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The Intersection of the Internet of Things and Smart Cities: A Tertiary Study

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Abstract Since the transition from an agricultural to an industrial economy, cities have attracted large masses of people in search of their facilities. Cities are symbols of progress and opportunities. However, urbanization also brings with it several problems and challenges. Smart Cities (SC) offer a way to address these challenges by using technology to make cities more efficient, sustainable, and livable. There are numerous technologies that enable the concept of smart cities, including the Internet of Things (IoT). The IoT provides the fundamental sensing infrastructure that allows connecting and virtualizing the physical world, extracting environmental variables that serve as initial inputs for decision-making processes. Such processes are provided by software systems whose construction and execution need to deal with the dynamism, heterogeneity and often serendipitous nature that permeate both the domains of smart cities and IoT. As the integration of IoT and Smart Cities paradigms is still at an early stage, and there are not yet holistic solutions to explore the full potential of such a synergy, we carried out a literature review on the topic. In particular, the objective of this article is to describe the results of a structured literature review to identify general concepts about quality attributes, applications, technologies, and challenges of IoT solutions applied to the SC domain. Our main goal is to assist in understanding the basic concepts of the research area through the search for secondary studies. This review is a tertiary study covering 17 reviews and aims to promote a high-level discussion on the identified characteristics and provide an overview of the area to promote a better perception of current development needs and opportunities.

Keywords: Smart Cities, Literature Review, Internet of Things

1 Introduction

Since the transition from an agricultural economy to an industrial economy, cities have attracted large masses of people in search of their facilities and opportunities. Urbanization is a worldwide phenomenon that became particularly significant from the mid-18th century onwards and has become increasingly aggressive. If recent predictions come true, by the year 2050, approximately 70% of the world's population will be concentrated in some type of city [United Nations and Affairs, 2018]. Historically a symbol of progress, opportunity and resilience, cities have continually driven major technological and social changes. However, such human concentration and the need to provide resources to sustain the growing population bring a vast range of challenges. The human cost of disasters in cities can be devastating, reflecting both their high population density and their interdependent infrastructure. In addition to dealing with natural or human-caused risks, it is necessary to ensure comfort and safety for citizens in order to maintain the vision of cities as prosperous and attractive places. Therefore, leaders, governors, scientists, and technologists have increasingly sought solutions to build truly resilient, pleasant, and sustainable cities.

In this context, the concept of Smart Cities emerged and has been consolidated, recently leaving theory to gain ground in practical implementations. The concept of smart cities dates back to the 1970s, when Los Angeles created the first urban big data project: "A Cluster Analysis of Los Angeles". The first smart city is considered to be Amsterdam, with the creation of a virtual digital city in 1994. Research and investment in Smart Cities accelerated in the mid-2000s, when IBM and Cisco launched initiatives exploring this concept. In 2011, the first Smart City Expo World Congress was held in Barcelona, which has now become an annual event charting the development of smart cities.

Although there is no standard definition, a city is considered smart if it incorporates Information and Communication Technologies (ICTs) to improve its operational efficiency and well-being for citizens by providing high-quality and optimized services [Alavi *et al.*, 2018]. Certainly, to deal with the countless facets of a smart city, it is necessary to make use of a myriad of techniques, technologies, services and enabling tools. Any technological solution aimed at meeting the requirements of building smart cities must first involve massive monitoring of the urban environment and the delivery of relevant data to decision-making systems. Such decision-making must be agile and cannot be performed in isolation, but rather providing administrators with holistic views of the various processes occurring in the city. To achieve this goal, deep and seamless integration of individual systems and applications that support urban processes is necessary. Given the highly dynamic nature of cities, adaptability and rapid response to variations in the environment are also fundamental requirements. All these requirements pose several challenges related to the building of software systems to support smart cities. Such systems must have a close relationship with the physical world, incorporating monitored data from the city's real environment as part of their inputs. In this context, the Internet of Things (IoT) [Atzori *et al.*, 2010] emerges as one of the most important enabling technologies.

IoT can be defined as a paradigm that allows composing software systems from uniquely addressable objects (things) equipped with identification, sensing, or actuation capacities and processing resources to communicate and cooperate to achieve a goal. This broader perspective considers that everyday objects can enhance their original behavior through software, introducing a new dimension of communication between humans and objects, as well as between objects themselves [Motta *et al.*, 2019]. The potential and advantages offered by IoT extend beyond the interaction of smart objects. They primarily stem from the wide range of applications that leverage the vast amount of data generated by the physical world and transform them into useful information to support decision-making and generate valuable knowledge for users [Qin *et al.*, 2016]. According to Dirks and Keeling [2010], the IoT serves as a foundational technology, particularly in the context of Smart City (SC), as a sensor infrastructure. Multiple applications in an SC exploit the IoT capacities. For instance, IoT devices geographically scattered, such as cameras, intelligent traffic lights, air pollution sensors, and location and presence sensors, can be used in cities for applications of public safety, road condition management, calamity alerts, and citizen health and well-being.

In this scenario, we performed a structured literature review to identify general concepts regarding quality attributes, applications, technologies, and challenges of IoT solutions applied to the SC domain. The goal is to help build an understanding of the basic concepts of the research area by searching for secondary studies.

This article is a tertiary study - a review of secondary studies - that intends to promote a high-level discussion on identified results. We aim to uncover the overlap between SC and IoT, contributing to advancing the understanding of this dynamic field. Since previous research in these domains is more independent, this review presents a richer overview by systematically synthesizing secondary studies. It provides an organized and collective view of characteristics, applications, and the technologies IoT solutions require when applied to the SC domain. Furthermore, by presenting multifaceted challenges and research gaps, this study can contribute to a roadmap for overcoming obstacles to their realization, thus providing insights for researchers and stakeholders. The remainder of the paper is structured as follows. In Section 2, we present the adopted methodology along with the quantitative results. Section 3 provides the answers to the posed questions with further discussions as well as validity threats. The main conclusions from the paper are summarized in Section 4.

2 Conceptual Background

The goal of this section is to give a summarized overview of the IoT and SC paradigms, as a way of providing the reader with some grounding for reading the article. Our intention is in no way to provide exhaustive material on two such broad topics, but only to contextualize and introduce the fields and relevant concepts.

2.1 Internet of Things

The term Internet of Things (IoT) was coined in 1999 by Kevin Ashton, co-founder of the Auto-ID Center at MIT (USA), now Auto-ID Labs. The initial focus of this laboratory's research, and therefore the context in which the IoT paradigm emerged, was on RFID technology. Such initial vision of IoT, centered on RFID, was later expanded to encompass sensors of the most varied types and wireless sensor networks, resulting in complex ecosystems integrating the physical and virtual worlds.

The Internet of Things is a paradigm that provides for the interconnection via the Internet of physical objects, and potentially these with other entities and virtual resources. In the IoT view, physical objects (things) are equipped with sensors and actuators, capturing environmental variables, and reacting to various external stimuli. Such objects can be addressed, controlled, and monitored via the Internet.

IoT ecosystems have high complexity, heterogeneity, and distribution. Organizing its elements according to an architecture helps to deal with such complexity when designing and developing IoT systems. There is a growing standardization effort for IoT protocols, and several architectural proposals can be found in the literature [Al-Fuqaha *et al.*, 2015], covering different numbers of layers (generally from three to six), each layer with different responsibilities. There is not yet a reference model for building IoT systems, but most proposals consider the organization of such systems into at least 4 layers, namely:

Things Layer: Also called the Physical, or Perception Layer, it encompasses sensors capable of collecting physical variables, obtaining the most diverse types of data, such as temperature, movement, vibration, acceleration, humidity, etc. It can also include actuators, devices capable of changing the state of the environment (for example turning on/off a switch). This layer is responsible for producing the big data volumes of the IoT. It digitizes and transfers such data to the Object Abstraction layer, preferably through secure channels.

Object Abstraction Layer: Also called the Network Layer, it abstracts the physical objects and transfers the data produced by the Object layer to the Service Management layer or directly to Applications that consume the data. Data can be transferred via various technologies such as RFID, NFC, 3G/4G/5G, GSM, UMTS, Wi-Fi, Bluetooth Low Energy, infrared, ZigBee, LoRa, etc.

Service Management Layer: Also called the Middleware layer, it is responsible for abstracting distinct types of heterogeneities in the IoT system, such as protocols, data formats, etc. This layer provides several types of infrastructure services, required by all applications, such as translation (of formats, protocols, etc.), discovery (of devices and services), synchronization, identity management, concurrency control, persistence, stream processing, etc. Using this layer allows IoT application developers to work with heterogeneous devices/data without considering specific platform/hardware/network details.

