15]-[20].

According to these studies, smart city platform can be considered as massive information system with IoT platform at its core that has enhanced capabilities to handle components for data storage, information retrieval, networking, and communication. Solutions delivered by smart city platform can transform cities by improving infrastructure and transportation systems, reducing traffic congestion, ensuring better waste management, improving street lighting and electricity consumption, etc.

There are a series of challenges related to realization of smart city platforms. The challenges are mainly grouped into two domains: technical and non-technical. In terms of technical challenges, the focus is on those related to building a platform and communication infrastructure that support intelligent traffic management. In this domain, the focus is also on regulations related to security and data privacy. From non-technical challenges point of view, the focus is on the citizens' computer literacy and simplicity of services delivered by the platform.

The purpose of this paper is to propose a novel smart city platform architecture model, determine the challenges related to information system management in smart cities, and to propose a strategy for mitigating these challenges. The smart city architecture must provide simple to use type of services to citizens regardless of their computer literacy. The proposed architecture model focuses on efficient data storage and distribution to facilitate various operations. The model is based on a modular decentralized service-oriented architecture where every use case scenario (e.g., smart light, smart waste, smart parking, etc.) is a separate module and every city/municipality represent a different zone.

II. Background

The smart city concept has evolved significantly over the past few decades. Although there have been several studies, one of the first research related to the smart city concept was published in 1994. During the 2000s, and especially in 2010, there has been a significant growth in the number of research in this domain. Further upward trend in the number of research is observed especially after technological giants like IBM, Cisco, and other multinational ICT companies started to express interest in this domain. This was an impetus for international bodies such as the European Commission and OECD to also focus on smart cities as one of the important areas of development [20]

There are also several papers related to smart city platform architecture design. Basmia *et al.* proposed Portunus - a distributed and scalable platform architecture designed to support collection and processing of complex space-time events in smart cities [21]. These events include both natural parameters (e.g., temperature, humidity, noise) and socio-urban occurrences (e.g., traffic incidents, train arrivals, population density changes). To address limitations of traditional systems in handling heterogeneous and evolving data types, the authors introduce an abstract event model capable of integrating diverse sources of information. The system is based on a microservices architecture, where independent services manage data collection, authentication, object registration, and system logging, facilitating flexibility, extensibility, and high availability. Chamoso *et al.* propose a distributed and modular smart city platform designed to enhance scalability, reusability, and citizen-centric services [22]. The architecture is divided into two key components: communication architecture responsible for seamless data exchange and reuse of existing functionalities and deployment architecture capable of adapting computational resources based on real-time demand. Through integration with diverse data sources - including IoT sensors, public data, and social networks - the platform supports real-time data analysis and generation of personalized recommendations to foster energy-efficient behavior and urban sustainability. In their paper, Harrison *et al.* proposed a three-layer architecture for a smart city. At the bottom is the instrumented layer, next is the interconnected layer, while at the top is the intelligent layer [18]. The instrumented layer is a network of sensors that generate real-world data such as water quality measurements, electric meter readings, energy consumption measurements, etc. The interconnected layer is tasked with incorporating real-world data (sensor network data) into enterprise computing platform and relating acquired data to events of interest. The intelligent layer is tasked with identifying and processing relevant data to identify city-relevant events that need to be analyzed or acted upon. Dirks and Keeling suggest that city operations affect six different pillars, namely: people, business, transport, communication, water, and energy [23]. The people pillar includes elements such as public safety, health and education, while the business pillar includes elements that directly or indirectly affect businesses such as policy and regulation. All six pillars form a single system.

Mahmoud *et al*. proposed creation of centralized smart city platform consisting of a four-level pyramid. At the lowest level is the sensor network, at the second level is the database, at the third level is the smart interface, with smart city applications at the highest level [24].

Anthopoulos and Tsoukalas propose a four-layer generic architecture [25]. The first layer is the user layer, which includes all end users of services delivered by the smart city platform. The second level is the service level which contains all the services delivered by the smart city platform. The third layer is the infrastructure layer that contains the technical tools necessary for delivery of services, while the last layer is the information layer which is responsible for presentation of collected information.

