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# Application Architecture for the Internet of Cities: Blueprints for Future Smart City Applications

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As smart cities evolve towards the Internet of Cities, it's essential to consider common problems and how to address them. Three representative types of smart city applications are outlined here, identifying key requirements and architectural guidelines for implementation.

The rapid rise and pervasive adoption of the smart city paradigm in conjunction with the Internet of Things (IoT) is reshaping the world's metropolises. Today's cities have evolved to become behemoths of connected devices cutting through all vital domains, starting with building management and operations to smart grids and multimodal traffic management up, to social media-driven citizen-participation processes. To deal with this increasing complexity, experts and stakeholders alike must be able to utilize this plethora of information to ensure optimal city planning, operations, and management. It's vital to provide stakeholders with capabilities for understanding the massive amounts of data generated, while also supporting the efficient operation and management of increasingly complex infrastructures.

This new city concept also comes with the ability to let citizens participate — this is an integral element in advancing the city as a whole. Thus, in previous work, we introduced the Smart City Application Ecosystem (SCALE) to provide citizens with a toolset to build novel kinds of applications.[1] (For others' work in this area, please see the related sidebar.) Figure 1 shows SCALE's architecture; beyond helping practitioners build applications with novel capabilities emerging through the IoT, it also helps them efficiently access the massive amounts of data. These applications in turn become composable, interchangeable abstractions of capabilities, much like the applications known from today's smartphones, but on a much larger scale. This evolution promises to be a vital stepping stone to reach the *Internet of Cities*,[2] an open market place where applications can interact and be exchanged between cities. The Internet of Cities will let practitioners use best practices and solutions from other cities to solve common problems in their own environment.

Such an ambitious move forward logically requires forethought about possible scenarios along the way. In order for practitioners to understand where and how to apply SCALE in such a capacity, we identified common application cases that today's smart cities are facing. Here, we present best practices (blueprints) for these common cases, show how they can be addressed, and explain which elements of SCALE — or more specifically, SCALE's core, the Smart City Operating System (SCOS) — must be applied to enable them.

## Blueprints for Smart City Applications

Here, we outline blueprints for three different cases we identified as relevant throughout our smart city research. We identify their integral requirements

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## Related Work in Designing Smart Cities

The broad coverage of the smart city paradigm in research initiatives around the globe has led to several approaches to address the inherent complexities. These approaches mainly focus either on the Internet of Things (IoT) aspect or on general complexity and integration issues surrounding smart cities.

SmartSantander[1] proposes a city-scale experimental research facility that supports applications and services in the smart city context. The primary focus is the IoT element of a smart city, and SmartSantander aims to provide a large-scale testbed that helps with issues arising from connecting and managing IoT infrastructure elements.

Jiong Jin and colleagues[2] present a framework that focuses on the IoT aspect for creating smart cities. Another approach in the context of IoT comes from Nathalie Mitton and colleagues,[3] where the authors propose the combination of a cloud and sensors in a smart city environment. In their work, they focus on pervasive infrastructures, where services interact with their surrounding environment.

In terms of integration, Jiafu Wan and colleagues[4] present an event-based architecture for machine-to-machine (M2M) communications for smart cities based on the Stratospheric Observatory for Infrared Astronomy (SOFIA) project, with a case study in the vehicular context. On a more abstract level, Hafedh Chourabi and colleagues[5] present a framework to understand the concepts of smart cities. The authors introduce a conceptual framework to comprehend the vital elements in a smart city by identifying critical factors. This approach is similar to that of Taewoo Nam and Theresa Pardo,[6] who try to identify how a city can be considered smart by aligning strategic principles in the context of technology, people, and institutions, which represent the main dimensions of a smart city. In this broader context, Catherine Mulligan and Magnus Olsson[7] discuss the architectural implications of smart city business models. The authors specifically discuss the architectural evolution required for ensuring a smooth rollout and deployment of smart city technologies.

In the context of citizen participation, Zaheer Khan and Saad Liaquat Kiani[8] introduce a cloud-based architecture for context-aware citizen services in smart cities. The authors argue that cloud computing can provide a suitable computing infrastructure for smart city applications and also emphasize the importance of security considerations in this context. In a similar manner, Roozbeh Jalali and colleagues[9] present a smart city architecture for community-level services through IoT. Their smart city architecture enables community service providers and citizens alike with access to real-time data, which has been gathered through IoT as a basis for decision processes and future planning.