Application Layer: Provides the specific services requested by customers/end users. In other words, it provides high-quality intelligent services to meet the needs of end users. The Application Layer covers multiple vertical markets (domains) such as smart homes, smart buildings, smart cities, industrial automation, and healthcare.

The realization of the IoT paradigm depends on several elements and enabling technologies (IoT Building Blocks). The literature points to at least five fundamental building blocks for the IoT. The **first Building Block** encompasses object identification and addressing. Identification denotes uniquely identifying a specific object (thing), and it is crucial for naming services and matching with their demands. There is no standardized way to identify objects in IoT, but a relevant example is electronic product codes (EPC), a standard designed as a universal identifier that provides a unique identity for every physical object anywhere in the world. Its compact binary format is suitable for efficiently storing an EPC identifier within RFID tags. Unlike an identifier, the address of an object refers to its identification within a communication network. Addressing methods for IoT objects include (but are not limited to) IPv6.

The second **Building Block** is sensing. Sensing in IoT means collecting data from interconnected objects and sending it, either to other objects, or to a gateway, a data warehouse, database, or to the cloud. Collected data is analyzed to make specific decisions/actions based on the services required by the application. IoT sensors include smart sensors, wireless sensors, wearable devices, RFID tags, they can integrate to compose a wireless sensor network, and are typically produced by several manufacturers. Communication is the third **Building Block**. There are several technologies for communication in IoT, which currently vary in terms of range and data rate. In contrast to the traditional Internet, which was leveraged by the ubiquitous use of the TCP/IP stack, there is no standardized protocol stack tailored for the IoT, but there are standardization efforts by entities such as IEEE and IETF.

Computing concerns low level data processing operations and operating systems. IoT data processing can be done in situ, in gateways or other devices located at the network edge, or in the cloud. This building block encompasses specialized and embedded hardware and their respective operating systems. In addition to embedded computing, another important part of IoT computing is cloud computing platforms. They provide facilities for processing large volumes of data produced by objects, and for end users to benefit from the knowledge extracted from the collected data, from any location. Finally, the services **Building Block** denotes high-level computational services, such as information fusion, discovery services, identity management, data analysis, among others. They are often provided by middleware platforms, and some require high computational power. In particular, services for extracting knowledge from data (inference processes, data analytics, data mining, etc.) are generally executed in the cloud.

The wide dissemination of IoT has the potential to generate a significant impact on people's lives in various application domains. Among these, the domain of Smart Cities stands out, where IoT is one of the main enabling technologies. Close and continuous instrumentation and monitoring of the physical world are fundamental requirements to provide the data that will feed decision-making processes capable of making cities truly smart and sustainable.

2.2 Smart Cities

The rapid advancement of contemporary urban centers has given rise to significant challenges in public sectors like healthcare, mobility, security, energy consumption, parking, and others. In this scenario, the smart city concept emerged as an application domain of IoT [Silva *et al.*, 2018], integrating physical, social, business, and ICT infrastructure. It leverages IoT devices, such as interconnected sensors and actuators, for collecting data and sending commands or signals, composing applications for improving public services and enhancing the efficient usage of resources.

Smart Cities rely on technology to enhance the resilience of cities in addressing challenges related to sustainability and the quality of life for their inhabitants. In this context, a fundamental transformation is necessary to truly make a city smart that can have positive impacts on social, economic, and human aspects. It is essential to have ICT components for gathering and analyzing extensive data from various sources, including sensor networks, traffic systems, and citizens' devices. The abundance of data facilitates the creation of applications capable of influencing the daily lives of individuals. These applications aim at improving urban services and play a key role in fostering economic growth, promoting environmental sustainability, and enhancing the overall well-being of both individuals and society.

In this scenario, smart city platforms offer potential solutions by streamlining application development, addressing the challenges posed by the dynamic and heterogeneous urban environment, and providing essential functionalities like managing extensive data volumes, data analysis, monitoring, scalability, and privacy policies. These platforms must deal with critical aspects, including the integration of data from diverse sources, ensuring secure access to data, incorporating geographic information that accurately reflects the real-world urban landscape, and establishing an integrated infrastructure with services spanning various city domains such as education, health, safety, and more.

In smart cities platforms, information from each domain is linked with geographic data specific to its location, providing a comprehensive and multidimensional view. This approach facilitates correlations across numerous aspects of a city, extracting valuable insights [Souza *et al.*, 2017]. However, dealing with data heterogeneity and the lack of standardization requires adopting a unified data model with semantic support, fostering both interoperability and semantic queries. Moreover, security emerges as a key concern in this complex scenario, characterized by thousands of users accessing information from diverse sources, underscoring the critical need for robust protection and controlled access. As smart cities are an ever-changing scenario that constantly evolves according to the context and urban demands, dynamic adaptation support is an important mechanism.

Although Smart Cities have been receiving considerable attention from both academia and industry, there are several open problems that require further investigation to deal with the extensive scope of Smart Cities.

3 Literature Review

The adopted research protocol followed the recommendations of Biolchini *et al*. [2007] and Budgen and Brereton [2006], well-established for this type of study, and it is available online [1].

Before undertaking any literature review, it is essential to observe its necessity. The initial step in this context of our research was to search for existing literature, and we found secondary studies on IoT for SC already published. For this reason, in this review, we consider secondary studies in SC, and therefore we classified it as a tertiary study.

A tertiary study refers to the analysis of existing secondary studies associated with defined research questions (in our case, in the domain of SC). Different from primary studies (firsthand empirical investigation for specific research questions) and secondary studies (reviews of primary studies), tertiary studies seek to explore mappings, identify patterns and trends through the synthesis derived from secondary studies.

As technology advances rapidly, numerous initiatives have been conducted regarding SC in general, and a few on the intersection of SC and IoT in particular. However, the available information is often dispersed across different sources, making it challenging to access a consolidated overview. This tertiary study aims at providing such a consolidated view, with a high level of abstraction, serving as a valuable resource, bringing together existing research findings, and fostering knowledge synthesis in the field.

The research goal [Basili *et al*., 1994] of our work is defined as follows: *To analyze IoT applications for Smart Cities with the purpose of characterizing them regarding their quality attributes, application areas, used technologies, and challenges from the point of view of software engineering researchers in the context of secondary studies available in the technical literature.*

3.1 Planning

The planning stage aids the research protocol's preparation. It includes the research objectives, search terms, selection process, and an extraction form to support gathering relevant information from the chosen articles.

Research Questions. This study aims to review secondary studies and identify general concepts regarding characteristics, applications, technologies, and challenges of IoT solutions applied to the SC domain. The goal is to help build an understanding of basic concepts of the research area by searching for secondary studies. The following research questions (RQ) were defined.

Quantitative Questions:

- RQ1: How many secondary studies have been identified per publication year?
- RQ2: What are the venues where the secondary studies have been published?
- RQ3: What are the authors' affiliation countries of the selected secondary studies?
- RQ4: Which types of secondary studies have been executed?
- RQ5: What is the number of primary studies analyzed by the selected secondary studies?

Qualitative Questions:

- RQ6: Which quality attributes are addressed in existing IoT solutions applied to the SC domain?
- RQ7: Which are the applications of IoT solutions in the SC domain?
- RQ8: Which technologies are used in IoT solutions for the SC domain?
- RQ9: What are the challenges for IoT solutions in the SC domain?

Considering the posed questions, we intend to search secondary studies, research-based peer-reviewed articles. By quality attributes, we denote characteristics, traits, features, or properties that make the solutions achieve their purposes, and it can provide an indicator on the degree of satisfaction of the solution in achieving its objective. Applications for IoT regards vertical applications, within the broader domain of SC, which will benefit from the full deployment of IoT in a Smart City, e.g., transportation, logistics, healthcare, etc. As for technologies, we are interested in techniques, methods, principles, and tools that enable the IoT for SC operationalization while challenges represent open issues and research gaps in the area.

Search Strategy. We defined the approach to select sources aligned with our research objectives. For source criteria, we defined it to include works presented as articles available on the web, ensuring accessibility and relevance to the selection. The language was set to English to maintain consistency and facilitate a comprehensive understanding of the material. Scopus [2] database served as the primary source, since it has an extensive coverage of academic literature with peer-review articles, indexing several databases.

Selection Criteria. To support the selection of retrieved studies, we defined the following criteria.

- **Inclusion Criteria**: Provide an answer to RQ1 AND/OR, provide an answer to RQ2 AND/OR; provide an answer to RQ3 AND/OR, provide an answer to RQ4.
- **Exclusion Criteria**: Not provide an answer to any of the RQs; OR Duplicate publication or selfplagiarism; OR Register of proceedings OR not in English.

Search String. Since the review focus is to retrieve information based on secondary studies, the search string should reflect the intersection with IoT and SC, and was defined as:

[1]The replication package is available online: https://doi.org/10.5281/zenodo.7786510.

