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IoT-Enabled Food Systems as Core Urban Infrastructure in Smart Cities

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Abstract – This study examines the digitalization of food systems in smart cities, focusing on the role of the Internet of Things (IoT). In much of the research, food systems are viewed as a logistical element rather than as part of the core urban infrastructure. At the same time, they are essential for the functioning of the urban environment, as they are directly related to sustainability, resource efficiency, and quality of life. The lack of a clearly defined architectural framework limits the possibilities for their systematic integration and management. This necessitates a new conceptual approach within which food systems are viewed as a separate infrastructure layer. In response, this paper proposes a conceptual architecture that positions IoT-based food systems as an equal component of the smart city. The proposed framework provides a clearer basis for the analysis and design of smart food systems. It supports better management, higher efficiency, and sustainable development of the urban environment.

Keywords – Food Safety 4.0, food systems, Internet of Things (IoT), smart cities, urban infrastructure.

1. Introduction

The concept of smart cities can be viewed as an integrated management approach that uses information and communication technologies to more effectively manage urban functions and resources, thereby achieving sustainable development, increasing service efficiency, and improving citizens' quality of life. In this sense, a smart city is not just a technologically equipped territory, but a complex system in which physical infrastructure, digital technologies, and human activities function as interconnected elements in a common environment [1–3].

A key factor in implementing this concept is the Internet of Things (IoT) – a network of connected devices and sensors that exchange data in real time and support the management of transport, energy, environmental, and other urban systems [1,3,4]. In recent years, significant scientific interest has been directed towards the development of multi-layered IoT architectures, in which data processing is performed both in a centralized cloud environment and at a local level near the data source. These approaches provide faster response, higher reliability, and the ability to efficiently process large volumes of information [5–8]. Similar architectural models are being applied across areas such as energy, intelligent transportation, environmental monitoring, healthcare, and public services, enabling adaptive, data-driven urban management [6,9,10].

Despite these technological advances, the integration of food systems into smart city infrastructure remains underrepresented in the scientific literature. Existing research emphasizes the importance of food systems for sustainability, public health, and quality of life, but most often considers them from a social, environmental, or political perspective, rather than as part of urban infrastructure [11–13]. At the same time, research in the field of smart food chains, precision agriculture, and IoT-based solutions in the food industry shows significant technological progress. They encompass smart manufacturing, food quality monitoring, cold chain management, and logistics process optimization, often using IoT platforms, data analytics, and artificial intelligence [14–22].

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However, most of these solutions are focused on individual stages of the food chain and are rarely considered in the context of the overall urban infrastructure. As a result, food systems continue to be treated as a stand-alone technological sector with limited interaction with key urban subsystems such as energy, transport, healthcare, and environmental management. This results in the absence of a comprehensive architectural framework that positions food systems as an infrastructure layer within the IoT ecosystem of the smart city. This deficit limits the possibilities for integrated management, data exchange, and systemic optimization of urban processes.

To address this problem, this study proposes an original conceptual framework for integrating IoT-based food systems into the smart city architecture. The main contribution of the study lies in the development of a structured architectural model framework that positions food systems as a stand-alone infrastructure layer, equivalent to traditional urban subsystems such as energy, transport, and healthcare. The proposed model defines clearly distinguished structural levels, key functional components, and explicitly specified interactions between them. It provides a systematic basis for the analysis, design, and management of digitalized food ecosystems and supports a more integrated and sustainable approach to urban development.

2. Methodological Approach

The present study aims to analyze the role of IoT-based food systems in the architecture of smart cities. The methodological approach is not aimed at empirical testing of a specific system, but at generalizing and interpreting existing scientific developments, technological models, and architectural solutions.

The study is based on an analysis of peer-reviewed scientific literature, standards, and conceptual models in the field of Internet of Things, smart city architectures, Food Industry 4.0, and Food Safety 4.0. The analysis considers the various technological and functional components of the urban environment as interconnected subsystems within a common infrastructure.

The study compares the main infrastructure systems of the smart city – such as energy, transport, water supply, and healthcare – with the architectures of modern digitalized food systems. This allows the identification of similarities, functional dependencies, and opportunities for integration between food systems and other urban infrastructures.

The literature is selected from established scientific databases, including IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and Taylor & Francis. The selection includes publications on IoT architectures in urban environments, the digitalization of food chains, and the integration of IoT with technologies such as artificial intelligence, data analytics, and blockchain.

In the study, food systems are considered not as a separate industrial sector but as part of urban infrastructure, alongside energy and transport systems. By unifying IoT sensor networks, data processing platforms, and intelligent analysis algorithms, a conceptual framework is built that positions food systems as an integrated component of smart city architecture.

It should be noted that the lack of empirical validation limits the ability to directly assess the effectiveness of the proposed framework in real urban conditions. However, the proposed approach can serve as a basis for future empirical studies and pilot applications.