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and present approaches for each case that demonstrate how best practices for each case should look like.

## Case 1: Smart City Planning

Today’s cities and their respective stakeholders want to provide their citizens with a sustainable, secure, affordable, and livable city. In order to provide stakeholders in a smart city environment with the optimal foundations for a reflected planning and decision process to support such a lasting evolution, it’s essential to enable a holistic view of the city. To achieve this, we must integrate every important aspect of the city, seen as a complex system, and provide an understandable view for the stakeholders. This can be achieved by enabling domain experts from relevant fields such as energy, mobility, sociology, or buildings, among others, to integrate their findings and views with one another. Such an integration allows for novel views as well as more meaningful integrated insights. For example, understanding the social milieu of a district could help derive certain mobility patterns, which in turn enable novel aspects of multimodal transport planning, and so on. The fuel for these integrated insights are the domains experts’ different models that express certain facets of their respective domains. To enable these models, we must supply

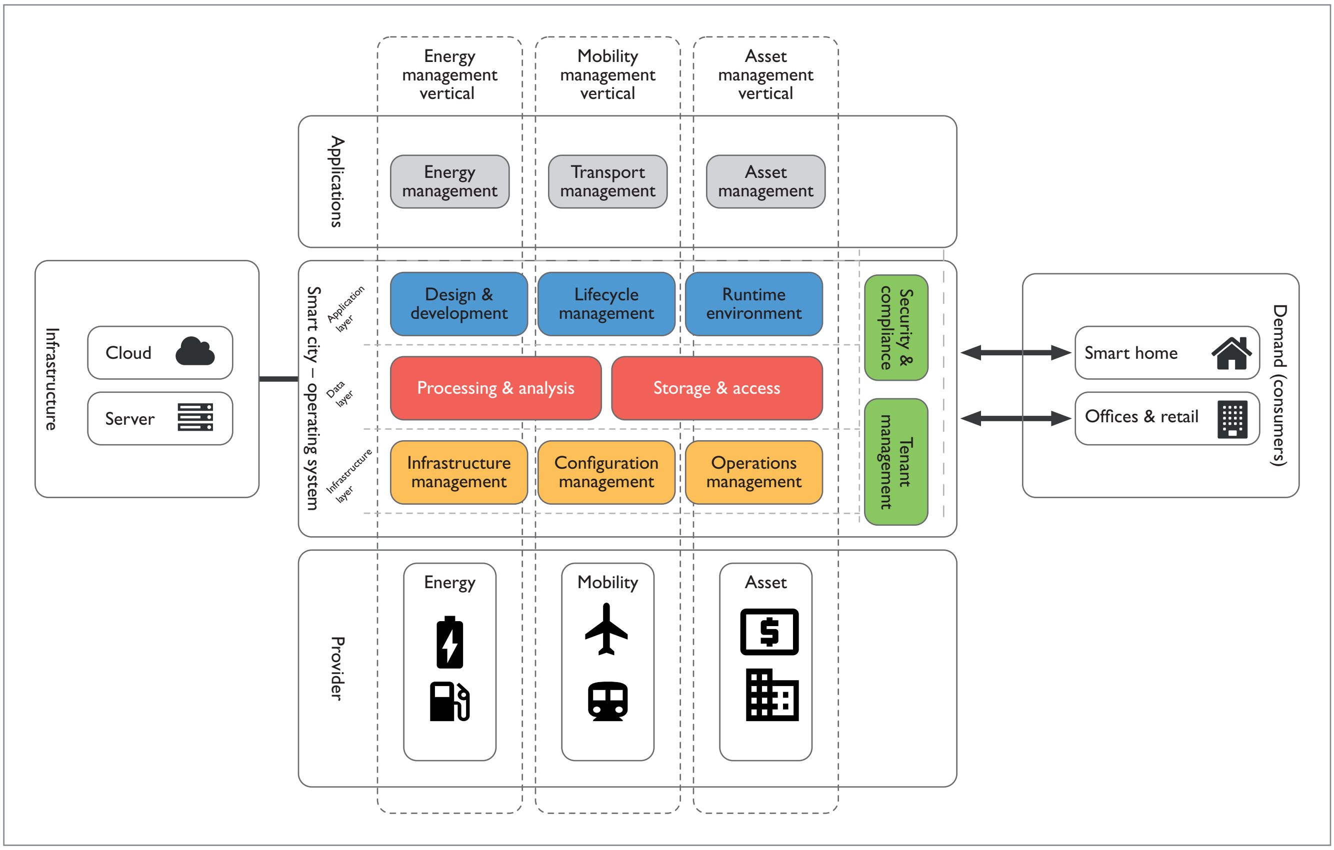

*Figure 1. Smart City Application Ecosystem (SCALE) architecture. Beyond helping practitioners build applications with novel capabilities emerging through the Internet of Things (IoT), SCALE also helps them efficiently access the massive amounts of data generated.*

them with the most accurate and novel data about the city. Then they can provide a more precise analysis of a city's current situation, while also supporting more accurate forecast and prediction models.