[2]Scopus has the broadest coverage of interdisciplinary citation database, making the odds of missing key publications reduced. More information: https://www.scopus.com/.

((”systematic literature review” OR ”systematic review” OR ”mapping study” OR ”systematic mapping” OR ”structured review” OR ”secondary study” OR ”literature survey” OR ”survey of technologies” OR ”review of survey” OR ”technolog* review*” OR ”state of*”) AND (”internet of things” OR ”iot”) AND (”smart cit*”))*

Procedures for Selection. Three distinct readers evaluated each study. The studies acceptance criteria were as follows:

- Title selection: One reviewer reads the title of each retrieved study and evaluates it according to inclusion and exclusion criteria.
- Abstract selection: The study is included if two readers accept OR one reader accepts, and one is in doubt. The study is not included if two readers exclude OR one reader accepts, and one excludes OR both readers are in doubt.
- Full-reading selection: The reviewers divide the remaining papers among themselves, read and extract according to the extraction form, and recommend including or not. The reviewers then cross-review each other’s extractions and reach a consensus on which papers will compose the final set. The study is included if two readers accept OR one reader accepts, and one is in doubt. The study is not included if two readers exclude OR one reader accepts, and one excludes OR both readers are in doubt.

3.2 Execution

Three researchers performed the review in March 2023 and the review was updated in April 2024. There were different trials for the string adjustment as we tried to balance coverage and relevance. Figure 1 presents an overview of the selection process.

- Initial: 892 documents.
  First filter: 33 proceedings removed (859 documents remaining).
  Title selection: 540 documents removed by title reading (319 documents remaining).
- Abstract selection:
  279 documents removed by abstract reading by the reviewers (40 documents remaining for full reading).
- Full-reading selection:
  23 documents removed by full reading by all three reviewers (17 documents accepted)

After establishing the search string, the search resulted in 892 articles, with 859 remaining after removing duplicates and proceedings. Later we applied Title (540 papers removed) and Abstract (279 papers removed) selection with 40 papers remaining for a full reading. The final set comprises 17 papers from which we extracted relevant information for the findings reported.

To support the selection and review of the articles, we defined a Data Extraction Form, as presented in Table 1. This step aims to aid in the capture of relevant information from the selected articles to answer the proposed research questions.

Figure 1. Steps for selecting the relevant studies.

Table 1. Data Extration Form

Field	Description
Reference Information	Authors, title, year, and venue (Support to answer RQ2, RQ3).
Abstract	Abstract.
RQ4 Type of Study	It is expected to have only secondary studies, represented by Survey, SLR, and others. Include study properties such as RQ, search string, selection criteria, number of primary studies. (Support to answer RQ5)
RQ6. Quality Attributes	Quality Attributes as characteristics, traits, features, or properties that make the solutions that define and make the solutions achieve their purpose. Verbatim, as presented in the article (Definition research-based derived or with reference) .
RQ7. Applications	The domain that will benefit from the full deployment of the IoT idea and its applications related to SC.
RQ8. Technologies	Techniques, methods, principles, and tools that enable the IoT for SC operationalization, including the development strategies used to build IoT software (requirements analysis, design, and so on).
RQ9. Challenges	Open opportunities in practice or research
Additional Information	Interesting information – if applicable.

A limitation of every literature review is regarding the study’s comprehensiveness and ensuring it is up to date. This concern is especially relevant in SC and IoT academic fields, where developments evolve quickly. Conducting a tertiary study is resource-intensive, requiring significant time and effort from researchers, and we consider this to be a comprehensive review of the literature covering up to 2023. However, as future work, we plan to execute an update. We intend to give time for more significant developments to accumulate, providing a richer body of data for analysis in future updates.

3.3 Results

In our findings, most of the studies define that a smart city’s objective is improving the quality of life of the citizen, along with its economic development. Despite the differences in achieving this goal, authors claim the importance of building a technological infrastructure to optimize, manage and support decision-making based on data and intelligent services.

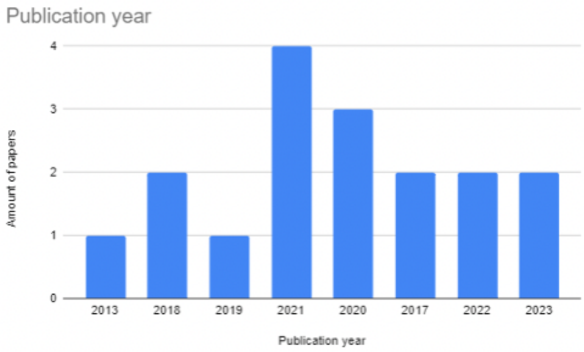

Figure 2. Selected study per Publication year.

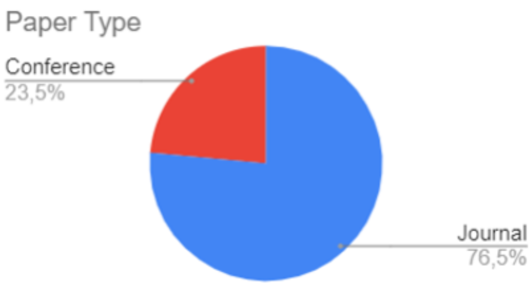

Figure 3. Publication venue for the selected studies.

The results of the RQs complement this understanding. We report in this section the findings for RQ1 to RQ5, that are of a more quantitative nature. To enrich the discussions, RQ6 to RQ9 are reported in the next section.

RQ1: How many secondary studies have been identified per publication year? Figure 2 presents an overview of the publication year, spanning from 2013 to 2023. A deeper discussion on this matter can be interesting, considering the primary studies selected in each paper.

RQ2: What are the venues where the secondary studies have been published? Figure 3 presents an overview of the publication venue, covering Journal or Conference. Most of the selected articles are from journals. This can relate to our study focus since review papers are more extensive than research papers. Considering the venues where the secondary studies have been published, IEEE Access had three publications among the selected ones. Other journals represented were Lecture Notes in Networks and Systems, Computer Networks, Smart Cities, Sensors, and ACM Computing Surveys, among others.

RQ3: What are the authors' affiliation countries of the selected secondary studies? Regarding the authorship of the 17 selected studies, we had 79 authors listed with 18 unique affiliation countries. Most of the selected studies have authors with affiliations from only one country, which can indicate low collaboration between countries in this topic. With 20 authors, 27for Brazil, and 1210Iran, China and Colombia each with 4Czech Republic, Greece, and Italy with 3representation we had Vietnam, Tunisia, Yemen, and Turkey with representation of one author. Regarding organization, 33four or three authors, while 20had five authors (13had eight authors listed.

RQ4: Which types of secondary studies have been executed? The article's study type is presented in Figure 4. During the selection and extraction, we covered the study type and study properties (such as protocol, RQs, search string, selection criteria, and others). If a study provided enough information to replicate it, it was considered an SLR (Systematic Literature Review). For Literature Survey and Bibliometric Study, they provided some information on the study execution but were not so formal. On the other hand, Informal Reviews provided no information on their execution and properties.

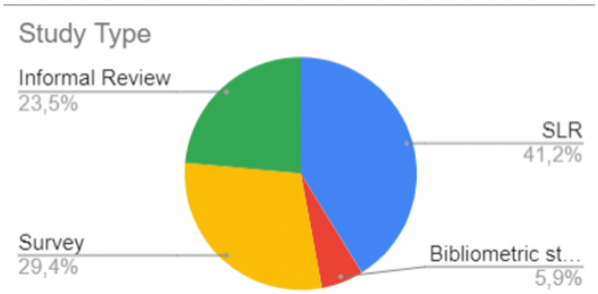

Figure 4. Study type executed in the selected articles.

RQ5: What is the number of primary studies analyzed by the selected secondary studies? There were 662 primary studies identified by the secondary studies that were included in this review. The paper with most primary studies listed is Ghannem *et al.* [2017], with 188 papers. Zhou *et al.* [2023] has 83. Both Zeng *et al.* [2023] and Asghari *et al.* [2019] had 72 primary studies. Kumar *et al.* [2022] considered 67, Singh *et al.* [2022] covered 52 papers, and Santana *et al.* [2017] included 47. In other studies, Ahmed *et al.* [2020] had 33 primary studies listed, Khan *et al.* [2020] with 19, Kirimtat *et al.* [2020] had 18 and Tomas *et al.* [2013] with 11 papers. For the remaining studies Nayak *et al.* [2021], Syed *et al.* [2021], Medina *et al.* [2017], Puliafito *et al.* [2021], Gopinath *et al.* [2021], and Hejazi *et al.* [2018] it was not possible to extract such information. It fits with what was identified in RQ4, since most of these are Informal Reviews.