Doran *et al.* proposed a smart city model that integrates three main components [26]. The first component is the economic component. Within this component, on one side, there are public administration employees in terms of e-governance, and on the other hand, technological companies that are responsible for providing the ICT infrastructure (cloud, big data, security, connectivity, etc.). The second component is the environmental component. This component includes public and alternative transportation, geographical information, climate change measurement, and more. The third component is the social component. This component involves the citizen segment in terms of community life, participation in democracy, social innovation, and more.

III. Smart City Architecture, Services and Implementation Strategies

This section outlines the proposed four-tier smart city architecture, detailing its core components and diverse range of smart services it enables. Additionally, this section elaborates strategic implementation approaches designed to overcome the complexities of urban technological integration.

A. Smart City Architecture and Services

The next generation information technology should support and assist existing development processes in cities, like the process of urbanization. Technology should enable people-centered type of urbanization or, in other words, urbanization should be developed to support the wellbeing of citizens. A smart city platform should represent a central nervous system that will monitor, analyze, optimize and present all relevant parameters. Hence the entire smart city solution should be aimed at integrating all smart components into one IoT (Internet of Things) platform regardless of the manufacturer.

To achieve openness of the smart city platform, a framework that enables integration of any application that uses any wireless communication technology and any type of sensor, regardless of the manufacturer, must be introduced.

When integrating different IT solutions, data security is a top priority. This includes data encryption, access controls, and conducting regular periodic security audits to identify any security vulnerabilities.

Connecting different applications to exchange data is done through application programming interfaces (APIs). APIs streamline the integration process and ensure compatibility between different systems

In essence, integration can be achieved in two domains.

- orchestration of (web) services from different SaaS/XaaS solutions into end-to-end workflows; and
- integration of user interfaces from different SaaS/XaaS solutions to support scenario-oriented user interface that will support execution of all human activities in the workflows, regardless which of the integrated SaaS/XaaS solution the actual user interface implementation belongs to.

To simplify the process, the first methodology for data integration is envisaged, i.e. orchestration of (web) services from different SaaS/XaaS solutions into end-to-end workflows.

In this use case scenario, sensor devices developed by various IoT manufacturers continue to send information to the cloud platform of the manufacturer by default. In order to collect the necessary data from these sensors, the smart city platform is connected to the cloud platforms of each individual sensor manufacturer via API.

Building upon this foundation of integrated data from diverse sources, the continuous evolution of technology is poised to redefine creation and delivery of IT services and SaaS solutions. Notably, Artificial Intelligence (AI) and Machine Learning (ML) have recently revolutionized service delivery to end users. These advanced technologies, by analyzing vast amounts of data, are capable of identifying intricate patterns and predicting future trends, thereby enabling intelligent decision-making. Consequently, predictive analytics, powered by AI and ML, offers significant potential for proactively identifying problems, envisioning optimization opportunities, and automating routine tasks, ultimately minimizing downtime and profoundly improving user experiences.

Our proposed smart city concept is based on four-level architecture (Figure 1).

The lowest level or the foundation layer of smart city is the ICT infrastructure. ICT infrastructure consists of an IoT platform deployed in cloud environment, wired and wireless network connectivity, enterprise-class data storage centers, Artificial Intelligence, an array of physical devices and sensors, and more.

The second level is collaborative governance. This level should provide a framework that will facilitate cooperation between various stakeholders in the public sector.

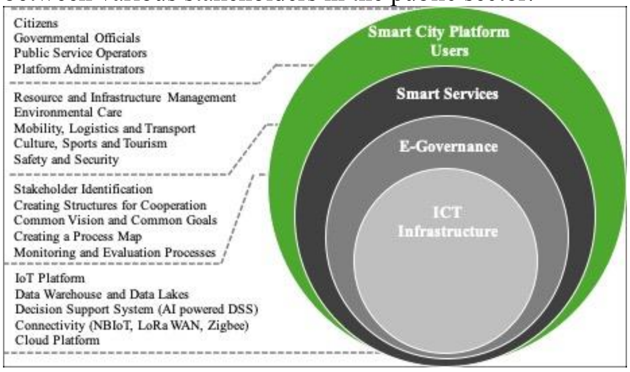

Fig. 1. Four-layer architecture

This layer should represent the roles and the process of cooperation between all stakeholders. The process of creating a framework for collaborative governance would consist of several steps:

- Stakeholder Identification: the first step consists of properly identifying relevant stakeholders who have an interest or appropriate expertise in the subject matter;
- Creating Structures for Cooperation: establishing a management structure that would consist of number of working groups focusing on specific aspects of the work to better coordinate and facilitate cooperation;
- Common Vision and Common Goals: in this step, the vision for a smart city should be shared and common goals should be created;
- Creating a Process Map: defining processes and establishing criteria for decision-making;
- Definition of Communication Protocols: defining communication channels and creating platform for sharing information, experiences and knowledge (knowledge management system);
- Monitoring and Evaluation Processes: in this step, mechanisms should be established to monitor the quality of services through collection of feedback from citizens.

Services that will be delivered by the smart city platform can be found in the third level.

The fourth level is comprised of end users of the services. We can identify four types of users: citizens, government officials, public service operators and platform administrators.

The smart city concept envisages use of digital tools that enable one-way and two-way communication, policy support, or e-participation in city/municipal governance. Involvement in decision-making processes by city residents is essential because it fosters civic awareness which, in turn, cultivates a sense of community and belonging [27]. This enhanced awareness and emotional connection play a crucial role in facilitating and expediting urban development [28], [29]. Although many authors argue that citizen participation is essential, actual citizen involvement is limited due to the low level of technical literacy and general lack of interest in civil engagement. Hence, municipalities must be focused on developing mechanisms that will increase citizen participation and interaction activities.

B. Implementation Strategies

Implementing a comprehensive smart city architecture like the one proposed here requires strategic, phased approach to effectively manage complexity, mitigate risks, and optimize resource allocation. Rather than monolithic deployment, our architecture supports a pilot-based, incremental implementation methodology, leveraging its inherent modularity and decentralized design.

The typical deployment process can be conceptualized through several key phases:

- Phase 1: Planning and Assessment. This initial stage involves thorough analysis of municipal needs, assessment of existing legacy infrastructure, and strategic selection of specific pilot zones or priority services (e.g., smart lighting for particular boulevard, waste management for designated district).
- Phase 2: Infrastructure Readiness. This phase focuses on physical and digital groundwork, including deployment and installation of heterogeneous IoT sensors and devices, establishment of robust communication networks, and initial configuration of the core IoT platform.
- Phase 3: Data Integration. Leveraging the Service-Oriented Architecture (SOA) and extensive use of REST APIs, this crucial phase involves seamlessly integrating data streams from diverse vendor cloud platforms and existing municipal data sources. This ensures interoperability and eliminates data silos.
- Phase 4: Decision Support System (DSS) Development and Configuration. Based on integrated data, specific algorithms for predictive analytics and operational optimization (e.g., route optimization, anomaly detection) are developed, configured, and fine-tuned within DSS. Concurrently, intuitive user interfaces for municipal operators and end-users are designed and deployed.
- Phase 5: Monitoring and Optimization. Post-deployment, continuous monitoring of system performance, data flows, and service effectiveness is paramount. This phase involves rigorous data collection, ongoing analysis, and iterative adjustments to algorithms and configurations to maximize efficiency and achieve desired outcomes.
- Phase 6: Scalable Expansion. Given its successful validation in pilot zones, the architecture's inherent scalability allows for a systematic expansion of smart services to other urban areas or introduction of new services without disrupting existing operations.

This phased approach facilitates continuous learning and adaptation, ensuring that the smart city platform evolves in alignment with urban needs and technological advancements. Furthermore, successful implementation demands robust collaboration among diverse stakeholders, such as local government, utility providers, citizens, and technology partners. This collaborative effort directly aligns with the principles embedded within our architecture’s collaborative governance layer. This strategic framework is designed to minimize initial investment risks, streamline complex deployments, and circumvent issues such as vendor lock-in by embracing open standards and flexible integration capabilities.

IV. HOLISTIC VIEW OF SMART CITY PLATFORM

Figure 2 shows a comprehensive overview of a modular decentralized smart city platform architecture. This approach envisages existence of Central Smart City Platform (CSCP) that is interconnected with multiple zones or subsystems. CSCP is where integration of data coming from different zones takes place. Modularity of the platform refers to the ability of CSCP to be divided into independent modules that can be switched on and off by the platform’s administrator (e.g., modules for functions such as smart light, smart parking, etc.).

