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Review

Multiple Dimensions of Smart Cities' Infrastructure: A Review

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Abstract: In recent years, there has been significant focus on smart cities, on how they operate and develop, and on their technical and social challenges. The importance of infrastructure as a major pillar of support in cities, in addition to the rapid developments in smart city research, necessitate an up-to-date review of smart cities' infrastructure issues and challenges. Traditionally, a majority of studies have focused on traffic control and management, transport network design, smart grid initiatives, IoT (Internet of Things) integration, big data, land use development, and how urbanization processes impact land use in the long run. The work presented herein proposes a novel review framework that analyzes how smart city infrastructure is related to the urbanization process while presenting developments in IoT sensor networks, big data analysis of the generated information, and green construction. A classification framework was proposed to give insights on new initiatives regarding smart city infrastructure through answering the following questions: (i) What are the various dimensions on which smart city infrastructure research focuses? (ii) What are the themes and classes associated with these dimensions? (iii) What are the main shortcomings in current approaches, and what would be a good research agenda for the future? A bibliometric analysis was conducted, presenting cluster maps that can be used to understand different research trends and refine further searches. A bibliographic analysis was then followed, presenting a review of the most relevant studies over the last five years. The method proposed serves to stress where future research into understanding smart systems, their implementation and functionality would be best directed. This research concluded that future research on the topic should conceptualize smart cities as an emergent socio-techno phenomenon.

Keywords: smart city; infrastructure; urban systems; sustainability; e-governance; IoT

1. Introduction

The year 2008 was a turning point for cities: the Earth's population became more urban than rural. Nowadays, more than half of the world's population—approximately 3.3 billion—lives in urban areas, increasingly in highly dense cities. By 2030, it is expected that the number of people living in urban areas will reach 5 billion. With the rapid increase in the urban population worldwide, cities are facing various challenges [1]. One of many challenges is the addition of new infrastructure, along with the need to operate and maintain existing infrastructure worldwide. New demand for resilient infrastructure opens the way for governments, in a combined effort with research and citizen input, to build smart cities that promote equity, education, health, and a better quality of life for everybody [2]. A smart city is defined as a city that is guided—through the Internet of Things (IoT)—in collecting data that is then interpreted and analyzed to efficiently and sustainably manage resources, urban systems, urban facilities, and community services. The smart city concept appeared as a solution that took into consideration the sustainability of cities in all domains and all phases of the implementation of projects [1]. The development of smart cities has been increasingly viewed as a way to meet the needs of transportation linkages and high-quality urban systems, thus achieving long-term economic growth [3]. Since the smart city concept is vast, it is necessary to narrow the research scope to one of its many areas. This study focuses on smart city infrastructure, that is:

- Infrastructure development using smart systems;
- Information and Communications Technology (ICT) and its role in infrastructure construction, management, maintenance and operation;
- Sustainability in current smart infrastructure.

Recent literature on smart city infrastructure highlights the importance of digital and technological cities, and their ability to tackle various current challenges faced in urban areas, including traffic congestion, long commutes, lack of parking infrastructure, city sprawling, and public safety. When it comes to smart city infrastructure, recent literature on the subject highlights the importance of digital and technological cities in tackling various current challenges faced in urban areas [4]. Publications in the literature focus on very specific topics, such as smart roadway infrastructure [5], future visions [6], and blockchain for smart cities [7].

However, understanding smart cities' infrastructure demands knowledge that accounts for technical, financial, and social constraints, as well as governance. It is also of prime importance to understand how these aspects are interconnected. This study's novelty lies in presenting a classification framework that covers these aspects—technological, social, financial, and institutional—of smart city infrastructure.

There are several literature reviews on smart cities: some focus on digital systems [8], and some on the IoT technologies involved [9]. Other studies are concerned with technical standards involved in smart cities [10] and sustainable ways of implementing new urban systems [11]. Additionally, e-participation and e-government (and their role in making smart infrastructure) planning and operation have been described [12], as have innovations in artificial intelligence (AI), which recently gained prominence in the discussion of how to manage urban services and urban governance autonomously [13]. A comprehensive review on public-private partnerships (PPP) for financing and delivering smart infrastructure has also been presented [14]. Yet, many studies mainly outline opportunities and challenges without proposing a classification framework for smart city infrastructure research. This paper's main contribution is the proposal of a framework, based on the literature, that identifies the close relationship between technical, social and governance-related aspects of smart cities' infrastructure and connects that with the approaches, techniques, and challenges that are envisaged. A systematic flowchart of the conducted analysis was proposed, based on bibliometric and bibliographic analyses of smart cities' infrastructure research. VosViewer software was used in order to create keyword clusters and identify the most influential key patterns in each scenario. A framework that highlights key themes and classes of research on smart city infrastructure conducted over the past eight years was presented.