To have more insights in our selection, this study applied the VOS viewer bibliographic tool [van Eck and Waltman, 2010] for mapping term co-occurrence. In this analysis, we created a map of the most frequently occurring keywords for all 17 publications. We selected co-occurrence from the title and abstract as the type of analysis. We isolated the 18 most frequently occurring terms in the articles and the VOS viewer transformed the data into a map, classifying the frequently occurring words into two main clusters. Larger circles and map labels represent greater importance and significance. and keywords with similar colors belong to the same cluster (Figure 5).

In Figure 5, clusters are differentiated by red and green. The first cluster (marked in red) exhibits nine frequently occurring keywords. In this cluster, challenge, architecture, technology, information, and citizen are very near each other and the Smart City, reinforcing the relationship with our research questions. The other cluster (in green) includes IoT and Review terms, having IoT, Internet, and Thing the most relationships.

Figure 5. Term co-occurrence map from VOS viewer.

4 Answers and Discussions

To answer the RQs, we used pertinent information, patterns, similarities, and differences in the extracted data as the basis for our qualitative analysis. The analysis was carried out using all the data extracted and enriched by discussions among the researchers.

4.1 RQ6: Which quality attributes are present in existing IoT solutions applied to the SC domain?

All 17 selected articles included information on quality attributes and presented a rich source of characteristics with several excerpts extracted. However, most authors simply list attributes (and their relevance in the respective context) without providing a detailed explanation of their meaning. The absence of definitions for quality attributes and the lack of insight into the authors' intentions makes it challenging to have a deeper understanding of this subject. The mere enumeration of characteristics without explicit definitions hinders a broader characterization of the topic.

Another thing to consider is that the quality attributes extracted cover a wide range of concepts. In this way, we organize the attributes according to the authors' statements regarding three categories: i) Smart Cities attributes (Table ii) IoT Applications attributes (Table 3), iii) Attributes related to network, cloud, edge, or fog (Table 4).

Some attributes are repeated between the categories, but without the proper definition, it is unfeasible to affirm if they have the same meaning. For this reason, we decided to list all the findings extracted from the source studies. These tables represent the strategy and rationale for analysis, being presented with the same structure. In the three tables, we list separately the attributes that were explicitly defined in their respective studies, and those that, although were not, have definitions that are well known and accepted in the community. We used these diverse analyses to represent the contribution of these findings since these three different perspectives can be applied to the three tables, providing valuable insights for further research.

Table 2 presents the list of extracted attributes related to Smart Cities. These attributes reflect the diverse and complex nature of SC systems, emphasizing their importance since they are not just technical specifications; but represent multifaceted goals of implementing IoT in urban environments.

Table 2. . List of extracted attributes related to Smart Cities.

CATEGORY				
SMART CITIES	**Characteristics with known definitions in the community**			
	Reusability	Reliability	Ubiquity	Accountability
	Energy Efficiency	Location awareness	Granularity	Trustability
	Characteristics with explicit definition from the primary studies (*verbatim*)			
	Sustainability: Sustainability is related to pollution, energy, climate change, and ecosystems [Singh *et al.* 2022].			
	Quality of life: The quality-of-life attributes of citizens are intended to progress their welfare [Singh *et al.* 2022].			
	Urbanization: Urbanization and smartness attributes include transforming technology, infrastructure, and management from rural to urban environments [Singh *et al.* 2022].			
	Intelligence: "Intelligence" is explained in terms of the wish to raise the community, environmental, and financial standards of cities and their people [Singh *et al.* 2022].			
	Cognitive abilities: Cognition is the ability of a system to learn from previous experiences and adapt its behavior based on them. A cognitive system can sense, perceive, and respond to changes in the environment, and can therefore improve a system's performance by increasing its adaptive capacity [Tomas *et al.* 2013].			
	Interoperability: Different devices, systems, applications, and platforms compose a Smart City environment, and all these components must operate in an integrated fashion [Santana *et al.* 2017].			
	Scalability: The number of users, data, and services of a Smart City platform will be massive and can increase over time [Santana *et al.* 2017].			
	Security: Malicious users can make fraudulent use of services and data provided by the platform [Santana *et al.* 2017].			
	Privacy: A Smart City platform collects and manipulates several citizen-sensitive data, such as medical records, user localization, and consuming habits. The challenge is to use these data while hiding, or to avoid saving identifiable information [Santana *et al.* 2017].			
	Context Awareness: As the city and user situation can change over time, many applications and services can provide better results using contextual information [Santana *et al.* 2017].			
	Adaptation: Many platforms adapt their behavior based on context to achieve fault-tolerance, choose a closer server to improve efficiency, decide for batch or real-time processing, and adapt data [Santana *et al.* 2017].			
	Extensibility: The capability to add services, components, and applications to the platform is important to assure that it meets evolving system requirements and user needs [Santana *et al.* 2017].			
	Configurability: A Smart City platform has many configuration options and parameters that define its behavior at execution time, such as defining pollution and congestion thresholds and the priority of services. Thus, it is important to allow (re)configuration of the many variables of the platform [Santana *et al.* 2017].			

Eight characteristics listed have known definitions, making it possible to infer what the authors mean by them, and analyze their relevance in the context of SC. For example, in software engineering, Reusability denotes the use of existing assets in some way in the software product development process; These assets typically include code, software components, test suites, designs, and documentation. This attribute promotes greater agility in the construction of systems, especially large ones that involve a great need for integration, as is the case with systems for smart cities. Reusing solutions or parts of existing solutions boosts development and reduces delivery time.

As SC systems can be considered systems of systems, there will certainly be a high degree of reuse in the building of such solutions. Reliability refers to the ability of a system to perform functions under specified conditions for a specified period [ISO/IEC, 2011]. In general, it covers subcharacteristics, of which availability and fault tolerance can be highlighted. Availability refers to the ability of an application to be operational and accessible when needed for use; in other words, it is the degree of readiness for usage. Fault tolerance denotes the ability of an application to function as intended, despite the presence of (partial) hardware or software failures. Both are relevant in smart cities, especially for critical applications, where a system failure or unavailability can pose risks to human life. Ubiquity or pervasiveness denotes the ability to be present everywhere, at any time.

The concept of ubiquitous computing, coined by Mark Weiser in the 90s, advocated transparent computing, integrated into the very fabric of daily life, emphasizing implicit interactions between computing systems and users. It can be considered as a precursor to the IoT vision, where the emphasis was on the provision of customized and personalized services, based on the instrumentation of the environment and the learning of human habits and preferences. It is easy to see the relevance of this attribute in a smart city, where computing will need to be present everywhere, supporting and enhancing the various processes, preferably in the least invasive way possible.

Table 3 presents the list of extracted attributes related to IoT Applications for SC. By examining the characteristics with and without explicit definitions in Table 3, we tried identifying potential relationships and dependencies between them. This mapping was based on the author's previous experience with SC and knowledge on this topic. While the explicit definitions provide clear insights, some characteristics without explicit definitions may still share underlying connections based on their general context and relevance within IoT and SC. For example:

- **Reliability and Dependability**: *With Definition:* Reliability is explicitly defined as the dependability and correctness of the IoT system [Syed *et al.*, 2021]. *Without Definition:* Dependability (dependable) is mentioned without explicit definition. These two characteristics typically have a close relationship, both contributing to the overall robustness of IoT applications. Reliability was already discussed in the context of SC, since it is typically a relevant attribute for such systems as well.
- **Security and Privacy**: *With Definition:* Security is defined as encompassing both physical security and cybersecurity [Khan *et al.*, 2020]. *Without Definition:* Privacy is a characteristic without an explicit definition. However, privacy is often a component of security in IoT applications.
- **Sustainability and Energy Efficiency**: *With Definition*: Sustainability is dealing with energy-efficient design, using renewable energy sources, and reducing the carbon footprint [Khan *et al.*, 2020]. *Without Definition*: Energy Efficiency is a characteristic without explicit definition. However, the relationship between sustainability and energy efficiency implies a connection, as both concepts relate to minimizing energy consumption.

Table 3. List of extracted attributes related to IoT Applications for SC.