Traditionally, cities and municipalities are divided into separate administrative zones. The proposed architecture fits well into such a scenario where each smart service will have zonal representation. Considering all the financial, social and technical challenges, we can assume that implementation of different user scenarios in different zones will be gradual. The proposed modular platform concept will enable an easy transition of cities and municipalities towards the smart city concept gradually, step by step.

Each zone will have its own system consisting of local cloud infrastructure where a local database will be placed, then a constellation of wireless sensors, and appropriate network infrastructure. Each database in each zone will contain information related to personal data of users. MySQL or PostgreSQL (open-source databases) can be used as database for this purpose. The main database, data warehouse/datalakes and business intelligent techniques such as OLAP - Online Analytical Processing and DSS will be integral part of CSCP. All zones communicate with CSCP via secure communication links such as SDWAN or L2/L3 VPN.

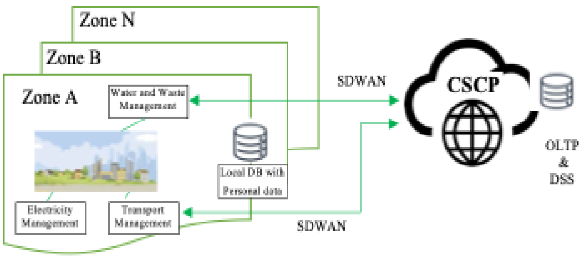

Fig. 2. Modular decentralized platform

CSCP is based on four-tier SOA (Service Oriented Architecture), as shown in Figure 3.

All levels of the software solution are interconnected by API (SOAP or REST), TCP/IP and HTTPS. Through API, the smart city platform is also connected to the cloud platforms of each individual sensor manufacturer.

API is basically a set of functions and procedures that allow one application to access certain functionalities of another application.

Preferable type of API is REST.

- REST is a web-based API that uses URL and HTTP protocol. The reason for using REST API is due to its simplicity, lower security requirements and compatibility with WEB browsers.
- TCP/IP is a set of standardized rules that allow computers to communicate on computer network such as the Internet.
- HTTPS is extension of HTTP. In HTTPS, the communication protocol is encrypted, which is why it is used for secure communication over the Internet. The main motives for existence and use of HTTPS are based on the need to protect privacy and integrity of data exchanged between the website accessed and the end user accessing the website.

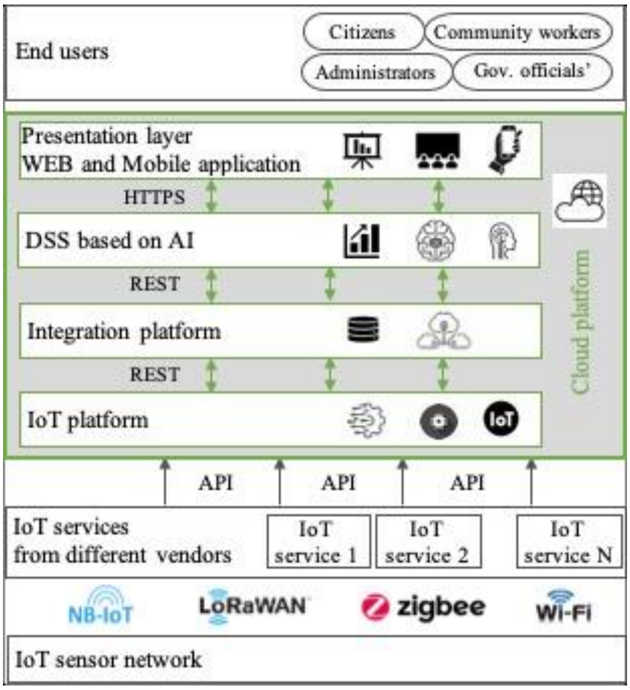

Fig. 3. Four-tier SOA (Service Oriented Architecture)

Below is a brief description of functionalities of each of the four levels:

A. First Level: Presentation Level

The presentation level consists of two components, namely a WEB-based integrated software solution for monitoring and controlling smart elements and Android/iOS application.

