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Editorial

Advancements and potential pitfalls for smart cities and sentient infrastructures

As urban areas struggle with increasing challenges related to population growth, climate change, the built environment, and public well-being, the concept of smart cities has emerged as a transformative solution. A smart city refers to the seamless integration of advanced information and communication technologies (ICT) with existing urban infrastructure to enhance efficiency, sustainability, and quality of life, thereby reshaping the future of urban living [2]. Originating in the early 2000s with a focus on "top-down" technology deployment [9], the practice has evolved owing to the rapid growth of digital infrastructure-such as broadband networks, smart sensors, and open data platforms, which has enabled cities to become dynamic environments that foster real-time decision-making and community participation [6]. Contemporary smart city initiatives increasingly recognize the importance of "bottom-up" innovation, where residents actively contribute to the design and improvement of urban services [17]. This evolution reflects a shift towards emphasizing connectivity, citizen engagement, and a more human-centric approach to urban challenges. The collaborative, living-lab approach positions citizens as agents of change, making cities more adaptive and responsive to evolving needs. Despite these advancements, the development of smart cities still involves several challenges. Beyond technological deployments, ethical issues such as privacy, data security, and equitable access to technology are critical hurdles that must be addressed [1]. Moreover, the growing complexity of managing interconnected urban systems demands innovative governance frameworks that ensure interoperability while balancing technological progress with inclusiveness and sustainability. Ultimately, the success of smart cities will depend on the ability to create resilient, data-driven communities that empower their residents and prioritize both human well-being and environmental stewardship.

Focusing on the internal components of smart cities, complex infrastructure system plays a pivotal role. These systems are becoming increasingly essential in urban management due to the growing complexity arising from interconnected components and parallel subsystems. They are characterized by evolving dependencies and spatiotemporal constraints and are integrated as System-of-Systems (SoS) ([8,11,13]). This complexity is compounded by abundant and diverse data, cross-disciplinary functional requirements, and complicated operational procedures [15]. Large-scale infrastructure systems are dynamically reconfigured based on updated events or uncertainties, where multiple resources and operations in different parallel subsystems must be synchronized in a timely manner [4,14]. Urban infrastructure systems comprise multiple heterogeneous components with differentiated functions, technologies, and forms, which frequently update real-time states and adjust control parameters of various parallel subsystems [10]. The large-scale and parallel nature of these systems further increases the complexity and uncertainty in the combinatorial solution space and optimal solution-searching schemes [7].

For instance, urban water supply systems face significant challenges due to aging infrastructure, particularly in U.S. municipalities where some pipes date back to the 19th century [5]. Almost all pipes are buried underground, system status is challenging to inspect, leaving many small leaks undetected. Consequently, limited information is available for efficient water distribution management. Cutting-edge concepts such as digital twins have been explored as a means to improve water systems [3], forming the sentient infrastructures. Sentient infrastructure refers to a next-generation infrastructure system that is embedded with advanced sensors, artificial intelligence, and real-time data processing capabilities, enabling it to "sense", "think", and "respond" dynamically to environmental conditions and user needs. The digital components in urban water systems, often based on hydraulic simulations, complements the physical water distribution system, which includes pipes, pumps, valves, and treatment stations [16]. The physical component comprises the water distribution system, including pipes, pumps, valves, and treatment stations. The link between the physical and digital components relies heavily on real-time sensing and SCADA (Supervisory Control and Data Acquisition). However, not all components, such as valve statuses and pipe conditions, are yet integrated into SCADA systems [12]. Developing and maintaining a sentient and intelligent infrastructure system must account for all changes to the digital twin system. Appropriate protocols are required to create and manage data streams. There are promising opportunities for deploying digital techniques in water distribution systems for applications such as leak detection, pump station design, pipeline condition assessment, pressure management, and pump operation optimization [18].

All in all, smart technologies will continue to influence how we plan and design cities, how we manage urban infrastructures, how we engage people in the decision-making processes. But this process also deserves a critical reflection: Is smart city an intellectual pitfall? The first pitfall is the real-time trap: in some situations, we do need real-time decisions to be made automatically (e.g. rerouting traffic, detecting gas leaks); but for others, we do NOT—and we should NOT. Decisions that have long-term impacts should not be made in real time, should not be automatized, and should not be deliberated by digital polls. They require time to let ideas and opinions to mature, to be molded by the community. The second pitfall is the to consider big data as the only acceptable data. Some phenomena do not generate any data. For instance, electronic waste in cities export has major environmental consequences; and as it is mostly a criminal enterprise it does not leave traces, even less big data. Should we ignore the problem because there is no big data available to train our A.I. models? The third pitfall is the

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hidden privacy leaks. When social media private posts, personal emails, or credit cards transactions data are exposed, this is major media scandal and a dangerous privacy invasion. However, the GPS traces of our smartphones, the energy consumption measure by smart devices, and home water consumption can also reveal how we live, our approximate socioeconomic profile, the places we visit in the city. All of this is essential for smart cities optimization; but they can also reveal people's profile very close to personal identification. This is the best moment to discuss the trade-offs between what smart technologies can bring to our cities and urban systems, making them more efficient and more livable in the present, while securing that our "real-time" decisions include a multi-generational perspective, be attentive to phenomena and social behavior that produce small or no data, and preserve a healthy balance between individual privacy and social benefits.

In conclusion, the concept of smart cities and internal sentient infrastructures holds immense potentials to reshape urban life through the integration of advanced technologies, dynamic data-driven decision-making, and the empowerment of citizens as co-creators of their environments. However, these advancements come with an imperative to critically assess the implications and ethical responsibilities of their implementation. The successful realization of smart cities depends not only on technological sophistication but also on a thoughtful approach that considers the long-term societal, environmental, and individual impacts. By fostering transparency, ensuring equitable access, and striking a balance between real-time efficiencies and mindful deliberation, we can harness the transformative power of smart cities while safeguarding the values of privacy, inclusivity, and human well-being. This dual focus on innovation and ethical reflection will be crucial for building urban environments that are not only intelligent but also resilient, adaptive, and humane, ultimately creating cities that truly serve the needs of both present and future.

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