Making Cities Smarter: A Literature Review of Characteristics, Technologies, and Challenges

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Abstract. *As the world becomes increasingly developed, there is a growing need to address of urbanization. Smart cities offer a way to address these challenges by using technology to make cities more efficient, sustainable, and livable. However, it is a recent field of development with a lack of understanding of some concepts. Therefore, we performed a literature review of secondary studies to characterize Smart Cities regarding their attributes, applications, technologies, and challenges. The findings indicate the research opportunities in the field, focusing on designing Smart Cities solutions, and a characterization of Smart Cities outlining issues that need to be addressed for them to be established.*

Resumo. *À medida que o mundo se torna cada vez mais desenvolvido, há uma necessidade crescente de abordar a questão da urbanização. As cidades inteligentes oferecem uma maneira de enfrentar esses desafios usando a tecnologia para tornar as cidades mais eficientes, sustentáveis e habitáveis. No entanto, é um campo de desenvolvimento recente com falta de compreensão de alguns conceitos. Portanto, realizamos uma revisão da literatura de estudos secundários para caracterizar as Cidades Inteligentes quanto aos seus atributos, aplicações, tecnologias e desafios. Os resultados indicam as oportunidades de pesquisa na área, com foco no desenho de soluções de Cidades Inteligentes, e uma caracterização das Cidades Inteligentes delineando questões que precisam ser abordadas para que elas sejam estabelecidas.*

1. Introduction

In recent years, we have witnessed a shift in technology and applications, using software in broader contexts, including embedded objects, and no longer limited to individual computers. Thus, society increasingly depends on solutions based on software and interconnected objects, as proposed by the Internet of Things paradigm [Atzori *et al.* 2010]. 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 view considers that everyday objects can enrich their original behavior through software and a new dimension of human-object and object-object communication [Motta *et al.* 2019]. The capacity and benefits brought by IoT are not limited to the interaction of smart objects but mainly due to the wide range of applications that explore the deluge of data made available by the instrumentation of the physical world and transform them into useful information to support decision-making and generate valuable knowledge for users [Qin *et al.* 2016]. Among potential IoT applications, the field of Smart Cities stands out.

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]. According to [Dirks *et al.* 2010], the IoT is a core technology as the sensor infrastructure for a Smart City (SC). 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. Despite the great interest and investments from academia and industry, many challenges must be overcome to leverage the IoT paradigm and its adoption in the context of SC.

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 review intends to answer the following research questions (RQs): RQ1. Which quality attributes are addressed in existing IoT solutions applied to the SC domain? RQ2. Which are the applications of IoT solutions in the SC domain? RQ3. Which technologies are used in IoT solutions for the SC domain? RQ4. What are the challenges for IoT solutions in the SC domain? The intention is to promote a high-level discussion on identified characteristics and give an overview of the area to promote a better perception of current development needs and opportunities. 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. Literature Review

The research protocol followed the recommendations [Biolchini 2007] established for this type of study, and it is available online[1]. Before undertaking any literature review, it is essential to observe its necessity [Budgen *et al.* 2006]. As technology advances rapidly, numerous initiatives have been conducted regarding SC. However, the available information is often dispersed across different sources, making it challenging to access a consolidated overview. This literature review serves as a valuable resource, bringing together existing research findings, fostering knowledge synthesis and consolidation in the field. In our perspective, "secondary studies" are those that survey primary studies to present a bigger picture of a domain (SC here). For this reason, in this review, we consider secondary studies in SC.

The research goal [Basili *et al.* 1994] is defined as follows: To analyze 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.

2.1. 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. Table 1 summarizes the adopted protocol.

[1] The replication package is available online https://doi.org/10.5281/zenodo.7786510 and the Technical Report can be accessed in https://shorturl.at/izBZ5.