This review developed a classification framework covering technical, social, and governance aspects associated with smart city infrastructure, thus providing a comprehensive overview of where the research on smart city infrastructure has focused. To achieve this objective, the literature review presented in this work aimed to address the following critical research questions:

a. What are the various dimensions that smart city infrastructure research focuses on?
b. What are the research themes and classes associated with these dimensions?

c. What are the main shortcomings of current approaches, and what would be a good research agenda for the future in smart infrastructure?

The paper's structure is as follows: Section 2 describes the review method adopted for literature research and presents the results of the bibliometric and bibliographic analyses. The classification framework proposed in this review is developed in this section. Next, Section 3 addresses the questions posed above and discusses general findings. Finally, Section 4 proposes a future research agenda on smart city infrastructure, along with concluding remarks.

2. Materials and Methods

In an attempt to address the research questions posed above, a systematic review of the literature was conducted, whereby technological, societal, and governmental considerations were examined. Both a bibliometric and bibliographic analysis were performed. The bibliometric analysis identified the diverse topics that examined smart city infrastructure via citation analysis and keyword clustering. Next, the bibliographic analysis was performed in order to qualitatively grasp the initiatives that were taking place within a specific topic by reviewing the content of the paper. Both types of analysis were required in order to develop a holistic understanding of the present literature [15]. Figure 1 illustrates the different steps that were utilized to build up the systematic procedure for this study. The bibliometric and bibliographic methods used form part of the overall review methodology adopted in this study and derived from Mayrin [16]. The key steps are summarized as follows:

- Step 1: Collection of relevant materials.
- Step 2: Descriptive analysis of the examined literature.
- Step 3: Presentation of a classification framework categorizing the smart city infrastructure studies examined.
- Step 4: Evaluation of the material identified in Step 1, based on the classification framework developed in Step 3.

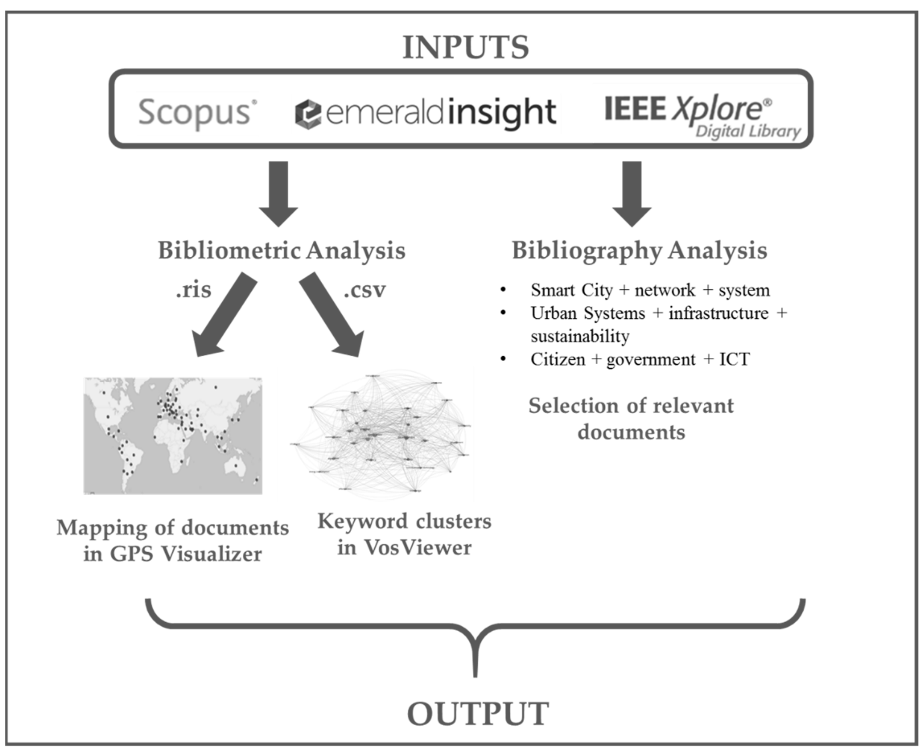

Figure 1. Bibliometric and bibliographic approach adopted in the review.

2.1. Collection of Relevant Materials

In this phase, a large and significant body of literature was collected. Before doing so, a set of keywords needed to be developed in order to enable the identification of relevant research articles. This ensured a structured search and filtration process for published documents that would provide a body of raw material aligned with the scope of the questions raised in the first section of this article. Three databases were chosen: Elsevier's Scopus, IEEE Xplore, and Emerald eJournals Premier. Two groups of keywords were developed. In Group 1, the following keywords were included: “smart city”, “ICT”, “citizen participation”, “government”. Group 2 focused on the infrastructure of smart cities, and included the following keywords: “smart infrastructure”, “smart urban systems”, “smart development”, “urban network”, “intelligent systems”, “sustainability”, and “intelligent transport”. A timeline starting in 1997 was chosen initially, in hopes of revealing developments in theory and contribution, and highlighting the significance of the subject over the past 24 years. This was later changed to 2014 given the sheer volume of research post-2010, and the drastic developments that took place in smart city research post-2014.