**Requirements.** To enable this case, the following requirements must be met: For the domain experts to be able to use the most current and accurate data in their respective models, they must be able to access all the relevant data provided by the city. This massive amount of data comes from a wide variety of sources, ranging from the IoT, to open data sources, up to old documents. This means that there needs to be a way to manage massive amounts of diverse data while also integrating heterogeneous data sources. Because the experts rely on proven tool stacks to implement their models, which in turn consist of a number of legacy systems combined with older mature system stacks, it's vital to support legacy systems and tool stacks for model building. Additionally, all these models need the computational capacity to provide their results in a reasonable amount of time, which calls for infrastructure resource provisioning for efficient model execution. Finally, the smart city domain with its many stakeholders and data providers has a highly complex set of security and compliance constraints. Therefore, to optimally use all the available data, it's essential to provide measures for compliance and security enforcement.

**Approach.** To enable the presented case, we must address the outlined requirements. Thus, we introduce a blueprint here that accomplishes this by utilizing several components of the SCOS. We show the blueprint for this smart city planning in Figure 2, which consists of four main parts. In order to support the stakeholders in understanding and exploring the complex aspects of the city in a holistic way, we introduce a visualization component. It enables geospatial visualizations of different aspects of the city by integrating the results of the domain experts' models.

The second component that's relevant for stakeholder interaction is the decision-support component, which provides detailed analytics and statistics based on the aforementioned integration of different domain model results. Both components rely on SCOS support in two main areas. First,