CATEGORY IOT APPLICATIONS	**Characteristics with known definitions in the community**			
	Openness	Precision	Privacy	Safety
	Connectivity reliability	Energy Efficiency	Transparency	Flexible
	Resilient	Dependable	Recoverable	Customizable
	Configurable	Data integrity	Versatile	
	Characteristics with explicit definition from the primary studies (*verbatim*)			
	Adaptable and self-adaptable. They can adapt their behavior to changes that may occur in their operational contexts, environments, and system requirements, and are called Adaptive Systems (ASs). Researchers define adaptive systems as systems that can modify their behavior and/or structure in response to their perception of the environment [Ghannem *et al.* 2017].			
	Reliability and robustness refer to the dependability and correctness of the IoT system. IoT is the backbone of future smart cities and being imperative to their operation, the IoT system needs to provide a smooth experience to its users [Syed *et al.* 2021].			
	Context Awareness: An ability of the system to obtain information pertaining to the nodes' locations and surrounding environment [Khan *et al.* 2020].			
	Sustainability: This deals with energy-efficient design and the use of renewable energy sources. In addition, sustainability refers to energy harvesting, which takes energy from environmental sources and radio- frequency sources and stores it for further use. The primary objective of sustainability is to reduce the carbon footprint [Khan *et al.* 2020].			
	Scalability: The ability of a system to enable elastic services as per user demands without losing QoS, resulting in a cost-efficient operation [Khan *et al.* 2020].			
	Security: This refers to a device's physical security and cyber security. More specifically, cyber security deals with the protection of the network, computing infrastructure, and data from attacks [Khan *et al.* 2020].			

Some potential relationships suggest that certain characteristics without explicit definitions may be conceptually linked to those with definitions, sharing common themes and functionality of IoT applications for SC. This is limited since we cannot confirm the relationships, and this exercise only covers some of the attributes listed. However, this analysis enhances the understanding of quality characteristics and their interconnected nature as a step to cataloging and defining SC-related attributes.

In this regard, although not mentioned explicitly, Zeng *et al*. [2023] consider attributes relevant to the urban disaster management domain. Whether trying to detect and prevent disaster occurrence or mitigate its consequences, context awareness and adaptation attributes are crucial. Furthermore, the authors mention the need to have universal sensor technologies. However, in this absence, technology interoperability will be extremely necessary to speed up the establishment of the sensing and communication infrastructure. Regarding attributes related to IoT, the need to build resilient systems (mainly the communication part) that are dependable, reliable, and robust is identified. Self-adaptation is also an important requirement for quickly dealing with and reacting to disasters.

Among the attributes without explicit definitions in the studies, we can highlight three of them, with well-known meanings in the distributed systems community: transparency, resiliency, and openness. An important goal of a distributed system is to hide from its users and applications the fact that resources are physically distributed across multiple platforms. A distributed system that can present itself as a single system is called transparent. There are different types of transparency, such as access transparency, location transparency, concurrency, and failure transparency. Transparency is important for the maintainability and scalability of a system. However, in contemporary systems such as IoT, it is necessary to negotiate the degree of transparency with the efficiency of the system, as in some cases it is useful to expose low-level information to the application. For example, it is not always possible to hide the physical location of a service as the application or user may choose to use a closer one, which will offer better performance (shorter response time). Resiliency can be defined as the ability of a system or application to return to an acceptable operating state after facing an event that affects its operating conditions. It is an attribute closely related to dependability and fault tolerance, and essential in critical systems. An Open distributed system is one that offers services according to well-defined rules and standards. The main characteristic of an open system is the possibility of integration with other systems to work together. For this integration to work, the information must be documented clearly, which is generally done using protocols. Both IoT and SC systems are characterized by the need for a high degree of integration. Therefore, openness is an essential attribute to obtain the behavior and holistic vision desired for such systems.

Table 4 presents the list of extracted attributes related to network, cloud, edge, and fog for SC.

In Table 4, we can see more explicitly the self-* attributes such as Self-Configuration and Self-Healing. Interestingly, these are cited more often when relating to cloud, edge, and fog, reflecting a shift towards more adaptive and self-managing systems within the context of network solutions for Smart Cities. These characteristics indicate the development of an ecosystem where SC systems have an elevated level of autonomy, adaptability, and intelligence. It is related to reducing manual interventions and optimizing resource utilization in the face of constant change in urban environments.

Table 4. List of extracted attributes related to network, cloud, edge, and fog for SC.

CATEGORY				
NETWORK CLOUD EDGE AND FOG	**Characteristics with known definitions in the community**			
	Versatility	Adaptability	Security	Availability
	Extensibility	Configurability	Adaptation	Integrity
	Authenticity	Confidentiality	Authentication	Reliability
	Context awareness	Self-healing	Self-configuration	Elasticity
	Sustainability			
	Characteristics with explicit definition from the primary studies (*verbatim*)			
	Scalability: This parameter reflects the ability of a system to expand its services in response to the increasing demands of the users [Khan *et al.* 2020].			
	Flexibility: An ability of the system to provide computing infrastructure in an elastic way [Khan *et al.* 2020].			
	Cost Optimization: This refers to the ability of a system to provide users on-demand computing resources for optimizing the overall cost. In addition, it also refers to the cost associated with hardware and software in the acquisition of computing resources [Khan *et al.* 2020].			
	Automation: The ability to perform cloud updates without any intervention of the end users [Khan *et al.* 2020].			

This provides a great research opportunity since investigating how these self-capabilities can be standardized and implemented across diverse components will be crucial for ensuring SC solutions.

Another case for discussion is the absence of explicit definitions for several characteristics that can be related to the multidisciplinary nature of Smart Cities, incorporating aspects of urban planning (such as Society's awareness), and technology (such as Precision), thus contributing to a wide range of perspectives and interpretations. This multidisciplinarity can make arriving at agreed-upon definitions challenging, as different fields may approach these characteristics differently. Table 5 presents a list of these attributes.

Table 5. List of extracted attributes with no explicit definition in the papers.

Characteristics with no explicit definition in papers			
Seamless integration	Society's awareness	Quality of outcome	Correctness of service
Precision	Consistency	Performance	Comfort
Public Response	Heterogeneity	Convergence	Identity
Mobility	Productivity	Efficiency	Reputation

The absence of explicit definitions for characteristics in the context of IoT solutions applied to Smart Cities can lead to research and practical implementation challenges. One example of this challenge is design ambiguity. Consider "Comfort", for example. Without a precise definition, designers may struggle to determine the specific features or parameters contributing to a "comfortable urban environment." Is it related to temperature control, ambient noise and light levels, or other factors? This lack of clarity can result in confusing design choices, where developers may prioritize certain aspects of comfort over others, leading to solutions that may not align with city residents' diverse expectations and needs.

Summary of the findings: Our interpretation and analysis were based on what was reported from the selected studies. Despite being related concepts, it is important to differentiate them. For example, the "security" attribute can be addressed related to people, in the smart city perspective, or to data if we consider the cloud.

In total, 78 unique quality attributes are present in existing IoT solutions applied to the SC domain, from which 26 have definitions presented. Attributes such as Adaptation, Cost, Interoperability, Reliability, Security, Scalability, Sustainability, and the ones related to resource management are the most cited in every category. It makes sense to have these attributes as the most cited by the very purpose of the smart cities. For example, SC should be able to adjust to changing conditions, such as shifting populations and unforeseen occurrences like pandemics or natural disasters. Therefore, adaptive behavior and self-abilities contribute to this direction. Cost-effective SC comes together with Sustainability. The solutions must balance implementation costs with long-term advantages to maximize the resources and reduce environmental impact. Interoperability is at the core of contemporary systems to enhance efficiency and efficacy, so SC solutions must be irrespective of manufacturer or technology. Cities tend to grow, for this, solutions must be expandable and adaptable to change (scalability) and guarantee that crucial systems continue operating even during technical difficulties (reliability). Finally, security, since the whole city and the citizens will be united in the same solution. Therefore, SC solutions must be built with robust security features and protocols to preserve sensitive data and important infrastructure from attacks and unauthorized access.

This extensive list can be an initial step for additional in-depth study to characterize Smart Cities and their applications. A more specific and well-defined set of characteristics can help create higher-quality applications and support testing.

4.2 RQ7: Which are the applications of IoT solutions in the SC domain?

Puliafito *et al*. [2021] presents an industrial IoT-based sensing system to monitor the temperature of a set of machines, and Gopinath *et al*. [2021] presents an Intelligent Waste Management solution. These two papers discussed the use cases of IoT solutions for SC in more detail.

One interesting proposal cited by Kirimtat *et al*. [2020] worth mentioning is the idea of "Smart Floating Cities." This idea integrates smart cities with the design of floating settlements, which becomes necessary due to the rising sea levels since the rising sea levels are highly damaging natural disasters worldwide due to global warming. The remaining papers present the application at a higher abstraction level that we analyzed and interpreted to organize the findings.

Ahmed *et al*. [2020] claims that "the main aim of developing smart cities is to provide facilities to the residents to improve their living standards from different aspects, such as IoT, education, transportation, communication, construction, energy, healthcare, finance, and services." This aligns with papers Asghari *et al*. [2019] and Santana *et al*. [2017], where they argue that to provide integration across all city subsystems (such as transportation, education, energy, and water), all city subsystems must be connected in a network as an organic whole.

Figure 6. Applications of IoT solutions in the SC domain.