The search was carried out initially by looking at all pairs of combinations in Group 1. The intention was to identify the major aspects of this very broad and comprehensive subject. Then, second and third analyses were conducted, looking at all pairs of keywords from Group 2, and by combining pairs between the two groups (i.e., one keyword from Group 1 and one from Group 2). The second and third analyses used the keyword combinations “’urban systems’ + ‘development’” and “’smart city’ + ‘infrastructure’”, respectively. The initial search resulted in 5200, 1636 and 286 documents on Scopus, IEEE Xplore, and Emerald Insight, respectively, totaling 7122 documents overall. The second search led to 834, 291 and 723 documents on each of the aforementioned databases, respectively, totaling 1848 documents. The third search retrieved 1031 documents in total, as presented in Table 1.

Table 1. Documents retrieved in the first three searches.

Database	Number of Articles		
	Group 1	Group 1 + Group 2	Group 2
Scopus Elsevier	5200	834	490
IEEE Explorer	1636	291	463
Emerald Insight	286	723	78
Total	7122	1848	1031

This paper’s proposed framework identified the close relationship between smart city initiatives and infrastructure via bibliometric and bibliographic analyses. Having obtained bibliometric results from the three aforementioned searches, the focus of future research was chosen. This bibliometric analysis was conducted using VosViewer Software, version 1.6.11, developed at Leiden University, Leiden, Netherlands, which is integrated with all three databases used. The research results were downloaded in (.ris) format and uploaded into the bibliometric software. Once the cluster maps were defined, they led to three other types of research, already enhanced by the results of the first three cluster visualizations generated by VosViewer software. The details of all conducted research are as follows:

2.1.1. Scopus

1. The “smart city” term was used in the “title” and “abstract” fields. The research was limited to the last 8 years (2014–2021), to article and book chapters (as document types), and to the English language. A total of 8370 documents were retrieved.

2. The “smart city” and “infrastructure” terms were used in the “title” and “abstract” fields. The research was limited to the last 8 years (2014–2021), to article and book chapters (as document types), and to the English language. A total of 1556 documents were retrieved.
3. The “urban systems” and “development” terms were used in the “title” and “abstract” fields. The research was limited to the last 8 years (2014–2021), to article and book chapters (as document types), and to the English language. A total of 720 documents were retrieved.
4. The “smart city”, “network” and “system” terms were used in the “title” and “abstract” fields. The research was limited to the last 8 years (2014–2021), to article and book chapters (as document types), and to the English language. A total of 1956 documents were retrieved.
5. The “urban systems”, “infrastructure” and “sustainability” terms were used in the “title” and “abstract” fields. The research was limited to the last 8 years (2014–2021), to article and book chapters (as document types), and to the English language. A total of 64 documents were retrieved.
6. The “citizen”, “government” and “ICT” terms were used in the “title” and “abstract” fields. The research was limited to the last 8 years (2014–2021), to article and book chapters (as document types), and to the English language. A total of 417 documents were retrieved.

2.1.2. IEEE Xplore

1. The “smart city” term was used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to books, journals, and conferences (as document types). A total of 3199 documents were retrieved.
2. The “smart city” and “infrastructure” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to books, journals, and conferences (as document types). A total of 656 documents were retrieved.
3. The “urban systems” and “development” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to books, journals, and conferences (as document types). A total of 785 documents were retrieved.
4. The “smart city”, “network” and “system” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to books, journals, and conferences (as document types). A total of 1054 documents were retrieved.
5. The “urban system”, “infrastructure” and “sustainability” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to books, journals, and conferences (as document types). A total of 1 document was retrieved.
6. The “citizen”, “government” and “ICT” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to books, journals, and conferences (as document types). A total of 8 documents were retrieved.

2.1.3. Emerald Insight

1. The “smart city” term was used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to articles and chapters. A total of 206 documents were retrieved.
2. The “smart city” and “infrastructure” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to articles and chapters. A total of 279 documents were retrieved.
3. The “urban systems” and “development” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to articles and chapters. A total of 84 documents were retrieved.
4. The “smart city”, “network” and “system” terms were used in the “abstract” field. The research was limited to the last 8 years (2014–2021) and to articles and chapters. A total of 311 documents were retrieved.

5. The "urban systems", "infrastructure" and "sustainability" terms were used in the "search term" field. The research was limited to the last 8 years (2014–2021) and to articles and chapters. A total of 2 documents were retrieved.
6. The "citizen", "government" and "ICT" terms were used in the "search term" field. The research was limited to the last 8 years (2014–2021) and to articles and chapters. A total of 167 documents were retrieved.