The WEB-based application is an administrator portal. The administrator portal is an administrative console from which various services can be managed. As minimum requirements, the administrator portal should offer:

- modularity, i.e. ability to include/exclude applications and application modules for different countries;
- the platform should enable rebranding at country/municipality level (logo, color, font);
- internationalization in a sense that smart city platform services should be able to be adopted for use in multiple countries (different style, idea, culture, language, text direction, dates, etc.).

Mobile applications are intended for end users (citizens, tourists, public service operators) and must be developed for smartphones with iOS and Android operating systems. The mobile application should provide an initial display of the smart elements from the zone in which the user is currently located. This means that the mobile application should be able to recognize which modules are active in each zone. The mobile application should enable secure creation of user profiles and ability to make payments with credit and debit cards.

B. Second Level: Decision Support System

DSS, or Decision Support Systems, are a type of AI system that is designed to help humans make better decisions. DSS enables introduction of new services that would be based on information received from smart sensor networks. The combination of these services can help local public enterprises improve service delivery to citizens, but it will also assist local governments in uncovering new insights or patterns when it comes to use of public services such as water, electricity, etc. In other words, citizens can have accurate insight into current consumption of water and electricity through mobile application, while municipalities/cities can make predictions about energy and water consumption in smart cities.

DSS can also be useful in the domain of transportation and smart waste. In IoT/DSS based transportation, real-time traffic network management systems can be created. This type of system can predict the dynamics of traffic congestion and will improve the decision-making process at city level.

C. Third Level: Cloud-Based Integration Platform

A cloud-based integration platform is open-source platform that provides integration of various components into single system. A cloud-based integration platform is PaaS (Platform As A Service). It provides hardware resources (data storage, processing power and network connectivity) based on application requirements, interoperability requirements and automatic execution. This layer also contains adapters for existing OSS/BSS systems.

D. Forth Level: IoT Sensor Integration Platform

IoT Sensor Integration Platform is responsible for collecting data from IoT sensors and devices. The platform contains various software libraries (SDKs) that enable integration of various applications, i.e. devices, over the Internet. In addition, the platform allows for management of any certified sensor equipment. Management includes provision of sensor information, connection monitoring, centralized fault management and service level monitoring, configuration management, sensor software management, device statistics graphs, sensor restart commands, etc. The platform has data visualization module via web user interface.

E. IoT Solutions from Different Vendors

There are several different IoT vendors that have numerous scenarios which, in the context of smart cities, are of great interest not only for improving the quality of human lives, but also in terms of reducing operating costs and protecting the environment. Services can be divided into five generic categories:

- Resource and Infrastructure Management: smart light, smart metering, smart building, etc;
- Environmental Care: smart waste, environmental measurements like air quality, noise level, solar radiation, wind, precipitation and other weather data;
- Mobility, Logistics and Transport: smart bike, e-scooters, fleet management for public transport, traffic signaling regulation, etc;
- Culture, Sports and Tourism: integration and promotion of cultural services, digitization of cultural heritage content, integration and promotion of tourist offers for different target groups;
- Safety and Security: sensors to monitor the environment and predict natural disasters, safety cameras, smart city operational center, etc.

In the next section, few examples of user scenarios that are integral part of the smart city concept are presented.

Smart metering - Smart metering systems utilize electronic devices to monitor, measure, and record consumption of electricity, gas, and water, subsequently calculating associated fees. Implementing such a system often necessitates IoT solutions with 'deep indoor' coverage, effectively eliminating the need for manual readings which, in turn, reduces operational costs and enhances environmental protection.

A key advantage of our proposed smart city platform is its ability to overcome challenges posed by diverse user scenarios across different cities or even in the same city. This includes integrating smart meters and devices from various manufacturers, even if they operate on different communication technologies (e.g., for devices in underground shafts requiring stronger transmitters). This flexibility allows municipalities to select cost-effective solutions tailored to specific needs, thereby reducing the initial acquisition cost of smart devices by avoiding vendor lock-in. Regardless of device manufacturer or communication technology, the platform presents all data on single, unified dashboard for the municipality or city.

Adopting smart metering systems has consistently demonstrated operational cost reductions by at least 10% related to manual meter readings, alongside an improved understanding of resource consumption patterns [30]. While a direct quantitative reference for specific innovative approach of integrating diverse manufacturers for cost reduction might not be widely available, the underlying principles of open standards and interoperability are well-established for enhancing system flexibility and efficiency in ICT deployments.