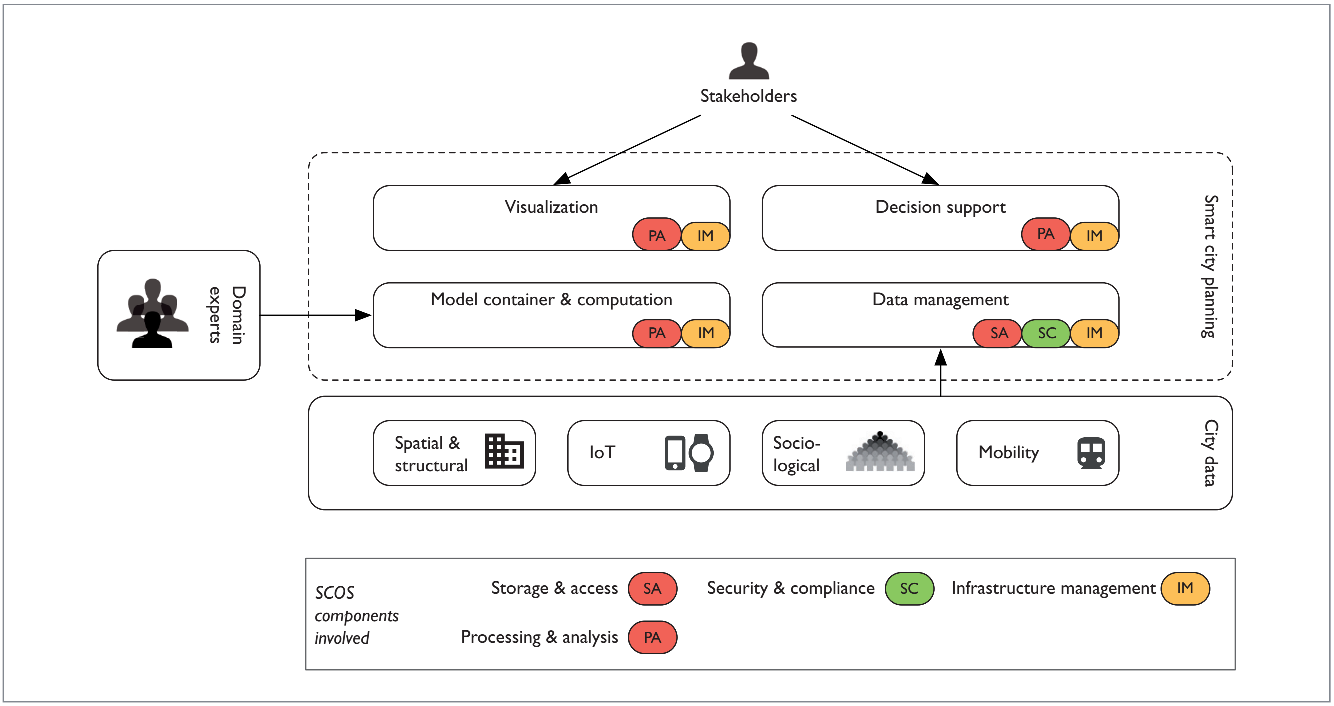

*Figure 2. Smart city planning blueprint. SCOS stands for Smart City Operating System.*

they need processing and analysis's pre-built services in order to be able to effectively prepare the data for visualization and decision support. Additionally, they rely on infrastructure management to provide them with the necessary infrastructure resources to efficiently perform their tasks.

Both components in turn rely on the model container and computation component, which is responsible for executing the domain experts' models. This component is tightly integrated with the data management component, which ensures that the experts are able to access all the diverse city data that's in turn used as the basis for their models. Additionally, it facilitates the standard and pre-built services provided by the SCOS's processing and analysis to support the model building when feasible.

The data management component acts as a domain-specific data managing entity, and is used by all other components. It ensures that the complex compliance and security requirements originating from the different data providers are being met by utilizing SCOS's security and compliance. Additionally, it utilizes the storage and access, as well as the infrastructure management components to ensure efficient and effective data handling of the massive amount of city data.

## Case 2: Smart City Infrastructure Management and Operation

A city consists of a network of complex systems that interfuse all layers of its infrastructure. From building and traffic management up to grid management, controlling all these systems becomes more data-intensive and complex, but also more capable. Increasingly, this is the case with the rise of the IoT, where more and more sensor and devices become critical elements of said infrastructure.

Thus for stakeholders, it's imperative to have processes that enable the effective management and operation of these complex systems in a transparent and efficient way. First and foremost, stakeholders need means to configure and control this cyber-physical infrastructure, so they can manage it in a logically centralized way (which is a vital factor for cost efficiency).

The second important facet is the distributed autonomous and timely control of this infrastructure, to be able to act and react to fast-changing circumstances. This is not only essential in areas such as building management — where heating, ventilation, and air conditioning (HVAC), lighting, or access control systems need to be managed — it becomes even more important in areas such as traffic and grid management. The ability to have fine-grained, instant control is crucial for enabling multimodal transport management or paving the way for the advent of autonomous cars, where crossroad management becomes a highly sophisticated task. Integrating smart metering facilitates smart management of grid use and leads to significant cost reductions for operators and consumers alike.

Finally, all this information needs to be composed in a smart manner, so that operators can control the systems and physical infrastructure efficiently.