Our goal in this research is to have an overview of IoT for the SC domain. Such a general goal was organized into four research questions, as presented in Table 1. Considering the questions, we intend to search for research-based peer-reviewed articles. We identify quality attributes, which means particular characteristics, traits, features, or properties that make the solutions achieve their purpose. Applications are the domains that will benefit from the deployment in Smart Cities, e.g., transportation, logistics, and healthcare. For technologies, we are interested in techniques, methods, and tools that enable the IoT for SC operationalization and challenges representing open questions and gaps in the area.

Table 1. Research Protocol Summary.

Research questions	RQ1. Which quality attributes are present in existing IoT solutions applied to the SC domain? RQ2. Which are the applications of IoT solutions in the SC domain? RQ3. Which technologies are used in IoT solutions for the SC domain? RQ4. Which are the challenges for IoT solutions in the SC domain?	
Search string	(("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 "technology* review*" OR "state of*") AND ("internet of things" OR "iot") AND ("smart cit*"))	
Search Strategy	Scopus (https://www.scopus.com/)	
Selection Criteria	Inclusion Criteria: • Provide an answer to RQ1 OR • Provide an answer to RQ2 OR • Provide an answer to RQ3 OR • Provide an answer to RQ4.	Exclusion Criteria: • Not provide an answer to any of the RQs; AND • Duplicate publication or self-plagiarism; AND • Register of proceedings AND • Not in English
Technical Report	Detailed information on the review execution – https://doi.org/10.5281/zenodo.7786510	

2.2. Execution

Three researchers performed the review between January and March of 2023. The search was performed in Scopus[2] since it indexes several peer-reviewed databases. 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.

Figure 1. Steps for selecting the relevant studies.

After establishing the search string, the search resulted in 759 articles, with 726 remaining after removing duplicates and proceedings. Later we applied Title (480 papers removed) and Abstract (213 papers removed) selection with 33 papers remaining for a full reading. The final set comprises 15 papers from which we extracted relevant information, which is the foundation for the findings and discussions reported.

2.3. Results

In our findings, most of the works define that a smart city's objective is improving the quality of life of the citizen, along with its economic development. Despite the differences

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

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. The results of the RQs complement this understanding. To enrich the discussions, we briefly present the quantitative results. Figure 2 (left) presents an overview of the publication year, spanning from 2013 to 2022. A deeper discussion on this matter can be interesting, considering the primary studies selected in each paper. Figure 2 (center) 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. The article's study type is presented in Figure 2 (right). 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.

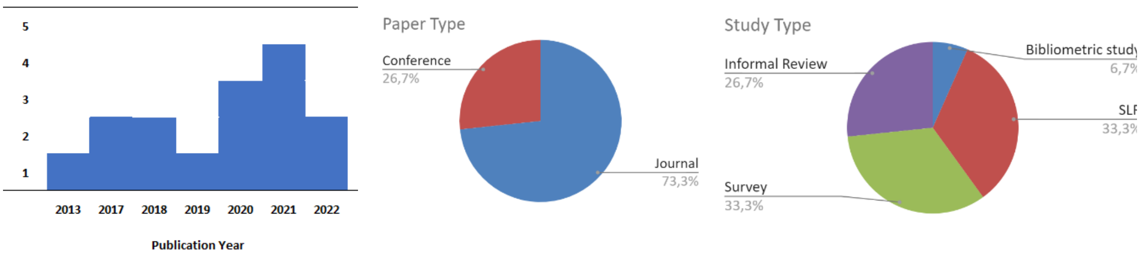

Figure 2. Publication year (left), paper type (center) and Study type (right)..

3. 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. It was carried out using all the data extracted and enriched by discussions among the researchers.

3.1. RQ1. Which quality attributes are present in existing IoT solutions applied to the SC domain?

All 15 selected articles provided some content on quality attributes and a rich source of characteristics with several excerpts extracted. Most authors simply list attributes without explanation of their meaning. As we cannot determine the definition of a quality attribute or what the authors intended by what they said, this absence of definitions makes it difficult to have a deeper understanding of this subject. Since the characteristics were not explicitly defined, merely enumerated, it prevents us from a wider characterization.