3. Conceptual Framework for IoT-Enabled Food Systems as Core Urban Infrastructure

Within smart city architectures, food systems have traditionally been viewed as sector-specific economic and logistical processes located outside the core of urban infrastructure. This study offers an alternative conceptual perspective, treating IoT-enabled food systems as a core infrastructure layer of the smart city, comparable in systemic importance to energy, transportation, and water supply.

3.1. Food systems as an infrastructure layer

Food systems in urban environments are essential to societal functioning, as they are directly linked to public health, social stability, and economic security. In this context, access to safe food, continuity of supply, and sustainability of food chains are considered key elements of a smart city, not merely the result of logistical or market processes [11, 23].

Modern research increasingly considers food systems as part of critical infrastructure, comparable to energy, transport, and water supply. This suggests that they should be modeled as a separate infrastructure layer that includes interconnected processes such as production, processing, storage, logistics, the cold chain, and distribution [24]. In this sense, the efficiency and sustainability of food systems depend not only on optimizing individual stages but also on coordinating and integrating the entire system, as well as on its interactions with other urban subsystems.

Within the proposed conceptual framework, the food system is defined as a separate infrastructure layer that operates through three main components: (1) physical processes related to food production,

storage and transport; (2) a communication environment provided by IoT technologies and sensor networks; and (3) a data processing and analysis layer that allows for real-time monitoring, forecasting and management. The interaction between these components ensures a continuous flow of data and creates conditions for integration with other urban systems.

IoT technologies play a key role in this structure by enabling continuous monitoring and management of processes across the food chain. Using sensors, low-power communication technologies, and analytical platforms, a digital-physical infrastructure is created that connects the individual stages within a single information environment [25]. This supports risk management, increases transparency, and optimizes resource use.

Empirical research shows that IoT-based solutions contribute to improving the sustainability of food systems through more efficient use of resources, reduced losses, and better adaptation to dynamic conditions in the urban environment [26]. In this sense, food systems should be considered not as an isolated sector, but as an integrated infrastructure layer that contributes to the sustainable development of the smart city.

3.2. Architectural components of IoT-enabled food infrastructure

This study proposes a four-layer adaptation of the classic IoT model widely used in smart city systems (Fig. 1). The architecture builds on the conceptual model presented in Section 3.1, formalizing the food system as an infrastructure layer integrated into the smart city's IoT ecosystem.

The proposed model is structured in four interconnected layers: (1) physical layer, (2) communication layer, (3) data processing and analysis layer, and (4) management layer. These layers function together in a single digital-physical environment in which real food processes, communication technologies, and analytical mechanisms are integrated [25].

The first layer of this architecture, called the Physical/Perception Layer, implements the physical processes of food production, storage, transport, and delivery. At this level, sensors monitor parameters such as temperature, humidity, and storage conditions. This allows for timely detection of problems and reduces the risk of food spoilage [23, 26]. Within the proposed architecture, food systems are considered as observable and controllable infrastructure integrated into the city's digital environment.

Next comes the communication layer, which provides a connection between devices and data processing systems. Through communication networks and protocols (e.g., LoRaWAN), sensor data is transmitted in real time [27] to the next layer for processing and analysis. Here, the data is stored and analyzed using cloud and edge technologies [11, 25]. This layer also uses artificial intelligence algorithms that process raw sensor data, support predictive analysis (e.g., risk of spoilage), and detect anomalies (e.g., elevated temperatures), thereby transforming the data into actionable information for food chain management. This improves logistics and food safety [26, 28]. The final layer is the management layer. It allows city authorities and operators to monitor the system and, based on analysis results, make informed decisions using artificial intelligence algorithms [25, 29]. Thus, the proposed architecture provides an opportunity for food systems to be integrated into the broader smart city management mechanisms as a full-fledged infrastructure component.