In a perfect world, the concept of a smart city goes beyond the conventionally defined bounds of a traditional city's administrative and social structure by allowing interaction between the two, allowing it to function in a more unified and engaged way. The government and the corporate sector have engaged in several smart city programs to address the expanding difficulties facing cities and metropolitan areas. A smart city offers modern, resource-saving, and high-quality living by utilizing simple-to-use information and communication technology.

Figure 6 represents the findings as we categorized them in ten groups, discussed as follows.

- Smart Living: This feature covers all aspects of improving quality of life, such as health, travel, safety, and culture. Cited by four articles, such as Singh *et al*. [2022].
- Smart Environment (or smart energy): Aspects related to resources management and efficiency, climatic situations, environmental impact, eco-initiatives, and efforts to minimize ecosystem footprints. Cited by ten articles, such as Kirimtat *et al*. [2020].
- Smart Transport (or smart mobility): Transportation includes information and communication technology availability, accessibility, and a sustainable transportation system in city planning, focusing on the collective use of technology. Cited by eight articles, such as Ghannem *et al*. [2017] and Khan *et al*. [2020].
- Smart Governance (or smart economy): This aspect refers to characteristics that include civil rights, administrative transparency, and political engagement. It can also cover concerns about a city's economic significance, entrepreneurship, flexibility, and innovation. Cited by eight articles, such as Zeng *et al*. [2023] and Kumar *et al*. [2022].
- Smart People (smart citizens): Concerns social aspects such as the degree of education and social diversity. Since people are the main users of smart services, improving the living environment and raising the quality of life are two important goals of SC. Some authors related this to smart education, defending citizens' digital inclusion. Cited by seven articles, such as Zhou *et al*.

[2023] and Syed *et al*. [2021].

- Smart Health: It refers to the application of software and IoT solutions to raise the accessibility and caliber of healthcare. It seeks to make healthcare accessible to as many people as possible. Cited by seven articles, such as Asghari *et al*. [2019].
- Smart Building: Generally, it relies on monitoring, sensing, and actuation behaviors in a given environment and may include devices that measure user behavior, such as motion trackers, environmental sensors, and power consumption. This group covers homes, offices, and smart spaces. Cited by four articles, such as Nayak *et al*. [2021].
- Smart Industry: It entails a networked factory with all its intermediary functionaries smoothly integrated and cooperating. The industry has benefited from using computing solutions in manufacturing and production processes. Cyber-physical and IoT systems integrate workers and machines for faster innovation, optimization, and increased product quality. Cited by five articles, such as Kumar *et al*. [2022] and Syed *et al*. [2021].
- Smart Agriculture: It entails implanting sensors in plants and crops, in general, to provide targeted measurements and subsequently enable the deployment of tailored care mechanisms. The future of food production will depend on precision and smart agriculture. Cited by three articles, such as Kumar *et al*. [2022] and Syed *et al*. [2021].
- General Smart Applications: Robotic, Surveillance, Security, Disaster Management, and Waste Management. In this group, a good example is the work presented in Zeng *et al*. [2023] for disaster management. This concept entails the mitigation, relief, response, and recovery encompassing the release of timely alerts, acquisition of real-time data, and support for damage assessment. For the authors, conventional methods for disaster management are becoming outdated due to their inability to gather data from several sources in real-time, making efforts in IoT solutions for SC an ideal alternative for such cases.

Figure 7 presents an overview of Domains cited for each paper. The most frequently cited Domains are Smart Environment (Energy - ten citations), Smart Transport (Transport - eight citations), Smart Governance, and Smart Health (with seven citations). The category named ”Others” stands for General Smart Applications. It had nine occurrences but generally represents a domain that was cited only once.

As for the paper's perspective, Syed *et al*. [2021] was the one that covered more domains, with all the domains cited. It was followed by Santana *et al*. [2017] and Nayak *et al*. [2021], with both citing seven domains. From the 17 selected papers, only Tomas *et al*. [2013] and Hejazi *et al*. [2018] did not provide any information on applications domains for SC.

Summary of the findings: We could identify ten wide-ranging and diverse application categories from the extracted data. Most of the solutions in the articles are concerned with optimization, resource management, reducing costs, and providing real-time data to help city planners with decision-making. Overall, IoT solutions have the potential to transform cities into more efficient and sustainable environments, improving the quality of life for citizens and reducing the environmental impact.

Paper		Living	Energy	Transport	Governance	People	Health	Building	Industry	Agriculture	Others
Ahmed et al. (2020)	DOMAIN	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐
Asghari et al. (2019)		☐	☑	☐	☑	☐	☑	☐	☑	☐	☑
Ghannem et al. (2017)		☐	☑	☑	☐	☐	☐	☑	☐	☐	☑
Gopinath et al. (2021)		☐	☐	☐	☐	☐	☐	☐	☐	☐	☑
Hejazi et al. (2018)		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Khan et al. (2020)		☐	☑	☑	☐	☐	☑	☑	☐	☑	☑
Kinmtat et al. (2020)		☐	☑	☑	☑	☑	☐	☐	☐	☐	☑
Kumar et al. (2022)		☐	☑	☐	☑	☐	☑	☐	☑	☑	☑
Medina et al. (2019)		☐	☑	☑	☐	☑	☑	☐	☐	☐	☐
Nayak et al. (2021)		☐	☑	☑	☑	☑	☑	☑	☐	☐	☑
Puliafito et al. (2021)		☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
Santana et al. (2017)		☑	☑	☑	☑	☑	☑	☐	☐	☐	☑
Singh et al. (2022)		☑	☑	☑	☑	☑	☐	☐	☐	☐	☐
Syed et al. (2021)		☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Tomas et al. (2013)		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Zhou et al. (2023)		☐	☐	☐	☑	☑	☐	☐	☑	☐	☐
Zeng et al. (2023)		☐	☐	☐	☑	☐	☐	☐	☐	☐	☑

Figure 7. Overview of Domains cited for each paper.

4.3 RQ8: Which technologies are used in IoT solutions for the SC domain?

From the 17 selected articles, Ahmed *et al*. [2020], Asghari *et al*. [2019], Tomas *et al*. [2013], and Gopinath *et al*. [2021] did not discuss technologies and enablers for the SC domain. The remaining articles presented varied technologies that are fit to answer RQ3.

Singh *et al*. [2022] presents technologies when it discusses the layered architecture paradigm, with the following: detection, transmission, data management, and application layers. With this layered perspective, the authors list a series of technologies and enablers for each. For example, the detection layer should catch various information from sensors and gadgets. This paper also cites specific platforms with services for deploying infrastructure available in the city, such as FIWARE, Carriots, and ICOS.

Aligned with this layered vision, Zeng *et al*. [2023] address the main technologies for sensing (Detection layer), communication (Transmission layer) and data analysis used in the stages of pre- and post-disaster in Urban Management Applications. The sensors used in the pre-disaster phase are mainly intended for collecting environmental data. Accelerometers, for example, are widely used to detect earthquakes and landslides. A serious and recurring problem in numerous cities is flooding, which is often caused by problems in urban drainage systems in situations of prolonged and intense rain. Numerous types of sensors can be used in flood monitoring systems, such as rain gauges, water level sensors, water pressure sensors, water presence sensors, soil moisture sensors, meteorological sensors, as well as drones and cameras. In addition to environmental data (for instance weather, chemicals, and movement sensors, water level and smoke detection sensors), the sensors in the post-disaster stage are mainly aimed at collecting human health and position data, so as to help and improve the efficiency of search and rescue. The human health data (including heart rate, breath rate, dizziness, sweating, chest pain, trembling, chills, choking, nausea, and the location of the individuals) encompasses the rescuers' health data and the stranded people's health data, and they can be gathered via body-worn sensors in wearable smart devices, such as smart glasses and smart watches.

Regarding the communication technologies and protocols used in the pre-disaster stage of disaster management applications, they range from traditional solutions, such as the TCP/IP stack, HTTP, Bluetooth, Ethernet, Wi-Fi, cellular communication, Radio Frequency, to solutions tailored for IoT, such as IPv6 with 6LoWPAN, IEEE 802.15.4, Message Queuing Telemetry Transport (MQTT), LoRaWAN, Zigbee, and Cat-M1. The role of drone technologies stands out as a possible solution to deliver sensor data to base stations, providing large-scale data transmission. Traditional communication technologies can also be used in the post-disaster stage, but often the city's communication infrastructure will be destroyed or severely damaged. Therefore, wireless and ad hoc mobile communication technologies must support this stage, where resilience is a key aspect. Solutions such as mesh networks and the use of drones are promising. Furthermore, many authors advocate the use of vehicle support used in search and rescue as information relays. The creation of opportunistic communication networks is essential to avoid interruption of data collection after disasters occur.