Smart Parking - Smart parking solutions are increasingly vital in urban areas grappling with traffic congestion and inadequate parking availability. These advanced systems typically integrate sensors, cameras, and wireless communication with data analytics and smart time meters to provide real-time information on vacant parking spaces. Beyond simply locating available spots, smart parking facilitates mobile application-based reservations, with payment for reserved parking space commencing at the moment of reservation. The system can also offer visual cues, such as colored light from a sensor, to indicate a reserved spot. Crucially, if a driver parks in a reserved space without authorization, they will not be able to initiate payment through the mobile application, preventing misuse.

Our proposed architecture for smart parking leverages the IoT sensor network layer, utilizing sensors and cameras to gather real-time parking availability data. This information is then processed through the IoT platform and integration platform, feeding into the Decision Support System (DSS) to predict congestion and optimize urban traffic flow. Real-world implementations of such systems have shown significant benefits; for instance, it is widely estimated that up to 30% of urban traffic congestion is caused by drivers searching for parking spaces [31].

Integrating a smart parking system effectively reduces average parking search time and localized traffic congestion, thereby contributing to substantial fuel savings and reduced CO_2 emissions.

Smart Waste - In waste management, smart solutions leverage sensor networks within containers to provide real-time information on fill levels. This data, often transmitted via SIM-equipped sensors, enables optimization of collection truck routes. Such optimization does not only lead to significant fuel savings ,but also directly contributes to reducing CO_2 emissions, thereby offering environmental benefits.

Within our architecture, smart waste management utilizes container fill-level data from sensors, which is integrated through IoT Sensor Integration Platform. Through Decision Support System (DSS), the platform intelligently analyzes this data to create efficient routing algorithms. A hypothetical scenario involving a large urban area illustrates that optimizing waste collection routes based on fill-level data, as facilitated by our architecture, can achieve significant efficiencies. Studies show municipalities analyzing data from smart bins have experienced up to 25% increase in collection efficiency, allowing better planning and more timely interventions, leading to substantial fuel savings and direct reduction in CO_2 emissions [32].

Furthermore, the diverse nature of waste management environments, encompassing various container sizes, as well as above-ground and underground containers, necessitates accommodation of different user scenarios and potential use of sensors from various manufacturers. Our proposed platform specifically addresses this by offering flexible integration framework. While precisely quantifying the economic effect from utilizing sensors from diverse manufacturers can be challenging, this approach undoubtedly brings significant economic benefits by fostering competition and reducing vendor lock-in.

Smart Lighting - Smart lighting systems consist of dimmable LED lamps, sensors, control system, and robust data transmission infrastructure. While LED lights inherently offer energy savings, their integration with motion sensors significantly enhances efficiency. These sensors can be configured to dim lights to, for example, 20% intensity when no traffic or pedestrians are detected. As a vehicle or pedestrian approaches the first streetlight, it can illuminate to 70%, with the sensor simultaneously signaling neighboring streetlights to gradually increase their brightness to 50% and 30%, respectively. This adaptive approach has been shown to achieve significant energy reductions, with research indicating over 50% reduction in electric lighting energy consumption with optimized sensor applications, while concurrently providing superior illumination quality and improved public safety [33]

Implemented through our framework, smart lighting deploys LED lamps with dimming capabilities and motion sensors as part of the IoT sensor network. Data from these sensors feeds into the Decision Support System (DSS), which proactively adjusts light intensity based on real-time pedestrian and vehicle presence. When implemented within a smart city framework like ours, any smart lighting pilot project is projected to yield substantial energy savings, in line with research indicating over 50% reduction in electric lighting energy consumption, maintaining optimal visibility and enhancing public safety.

V. Challenges Associated with ICT Infrastructure

The proposed architecture model envisions implementation of smart services by zones using a modular approach, meaning that the entire infrastructure does not need to be built all at once. This concept allows for gradual transition towards a smarter city.

The proposed smart city concept is characterized by heterogeneity of communication networks, vendors, devices, and applications. Therefore, from an architectural perspective, the platform must enable scalability and high availability, given that requirements for data processing, management, and analytics may increase exponentially. The proposed model envisions use of web services to connect the platform with platforms of other IoT vendors. This means that security and privacy are some of the challenges we face when building such platform. Cyberattacks on zones cannot affect the entire platform, but they cannot be completely minimized as well, as there is still potential for loss or misuse of personal data.