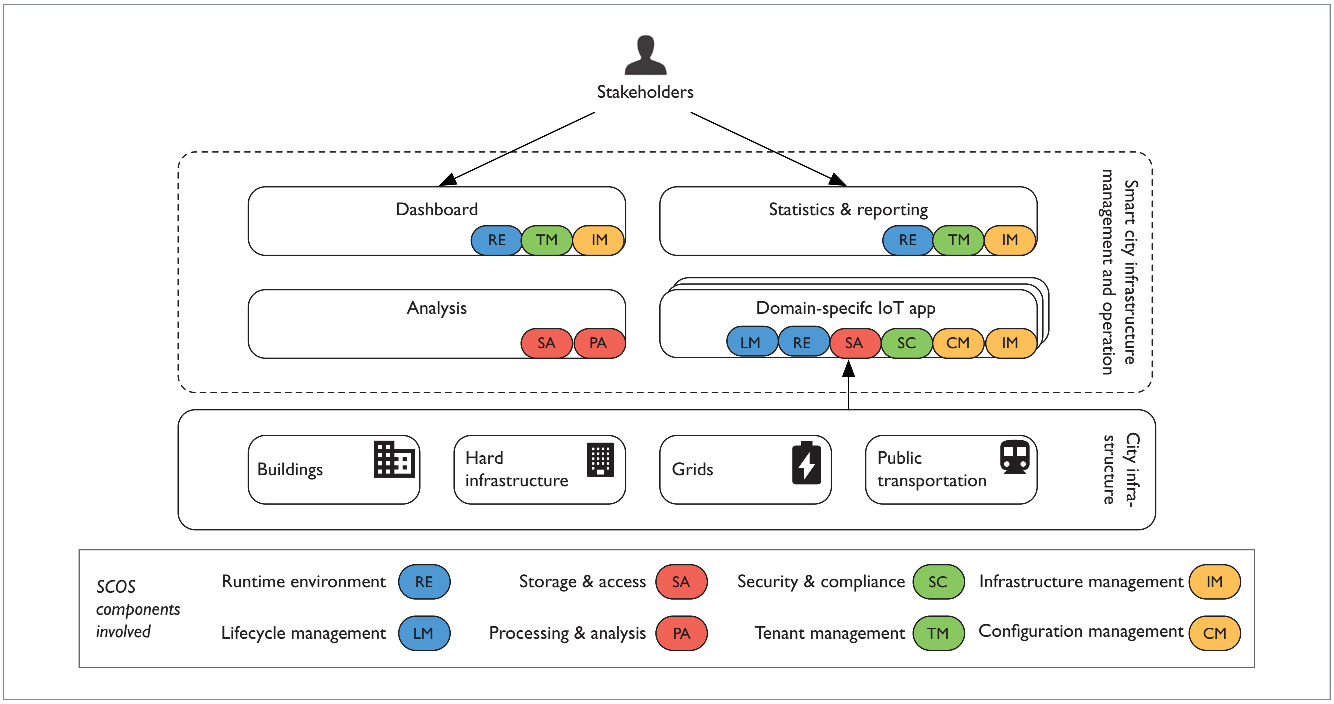

*Figure 3. Smart city management and operation blueprint. The blueprint consists of four main parts, supported by various components of SCOS, to manage and operate available smart city infrastructures such as buildings, hard infrastructure (traffic lights, bridges, and roads), energy grids, or public transportation.*

**Requirements.** In order to allow such smart infrastructure management and operation, several requirements need to be met. First, there needs to be a way to provide IoT device lifecycle management. This includes ways for device provisioning, management, and integration. Next it is vital to provide IoT cloud application lifecycle management, which calls for means to provide the necessary cloud infrastructure resources to enable these IoT devices. Additionally, means for IoT applications lifecycle management need to be covered to ensure applications can be deployed and updated including the vital element of fault handling. The large amounts of data these systems generate call for a way to manage this massive amount of diverse data. Last but not least, these integrations touch many security critical domains so it is essential to provide compliance and security enforcement.

**Approach.** To address the identified requirements for the presented case, we introduce the Smart City infrastructure management and operation blueprint in Figure 3. In essence, the blueprint consists of four main parts, which are supported by various components of SCOS, to manage and operate available smart city infrastructures like buildings, hard infrastructure (traffic lights, bridges, roads), energy grids, or public transportation.

First, to allow stakeholders to easily gain insights of the managed smart city infrastructure, we introduce a dashboard component. Dashboards support displaying both real-time, processed, and historical performance data (such as energy consumption) of the infrastructure. Furthermore, dashboards are specifically built for non-technical users, to avoid the need for custom programming, while supporting great flexibility by providing visual designers that allow stakeholders to create visualizations that are tailored to the available data and demands.

Second, next to dashboards, another important aspect in infrastructure management and operation is the statistics and reporting component. This component supports stakeholders in creating customized reports and statistics about the managed infrastructure, which can be used to deliver transparency into the gained performance data, and furthermore promote compliance.