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: 1) Smart Cities attributes, 2) Software Systems or IoT Applications attributes, and 3) Attributes related to network, cloud, edge, or fog. Some attributes are repeated between the categories, but without the definition, it is impossible to affirm if they have the same meaning. For this reason, we decided to list all the findings extracted from the source studies. The complete list of attributes is available online[3].

Summary of the findings: Our interpretation and analysis were based on what

[3] Supplementary material: Answer to RQ1 – http://www.shorturl.at/iCHO6

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 different quality attributes are present in existing IoT solutions applied to the SC domain, from which 20 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.

3.2. RQ2. Which are the applications of IoT solutions in the SC domain?

From the 15 selected papers, only [Tomas *et al.* 2013] and [Hejazi *et al.* 2018] did not provide any information on applications for SC. The government and the corporate sector have engaged in several SC programs to address the increasing difficulties facing cities and metropolitan areas. An SC offers modern, resource-saving, and high-quality living by using simple-to-use ICTs. We categorized the finding from the papers in ten groups:

- Smart Living: This feature covers all aspects of improving quality of life, such as health, travel, safety, and culture. Cited by five 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 seven 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 seven articles, such as [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 six articles, such as [Syed *et al.* 2021] and [Medina *et al.* 2018].

- 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 [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 [Kumar *et al.* 2022] and [Syed *et al.* 2021].
- General Smart Applications: Robotic, Surveillance, Security, Disaster Prevention, and Waste Management.

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.

3.3. RQ3. Which technologies are used in IoT solutions for the SC domain?

From the 15 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 is 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. Similarly, [Medina *et al.* 2018] 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 WiFi, 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.* 2018], 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.

Summary of the findings: A wide variety of technologies are used in solutions for smart cities. The most cited ones are the equipment and mechanisms to materialize SC applications, such as sensors and actuators (used to collect, act and transmit data from a variety of sources), network technologies (used to provide connectivity among the application nodes), and analytics (used to process and analyze the vast amounts of data generated, providing insights into trends and patterns that can inform decision-making). Other technologies are wider concepts that we can see as enablers of SC. Cloud computing, Artificial intelligence, and Blockchain are some examples of enablers. Overall, the technologies used in solutions for smart cities are diverse and constantly evolving since new options emerge and existing technologies are refined.

3.4. RQ4. Which are the challenges for IoT solutions in the SC domain?

From the 15 selected articles, [Hejazi *et al.* 2018], [Kirimtat *et al.* 2020], and [Medina *et al.* 2018] 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 main 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 important 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).

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 new technologies emerge and existing systems are updated.

3.5. Threats to Validity

Although it is possible that some pertinent studies were not included, as only Scopus was used, we know from experience that it can provide a respectable level of coverage since it indexes several databases. To lessen the researchers' bias, we paid attention to the terms of our search string. Cross-checking among the three researchers helped to reduce biases in the interpretation process. To lessen selection bias, this review underwent peer review at every stage, and any doubt was discussed among the reviewers. Quality Assessment was not performed for the selected studies; hence this is another threat to this study.

4. Conclusion

This work presented the research on the SC paradigm, detailing the activities performed for the literature review and analyzing the findings and discussions to answer four research questions, covering quality attributes, application, used technologies, and challenges. These findings were related and summarized to enrich the IoT paradigm comprehension. One contribution of this work is to present an organized perspective regarding the current state-of-the-art of the IoT paradigm applied in the SC domain. A critical step towards establishing SC is to define which quality attributes should be contemplated. With RQ1, we moved forward in this direction. We recovered 78 different attributes, from which 20 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 15 papers from the final set, but rather the whole array of primary studies involved. These results relate to RQ4 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 can be an asset to practitioners in the processes of idealizing, engineering, and developing SC solutions. With this review we emphasize the need of ongoing study and cooperation for researchers and practitioners to handle the challenges posed by SC and their potential to influence urban development.

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