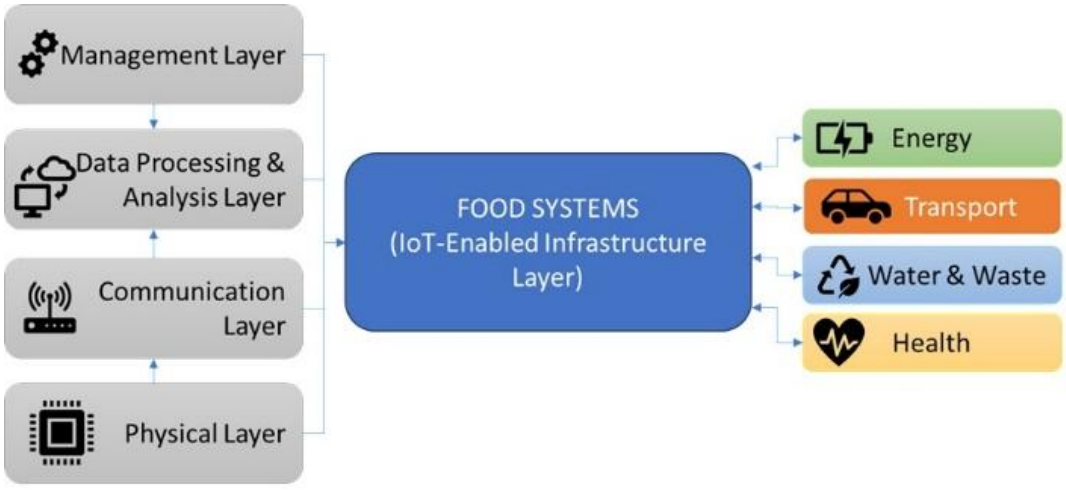


Figure 1. Conceptual architecture of IoT-enabled food systems as an infrastructure layer in smart cities

3.3. Horizontal integration with other urban subsystems

In addition to being a stand-alone multi-layered system, IoT-enabled food infrastructure should also be considered in the context of its integration with other smart city subsystems. In modern smart city architectures, it is assumed that effective management of urban resources requires the exchange and joint analysis of data between different infrastructures, rather than their isolated operation [11, 25].

One of the main examples of such interaction is the relationship between food systems and intelligent transport systems. Real-time data on the status of cold chains, warehouse inventory, and logistics flows can be combined with transport data on traffic and route load. This allows for supply optimization and reduction of losses along the food chain [30].

Interaction also exists between food and energy infrastructure. In urban and vertical farming, food processes are closely linked to energy and water consumption. Data from IoT sensors for lighting, irrigation, and microclimate enable better resource management and coordination with urban energy networks [11, 26].

An additional aspect is the link between food systems and waste management. Data on food surpluses, shelf-life, and logistics flows can be used by smart waste collection and processing systems, creating opportunities to reduce food losses and use resources more efficiently [31, 32].

Finally, integration with public health systems enables analysis of data on food consumption, safety, and quality. This can support risk monitoring and the development of preventive health policies [29].

In this sense, food systems function not only as logistical processes but also as connecting infrastructure elements in the digital-physical architecture of the smart city.

3.4. Technological Eutopia in the Context of Food Systems

The proposed architectural model allows the interpretation of IoT-based food systems not only as a technological solution, but also as part of the broader concept of technological utopia. In this context, digital technologies are applied to achieve balanced and sustainable urban development by integrating various infrastructure systems [11, 32].

Within the presented architecture, IoT-based food systems enable continuous monitoring, data-driven decision-making, and coordinated management across the different stages of the food chain. This allows for more efficient use of resources, increased transparency, and a more reliable food supply.

The integration of sensor technologies, communication networks, and analytical platforms creates opportunities for early risk detection, improved traceability, and better control of food quality and safety [28, 29]. These functionalities are directly related to the layered architecture described in Section 3.2 and to the horizontal integration mechanisms discussed in Section 3.3.

At the urban level, the proposed model supports the development of more sustainable and adaptive food systems by improving coordination with transport, energy, and environmental infrastructure. This contributes to reducing food losses, more efficient use of resources, and improved public health.

4. Discussion and Implications

The proposed architectural model provides a structured framework for integrating IoT-enabled food systems into smart city infrastructure. Its adoption and implementation can help city authorities make more informed decisions, improve food chain management, and contribute to a more reliable supply of safe food to the population, while having a positive impact on public health and quality of life.

The use of data generated by IoT-enabled food systems enables better logistics planning and more effective control over food storage and transportation conditions. Combining it with information from intelligent transportation systems helps optimize routes and reduce delivery delays. This contributes to reducing food losses along the supply chain and to more efficient resource use. At the same time, fuel consumption and carbon emissions are reduced, which has a positive impact on the environment.

Implementing this architecture faces several challenges. On the one hand, compatibility between sensor networks, communication protocols, and analytical systems is required. For the food industry, this implies a transition from isolated technological solutions to integrated platforms connected to the rest of the urban systems. On the other hand, integrating IoT and artificial intelligence into food systems raises questions about data protection and algorithm transparency. This highlights the need for responsible information management and clearly defined control mechanisms. Despite its potential benefits, the proposed framework is conceptual and has not been empirically validated. This opens up opportunities for future research, including piloting in real urban settings and assessing its impact on the efficiency of food chains, public health, and sustainable management of urban resources.

5. Conclusions and Future Research Directions

This paper presents an expanded conceptual framework that includes IoT-enabled food systems in smart city architectures, positioning them as a core

infrastructure layer rather than a peripheral application.

The main contribution of the study is to argue for integrating food systems at the architectural level through IoT sensor networks, analytical platforms, and intelligent information systems. Such integration can improve traceability along food chains, reduce food waste, and better manage risk in urban environments.

Despite its conceptual value, the study has limitations related to the lack of empirical validation. Future research could focus on the practical application of the proposed framework in real urban settings, as well as on assessing its impact on food system efficiency and public health.

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