Third, to provide the required data for the first two components, we introduce an analysis component. Based on the gathered and processed data that's provided by SCOS via the storage and access, the analysis component is able conduct specific operations such as examining trends in the collected infrastructure data (for example, power conditions or temperature readings). Additionally, the analysis component facilitates standard and pre-built services provided by SCOS's processing and analysis. The analysis results can then be used to identify problems in the future or areas that require maintenance. Following this approach can increase the uptime of the infrastructure by

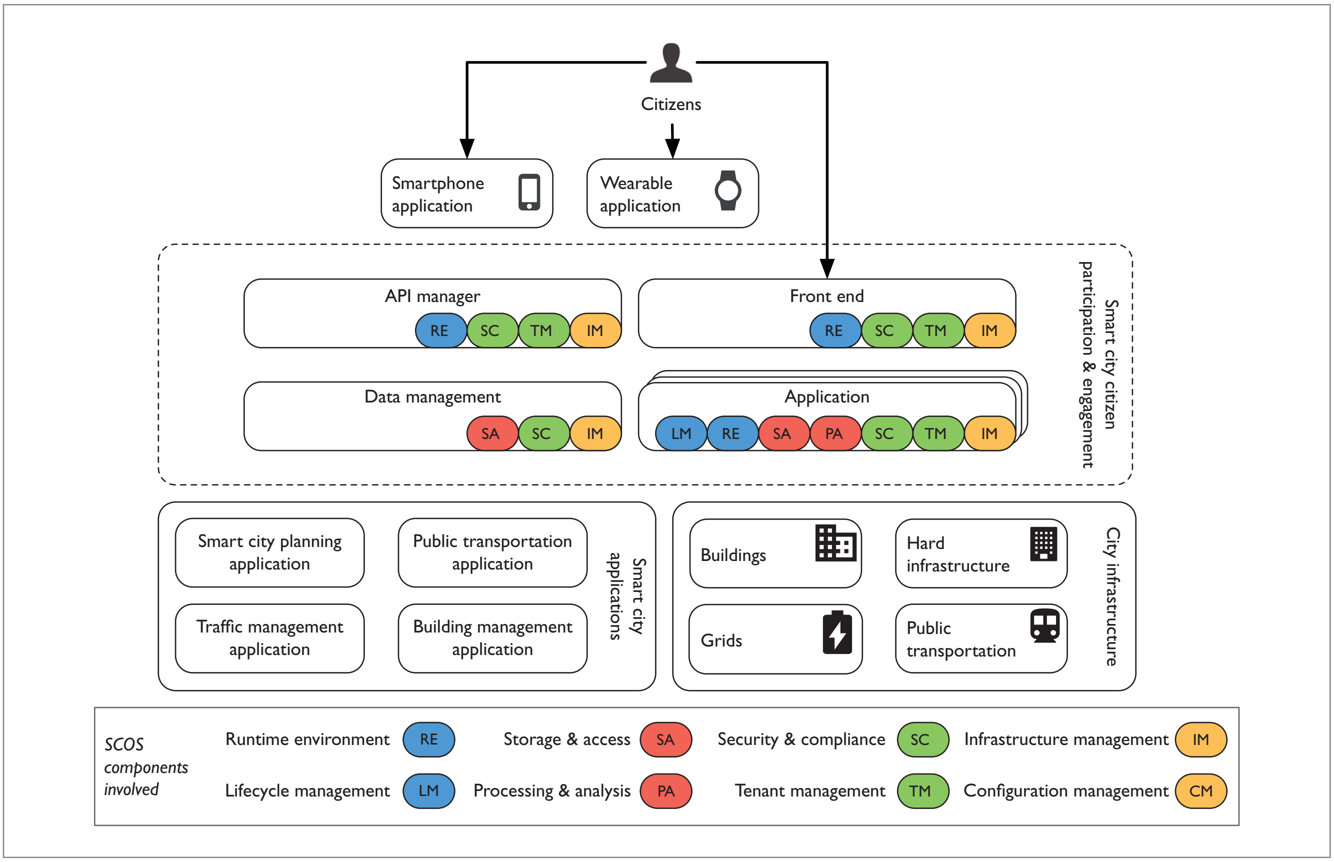

*Figure 4. Smart city citizen participation and engagement blueprint. Citizens access the application using Web-based front ends or native applications deployed on smartphones or wearable devices that access the application through a managed API (provided by the API manager).*

dealing with issues before they cause downtimes.