One of the critical aspects for successful implementation and adaptation of a smart city platform is related to ensuring high level of efficiency. Citizens expect faster access to emergency services, more efficient planning, and better resource utilization. This implies that the platform must contain services that process queries from multiple domains in real-time.

Considering all the above, there are a number of challenges associated with implementation of smart city platform. Here, we focus on the most common ones.

Costs - Securing adequate funding and financial resources represents one of the primary obstacles encountered by cities in implementation of smart city initiatives [6], [13], [34], [35].

A cloud-based model does not offer only possibility for high availability and scalability, but it also reduces upfront costs.

In the long run, use of smart city as platform for providing public services will improve not only the public administration efficiency and will help reduce costs as well [35].

Horizontal Scalability - The proposed smart city architecture based on open standards provides horizontal scalability. Horizontal scalability means that a new type of service can be included in an easy and simple way or that existing services can be extended by including new vendors.

Availability and Vertical Scalability **-** The cloud nature of smart city platform provides high level of availability and vertical scalability. Vertical scalability allows automatic scaling of hardware resources in order to handle demand fluctuations. The platform's high availability will be ensured by using backup instances for critical components in different zones and using automating failover in order to minimize downtime. Also, load balancing will be implemented to distribute traffic and spread resources across multiple locations to protect against localized failures.

Security and Compliance: The security of the smart city platform must be aligned with the national legislative framework, in particular the Cyber Security Strategy 2025-2028 and Draft Law on Security of Network and Information Systems [36], [37]. These regulations emphasize the obligation of digital service providers and operators of essential services to ensure high level of cybersecurity, including protection of critical infrastructure, sensitive data, and public digital services. In the context of smart cities, these obligations become even more pronounced, given the wide surface of potential threats and the interconnected nature of systems. To clearly distinguish between legal requirements for compliance and practical measures for security implementation, this section is organized into two separate parts: security and compliance.

A. Security Implementation Measures

The smart city platform, based on Service-Oriented Architecture (SOA), inherently includes a wide range of services that may be exposed to Internet-based threats. Additionally, the platform integrates a large number of heterogeneous IoT devices deployed in public areas, distributed databases containing personal information, and a centralized cloud infrastructure. These components present multiple attack vectors and require a comprehensive cybersecurity strategy.

To ensure security across all layers of the system, the following measures should be implemented:

- asset inventory;
- threat detection (e.g., SIEM - Security Information and Event Management; SOAR - Security Orchestration, Automation, and Response; XDR - Extended Detection and Response);
- network segmentation (e.g., VLAN - Virtual Local Area Network);

- encryption (e.g., IPSEC - Internet Protocol Security; MPLS VPN - Multiprotocol Label Switching Virtual Private Networks; or SDWAN - Software-Defined Wide Area Network);
- security procedures for data access (e.g., PAM - Privileged Access Management; and MFA - Multi-Factor Authentication);
- disaster recovery and business continuity plan.

The proposed SOA-based architecture inherently enhances security by promoting modularity; cyberattacks on individual zones or modules cannot compromise the entire platform. The strategic deployment of SIEM, SOAR, and XDR tools ensures proactive threat detection and automated response capabilities across this distributed environment, moving beyond traditional reactive security. Furthermore, the adherence to 'security by design' principles for all digital services ensures that robust security safeguards are integrated from the earliest stages of development, rather than being an afterthought, significantly strengthening the platform's resilience against evolving threats.