Regarding data analysis, techniques such as machine learning, deep learning, and time-series data analysis are typically employed, mainly in the pre disaster stage. The goal is using sensed data and comparing the current situation with past cases to try to detect disasters before their occurrence. For post analyses, ML techniques can be adopted for analyzing position and health data in order to plan evacuation routes, allocate ambulance vehicles and provide synthetic and integrated information about the health of individuals.

Similar to Singh *et al.* [2022], Medina *et al.* [2017] grouped into three levels regarding the architecture of a Smart City from the technological IoT perspective: A. Device level, with sensors and Near Field Communication. B. Communication level, with 6LoWPAN, Bluetooth LE, and Wi-Fi, C. Server level, with Big Data; Data Mining.

Ghannem *et al.* [2017] gives an interesting overview of the modeling methods used in Requirements Engineering activities for Adaptive Systems. They report KAOS, Context Model, Tropos, Domain Specific Models, i*, RELAX, LTL, and Business Process Models as the leading used technologies. They found that 58% of technologies are focused on runtime, which corroborates with the scope of adaptive systems.

At a high-abstraction level, Khan *et al.* [2020] considers Cloud, Edge, Cloudlets, and Fog computing. Kirimtat *et al.* [2020] lists IoT, big data, and cloud computing as the "main pillars of smart solutions" for SC. Nayak *et al.* [2021] also considers Big Data, Artificial Intelligence, Blockchain, and ML as technologies for SC. Santana *et al.* [2017] discusses four main technologies used by software platforms for Smart Cities: Cyber-Physical Systems, the Internet of Things, Big Data, and Cloud Computing. We consider these technologies as larger paradigms in themselves, that act as enablers for Smart Cities.

Hejazi *et al.* [2018] presents a comparison of Software Platforms covering many aspects, including device management, integration, security, data collection protocols, analytics types, and visualization support. It compares twenty platforms, including Amazon, IBM, Intel, and Microsoft solutions. Kumar *et al.* [2022] organizes the technologies in commercial, healthcare, and agriculture sectors. For example, for the healthcare sector, the following technologies are listed: field communication, IoT-based special sensors, MEDiSN, Wisepill technologies, COAP, MQTT, artificial intelligence, Sensors, Wearables, and telemetric systems. In Medina *et al.* [2017], the Stack4Things was adopted, and its services and functionalities were exploited to integrate CPSs and pave the way toward smart cities. It lists several enabling technologies such as Digital Twins, Semantic Models, Cybersecurity mechanisms, and Microservices Applications.

A technology that has proven to be extremely relevant for IoT in general, and especially in SC scenarios, is 5G networks. Given its relevance, many of the studies emphasize this technology. Several studies explicitly mention cellular networks as part of the communication layer in an IoT system for SC. For instance, when discussing protocols and network technologies used in IoT, the authors in Syed *et al.* [2021] mention cellular technologies (3G, 4G, and 5G) as being capable of providing high data rates and supporting richer applications compared to other IoT protocols. They emphasize that because they provide long-range communication, such technologies are very useful for various applications where energy consumption is not a problem. As part of fourth-generation cellular technology, they highlight NB-IoT (Narrow Band IoT), a type of LPWAN that operates on a Global System for Mobile Communications (GSM) and Long-Term Evolution (LTE) bands. NB-IoT is considered part of the so-called cellular IoT. When discussing communication technologies and protocols used in IoT for urban disaster management, the authors in Zeng *et al.* [2023] mention cellular communication including GSM, GPRS and 3G. Given its pervasive nature and resilience, it is easy to see the relevance of cellular communication in such a scenario. The authors in Singh *et al.* [2022] include cellular technologies (3G, 4G (LTE), 5G) in the transmission layer. At the time of publication of the work, LTE technology was seen as a very promising technology, better than 3G and Wi-Fi in terms of speed, bitrate, and inertia. 5G technology was still in its infancy, but its potential and adoption trend as a communication infrastructure in smart cities were already visible.

In Furstenau *et al.* [2022], the authors mention the use of cellular networks as a communication infrastructure for IoT and discuss their adoption as part of the data processing infrastructure. Their discussion aligns with new trends of not relying solely on centralized cloud servers to process IoT data but distributing such processing along the edge-to-cloud continuum. In this context, they mention cellular network edge, mobile cloud computing, and mobile edge computing paradigms. The role of 5G networks will be crucial in these distributed computing environments of the future, which will potentially serve as backend platforms for processing IoT data. Also discussing the potential of 5G for SC, in Khan *et al.* [2020], the authors consider 5G networks to play a fundamental role in communication in smart cities, even using the term 5G-enabled smart cities. In this sense, they mention using 5G as a support technology and the distribution of data processing generated at the edge of the network in conjunction with paradigms such as SDN (Software-Defined Networks).

In Puliafito *et al.* [2021], the authors emphasize 5G networks, along with IoT and the Edge Computing paradigm, as important enabling technologies for smart cities. In particular, they consider that integrating cloud-edge-IoT, adopting artificial intelligence techniques, and cellular technologies are fundamental to leveraging next-generation CPS systems for Smart Cities. 5G technologies are included by the authors in the infrastructure layer of a typical SC, able to provide not only communication resources but also, as part of a 5G/Edge system, computing resources. The authors claim that 5G and IoT evolutions are highly interrelated, as 5G is considered an enabler for massive IoT (MIoT) support. One of the classes of services supported by 5G networks is exclusively aimed at meeting the specific requirements of IoT applications. One of the concepts in 5G is network slicing, where each slice consists of a logical network with resources allocated to serve a specific class of services. Therefore, the creation of IoT slices is expected to meet high connectivity requirements, dense device installation, and reliability, among others. Service providers can create such slices on top of the network's physical infrastructure and then offer them to applications. In Smart Cities, network slicing and the provision of virtual services at the network edge will be essential to meet the demands for IoT services in an agile, flexible, and scalable way.

Summary of the findings: A multitude of technologies are used in solutions for smart cities. Among the most frequently mentioned are the tools and mechanisms employed to realize SC applications, including sensors and actuators (used to data collection, action and transmission from several sources), network technologies (used to provide connectivity among the application nodes), and analytics (used to process and analyze the vast amounts of data generated, offering insights into trends and patterns that can guide decision-making). Additionally, broader concepts such as Cloud computing, Artificial intelligence, and Blockchain serve as enablers for SC. In essence, the technologies integrated into smart cities solutions are diverse and constantly evolving, with new options emerging and existing technologies undergoing refinement.

4.4 RQ9: Which are the challenges for IoT solutions in the SC domain?

From the 17 selected articles, Hejazi *et al*. [2018], Kirimtat *et al*. [2020], and Medina *et al*. [2017] did not discuss challenges and gaps in the SC domain. Some papers mention the challenges as simple lists without getting deep into context or explanation.

Ahmed *et al*. [2020] highlights security challenges with special attention to security breaches and assaults. Khan *et al*. [2020] focuses on cloud-related challenges such as intelligent caching and cooperative and sustainable load balancing. Nayak *et al*. [2021] presents data-related challenges, for instance: Data Transfer, Storage, Recall, and Computational Resources. As for Syed *et al*. [2021], Security, Privacy, Data Integrity, and Trustworthiness are the main challenges. Asghari *et al*. [2019] lists Security, Privacy, Context-awareness, Interoperability, Formal verification, and Energy consumption as challenges in SC. Santana *et al*. [2017] reports on Privacy, Data Management, Heterogeneity, Energy Management, Communication, Scalability, Lack of Testbeds, Lack of City Models, and Platform Maintenance. With deeper discussions regarding the challenges, Puliafito *et al*. [2021] reports 1) the need for convergence of IoT technologies; 2) Applications development; 3) Improve Intelligence and Automation; 4) Human-centric solutions; and 5) Efficient data management.

Singh *et al*. [2022] presents a wider discussion on challenges, arguing that the key issues are costs, heterogeneity, security, data analysis, and comfortability. Regarding costs, the authors divide them into design and operation. The financial investment required to construct a Smart City is the design cost. The city's regular operations and maintenance tasks cause operational costs. One could argue that low running expenses would guarantee a comfortable facility supply without placing an additional financial burden on the town. Another critical issue for the paper is heterogeneity. Many sensors, devices, and equipment are required in an SC. The desired outcomes in an SC are bound to overcome the heterogeneity challenges. Security is one of the greatest challenges in SC since smart city-management systems coordinate different functionalities, which offers multiple options for harmful attacks. This situation can lead to a tradeoff where high security can require additional design and maintenance costs.