Finally, to collect data from the actual infrastructure and execute business logic, we facilitate a set of domain-specific IoT apps. These domain-specific apps can be executed in SCOS or directly in the actual smart city infrastructure. The apps gather data by facilitating the magnitude of IoT resources that are residing in the smart city infrastructure and are managed by SCOS. Furthermore, next to data collection, the domain-specific apps are able to control IoT resources to react to changes in the environment or optimize energy consumption of the managed infrastructure. To discover and communicate with IoT resources, the applications use the infrastructure management and configuration management of SCOS. While the apps are executed by facilitating the runtime environment of SCOS, SCOS also manages their complete application lifecycle via the lifecycle management. Furthermore, because both the dashboard and statistics and reporting component require data and resources of multiple domains, SCOS handles and possibly restricts access to shared resources via the tenant management.

## Case 3: Smart City Citizen Participation and Engagement

Another core tenet of smart cities is the close integration of citizens with various aspects of the city to increase citizen well-being and quality of living. Examples of such citizen participation and engagement applications are smartphone-based city transport information systems that let users quickly, efficiently, and ecologically travel through the city while anonymously providing data to transportation providers and city administrators. In turn, this data can be used to more accurately estimate upcoming demand, optimize city traffic by redirecting citizens away from congestions in both public and individual transports, and guide infrastructure planning.

Another case is the integration of social media feeds to detect potential trends in citizen movement or concentration points, to help first responders prevent or shorten the detection time of disaster scenarios. The utility of such applications is manifold, and not only benefits providers and citizens alike, but also creates a better understanding of the city as an adaptive system that benefits engagement. To enable the creation of such services, it's essential to provide means for composing and integrating data from multiple smart city applications, ranging from transport and infrastructure management to grid control, up to applications in the social media domains. Based on these data, we need fast-feedback loops that let citizens and providers act on new information as soon as possible.

**Requirements.** Such citizen participation and engagement applications are characterized by a number of requirements. Because these applications heavily rely on data from many different stakeholders in the smart city — ranging from public transport providers and road traffic authority, up to energy providers — we must ensure that there's a unified way to securely and efficiently access data from multiple other smart city applications. Also, due to the integration and enrichment of information from multiple sources, there must be a way to effectively manage large amounts of diverse data. Integrating data about citizen movement and the use of city infrastructure further requires that compliance and privacy regulations are guaranteed, and that relevant security policies and tenant requests are enforced. Additionally, the runtime infrastructure for the application must be elastically provisioned and, if possible, deployed on cloud and edge infrastructure to minimize latency and communication costs while maximizing utility for citizens.

**Approach.** The blueprint shown in Figure 4 serves as a guideline to successfully implement citizen participation and engagement applications in smart cities based on four core building blocks. Citizens access the application using either Web-based front ends, or using native applications deployed on smartphones or wearable devices (such as smart watches) that access the application through a managed API (provided by the API manager). These two components are deployed on the SCOS utilizing the runtime environment and they handle all citizen-facing interactions. Additionally, they rely on security and compliance to ensure that the critical compliance and privacy regulations are met, as well as on tenant management to respect the various different tenant requests. Last, they rely on infrastructure management to provide the necessary resources for elastically running them on cloud or edge infrastructures.

The data management component provides a unified and secure abstraction for access to data from multiple underlying smart city applications. To ensure this, it relies on storage and access for data integration into the smart city applications and city infrastructure. Additionally, it utilizes security and compliance to ensure no data regulations are infringed, as well as the infrastructure management to acquire the necessary resources. At the core of every citizen participation and engagement application is the custom application logic that actually provides added value and comfort to citizens. Applications can make use of a number of SCOS components to ease provisioning and management, as well as deployment and runtime.

The ideas we presented here are an essential stepping stone along the path of smart cities evolving towards the Internet of Cities, an open market place where applications can interact and be exchanged between cities. To enable these applications and to encourage a rapid adoption and deployment, it's essential to understand common problems and how to address them. Here, we outlined blueprints for three representative types of smart city applications, and identified their key requirements, along with architectural guidelines to implement them based on our experience with SCALE. While smart city applications are diverse, there are multiple common aspects that should be present in a smart city application platform — primarily infrastructure and data management; security and compliance management; and a lifecycle and runtime environment for applications. Using an ecosystem such as SCALE, which incorporates these elements, lets practitioners efficiently and effectively implement complex smart city applications that are secure, scalable, and resilient. In our ongoing and future work, we plan to identify additional types of smart city applications and provide respective blueprints to address arising challenges.

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