B. Compliance Requirements

To achieve compliance with the National Cyber Security Strategy 2025-2028 and the Draft Law on Security of Network and Information Systems and Digital Transformation, the smart city platform needs to implement the following key measures and adhere to these principles:

- establish a clear and robust cybersecurity governance structure: this includes defining roles and responsibilities within the organization for managing the platform's cybersecurity;
- develop and implement comprehensive cybersecurity risk management measures: this entails regularly identifying, analyzing, and evaluating potential risks and implementing appropriate controls to mitigate them;
- establish incident reporting obligations: the platform must have mechanisms for detecting, reporting, and managing cybersecurity incidents, in compliance with legal requirements;
- ensure information sharing related to cybersecurity: procedures should be established for sharing relevant information with other stakeholders and national cybersecurity bodies;
- implement "Security by Design" and "Privacy by Design" principles: all digital services on the platform should be developed and maintained with built-in security safeguards from the earliest stages of development;
- foster cooperation and coordination: establish mechanisms for cooperation and coordination with relevant institutions and other service providers in the field of cybersecurity;
- conduct continuous risk assessments: regularly perform risk assessments (such as vulnerability assessment and penetration testing) to identify and address new potential threats;
- provide cybersecurity training: ensure regular training for employees and platform users to raise awareness about cybersecurity.

In addition to meeting legislative mandates, the robust cybersecurity governance structure and continuous risk assessments within our framework represent an innovative commitment to maintaining a dynamic security posture, adaptable to new threats and regulatory changes.

Interoperability: Interoperability is a critical aspect of developing successful and sustainable smart city. It refers to the ability of different systems, devices, platforms, and organizations within the city ecosystem to seamlessly exchange information and utilize data that has been exchanged. Achieving true interoperability, however, entails addressing several critical challenges, including data silos and system heterogeneity, semantic mismatches, and issues related to governance, coordination, and cross-organizational collaboration. Addressing these challenges requires a collaborative effort involving development and adoption of open standards, implementation of robust data governance frameworks, and fostering collaboration among all smart city stakeholders. Overcoming these hurdles is essential to unlocking the full potential of integrated smart city solutions and achieving true sustainability and efficiency.

The cornerstone of our architecture's innovative approach to interoperability is its foundation on open Service-Oriented Architecture (SOA) and extensive use of REST APIs. This allows for seamless integration of heterogeneous IoT platforms from diverse vendors, effectively overcoming data silos and system heterogeneity. By orchestrating web services from different SaaS/XaaS solutions into end-to-end workflows and enabling integration of user interfaces, our model actively fosters cross-organizational collaboration and minimizes the need for costly, proprietary integration efforts, thereby unlocking the full potential of integrated smart city solutions

Privacy: The privacy of the smart city platform must be in line with the national legislative framework, in particular with the Law on Personal Data Protection [38]. Pursuant to this legislation, within the proposed smart city model, the user is defined as the owner of personal data. Personal data is provided only to known and authorized users. Exposure of anonymized data via web services will be done exclusively after obtaining electronic consent from the personal data owner.

Our approach innovatively embeds 'privacy by design' principles into every layer and module of the smart city platform, ensuring that data minimization and protection mechanisms are fundamental to its operation. The decentralized nature of data storage, with personal data residing in local databases within each zone, further limits disclosure of sensitive information, while open-source databases like MySQL or PostgreSQL can be rigorously configured to enforce strict access controls and robust privacy measures, ensuring that personal data remains secure and under the user's explicit control.

VI. Conclusion

This paper has presented a novel four-tier architectural framework designed to foster development of sustainable and efficient smart city solutions. At its foundation lies the ICT infrastructure, supporting a collaborative governance level that facilitates cooperation among public sector stakeholders. Above these, the architecture defines the smart services layer, ultimately serving the end users, categorized as citizens, government officials, public service operators, and platform administrators.
The proposed smart city concept inherently addresses challenges arising from heterogeneity of communication networks, vendors, devices, and applications. This paper has detailed how the platform's design actively mitigates common implementation hurdles, including managing costs, ensuring horizontal and vertical scalability, and critically, innovatively addressing concerns related to security, privacy, and interoperability. By promoting 'security by design' and 'privacy by design' principles, leveraging open standards, and utilizing REST APIs for seamless integration of diverse IoT platforms, our framework provides a robust and adaptable solution.

Although specific large-scale deployments of this architecture are not yet available, the illustrative examples across smart metering, parking, waste management, and lighting, rigorously backed by empirical research, compellingly demonstrate the significant potential and inherent resilience of our framework in yielding substantial operational cost reductions, environmental benefits, and improved quality of life for citizens. This comprehensive approach positions our architecture as viable and forward-looking model for urban digital transformation. Future work will focus on validating this architecture through pilot projects in specific urban contexts, aiming to provide empirical data on its real-world performance and scalability.

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