Tomas *et al*. [2013] highlights the architecture challenges for SC solutions, arguing that to enable the SC vision, there is a need to establish an architecture able to store, combine, process, and deliver contextualized information. Ghannem *et al*. [2017] discusses challenges related to requirements engineering. They recommend more research for requirements in SC since they reside primarily in the problem space, whereas other software artifacts reside mainly in the solution space. There is also a discussion on challenges for adaptive behavior. One of the gaps presented is that most solutions based on the "context model" do not specify context uncertainty. Kumar *et al*. [2022] considers that SC relies on creating a network of interconnected devices that can share data. As a result, connecting several devices for communication is a major challenge in developing IoT systems. Together with connectivity, data management has an associated challenge since SC deals with the data's complexity in terms of volume and velocity.

Gopinath *et al*. [2021] focuses on challenges related to data management. For them, compiling an SC requires using numerous sources of supplemental urban data. Thus, it is essential to maintain the capability of updating and visualizing multidimensional spatial and temporal data. Another issue is the difficulty of dealing with the variety of sensor data in terms of position attributes, detected objects, status, and time, and the problem of handling the high volume of unstructured information that must be processed quickly (related to heterogeneity and response time).

Zhou *et al*. [2023] examined the area of inclusive smart cities, focusing on how to connect citizens with disabilities who face significant challenges in urban living and improve their quality of life. The results and challenges presented are provided using the Quadruple Helix Model, which, according to the authors, provides a framework to address research gaps critical to further development. Their model considers citizens, industry, government, and university, each with demands and challenges. Finally, the authors provide a series of RQs to motivate research in the area, such as "How can the government ensure people with disabilities' participation in social activities through applications and platforms of smart technologies?"

Summary of the findings: Security is the paramount challenge reported in most papers. Solutions for SC rely on collecting and processing vast amounts of data, raising concerns about data privacy and security. Ensuring data is collected, stored, and processed securely is critical to maintaining public trust and avoiding potential data breaches. Smart Cities generate and collect massive data amounts. Thus, Data Management is one of the major challenges, including concerns with quality, integration, analysis, and transmission. Developing smart cities is another challenge since it requires careful planning, investment in infrastructure and technology, collaboration between stakeholders, and engagement with citizens and communities to ensure that SC solutions are effective and sustainable. Therefore, requirements, technologies, and enablers are important for further research and development. Legal and Social challenges, such as regulations and laws, are typically complex and differ between towns and regions, making it difficult for SC solutions to operate in this scenario. Ensuring that SC solutions adhere to pertinent laws and policies might be difficult. Interoperability is also a frequently reported challenge: SC solutions often involve multiple technologies and systems, which must communicate and integrate seamlessly to function effectively. Ensuring interoperability between these systems can be challenging, particularly as recent technologies emerge, and existing systems are updated.

Final Takeaway. From the RQs and challenges observed, we organized a summary of suggestions based on the findings.

1. **Context of IoT and Smart Cities Integration**: Urban planners and technology developers should prioritize security, interoperability, and adaptability when integrating IoT technologies within Smart Cities. These quality attributes are critical for ensuring the resilience and effectiveness of smart urban systems.
    - Context: In urban environments where technology integration directly impacts public services and governance, addressing these attributes can lead to better solutions.
    - Motivation: Our findings indicate that these attributes are frequently discussed and pose significant implementation challenges. Addressing these can help overcome some barriers to successful Smart City initiatives.
2. **Quality Attributes Roadmap:** Future research should focus on developing clearer definitions and measurement metrics for quality attributes in SC frameworks. This effort could involve collaborative research encompassing academics and practitioners to ensure practical relevance and applicability.
    - Context: This suggestion is particularly relevant in academic and research institutions exploring IoT applications within urban development projects.
    - Motivation: The study identified a significant gap in clear definitions and evidence-backed attributes, hindering SC solutions' development. Enhancing clarity and metrics would facilitate better design and evaluation of smart urban infrastructure.
3. **Technology Selection:** Practitioners should consider the comprehensive list of technologies and applications highlighted in this review as a starting point for designing and implementing SC solutions.
    - Context: This aspect applies to the technology development phase within planning departments looking to upgrade or build new smart infrastructure.
    - Motivation: By leveraging well-researched and proven technologies, practitioners can reduce the risk associated with new deployments and ensure compatibility and scalability in their projects.

4.5 Threats to Validity

As is in any study, in this literature review, we also acknowledge and address potential threats to the validity of our findings.

- Quality Assessment: The quality evaluation depends on whether the papers follow (or not) a rigorous methodology or explicit study properties (research questions, search strings, databases, inclusion criteria, selected articles, etc.). We included in the extraction form the study type and properties, to retrieve any relevant information on the study setting. However, after the selection, we realized that many papers did not follow a rigorous approach. For this reason, we did not perform the Quality Evaluation since there is no methodology information to be evaluated. Therefore, not performing the Quality Evaluation represents a threat to this study's validity. Instead, we assessed the papers in matters of adequacy, meaning how the papers contributed to the research questions.
- Publication Bias: Since it was our selection, the inclusion of secondary studies relies on the availability of published literature. To mitigate this threat, we attempted to include a diverse range of sources of peer-reviewed material. Although some pertinent studies may not be included, as only Scopus was used, we know from experience that it can provide a respectable level of coverage since it indexes several databases.
- Selection Bias: Another potential threat arises from including relevant studies in the review. We employed a systematic approach to lessen selection bias, clearly defining our research questions and criteria for study inclusion. This review underwent peer review at every stage, and any doubt was discussed among the reviewers. Cross-checking among the three researchers helped reduce selection and interpretation biases.
- Temporal Bias: The field of SC is rapidly evolving, and technological advancements occur quickly. Since a literature review primarily relies on existing publications,

it may not capture the most recent developments. Considering the dynamic nature of the field, some emerging trends or technologies may not be fully represented in this review.

- Generalization of Findings: The characteristics, attributes, and challenges identified are not universally applicable to every Smart City initiative due to contextual variations. Researchers and practitioners should consider the specific context and goals of individual Smart City projects when applying the insights gleaned from this review. Quality Assessment was not performed for the selected studies; hence, this is another threat to this study.

5 Conclusion

In this paper, we have presented a comprehensive tertiary study that delineates the intersection of IoT and SC. Despite having several secondary studies investigating the application of IoT to SC, these are very wide areas with varying topics. Therefore, most of these studies limit their scope to an orthogonal division of one or both areas. That is one of the motivations for his tertiary study on the intersection of the Internet of Things and Smart Cities.

By adopting a systematic approach to review and synthesize these studies, our work not only enhances reproducibility, by providing internal consistency to the results, but also fortifies the results by focusing the discussion on available evidence in existing secondary studies. One contribution of this paper is the methodology and approach that can serve as a framework for conducting future tertiary studies in other domains, showcasing how to synthesize secondary studies effectively.

A tertiary study is an appropriate method for organizing a broad research area, making it fitting for our investigation given the extensive and diverse nature of IoT and SC fields. Secondary studies often focus on narrower sub-domains as they should answer precise RQs. Thus, another contribution of this paper is to explore the interactions between IoT and SC extensively, giving an in-depth overview of the existing research on IoT applications in smart cities.

These findings were related and summarized to enrich the paradigms understanding, in particular their synergy. To present an organized perspective regarding the current state-of-the-art of the IoT paradigm applied in the SC domain, our review aimed at uncovering evidence on how IoT technologies have been integrated into Smart City systems to reveal similarities and points of articulation established between the two areas of investigation.

A critical step towards establishing SC is to define which quality attributes should be contemplated. A notable finding of our investigation is the results for RQ6, as we move forward in this direction. We recovered 78 different attributes, from which 26 of them have clear definitions and evidence from the sources. Considering that the results retrieved are from secondary studies, the represented characteristics reflect more than just the seventeen papers from the final set, but rather the whole array of over six hundred primary studies involved.

These results relate to RQ9 discussed challenges since the main are precisely attributes (security, interoperability, and adaptation). Alongside that, the overview of SC applications and used technologies can contribute to any future research. In particular, the list of technologies, presented in RQ8, can be an asset to practitioners in the processes of idealizing, engineering, and developing SC solutions.

In conclusion, this paper contributes to research advancement and serves as a resource for researchers and practitioners. It provides a comprehensive list of technologies and applications that can guide the development and implementation of innovative IoT solutions for SC. By fostering a clearer understanding and encouraging continuous collaboration among stakeholders, our study underscores the ongoing need to leverage the potential of Smart Cities to transform urban landscapes. This research sets a foundation for future explorations and highlights the importance of quality attributes, technologies, and domains to explore the complexities and opportunities the Smart Cities paradigm presents.

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Authors' Contributions

Rebeca Motta: Conceptualization, Methodology, Investigation, Writing - Original Draft
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Flávia Delicato: Conceptualization, Analysis, Writing - Review & Editing.
All authors read and approved the final manuscript.

Competing interests

The authors declare that they do not have any competing interests.

Availability of data and materials

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