2.2. Descriptive Analysis of the Materials

By tracking the publication rate of a subject over a considered time window (2014–2021), Figure 2 indicates that the number of papers published on smart city infrastructure has been constantly rising. This can be explained by the growing attention that the subject of smart cities has received in the last few years, due to the fact that the high population growth rates of the last few decades were not accompanied by an equivalent level of infrastructure investment. The saturation of current infrastructure and the urgent need to modernize it and create more resilient new constructions is reflected in the increasing rate shown in Figure 2.

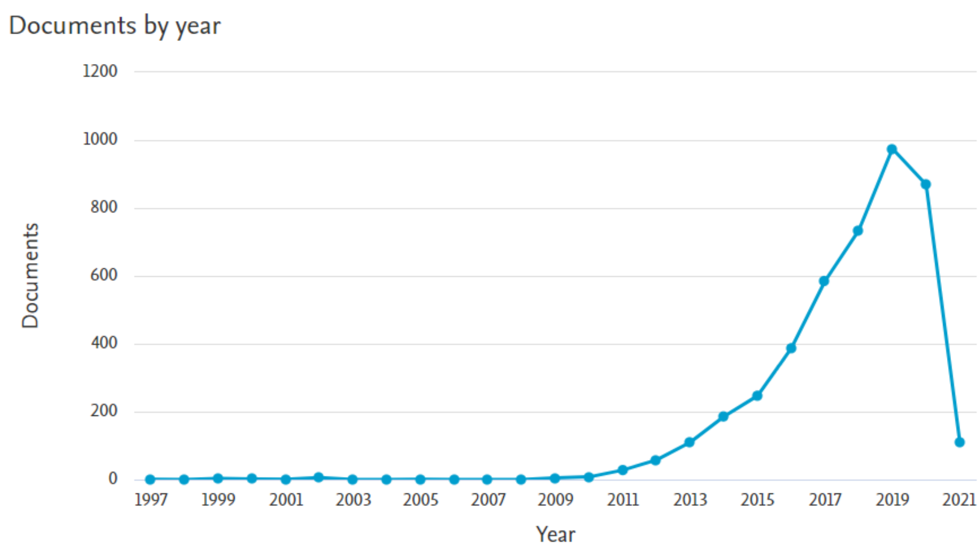

Figure 2. Documents with the keywords "smart city" and "infrastructure" by year.

The papers included in this review came from 34 different journals and conference proceedings and 54 countries. Figure 3 displays the spread of papers analyzed across the various origins. Although the United States is the biggest source of information on the subject, China has increased its output over the last few years. It is also important to note that only papers in English were considered in this review, which may have directly affected research output.

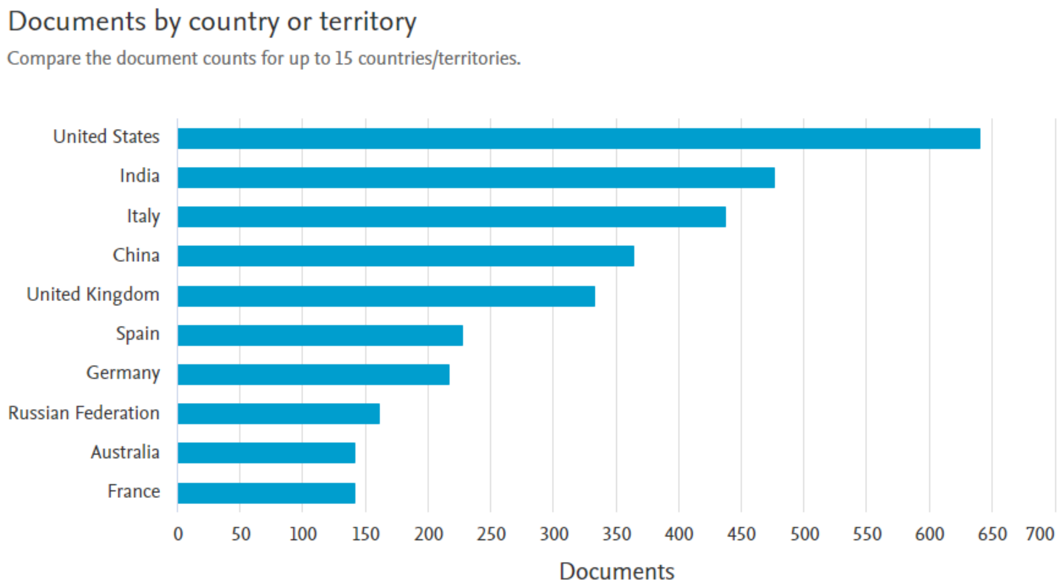

Figure 3. Documents by country on the Scopus database.

Figure 4 highlights the spread of papers analyzed across the various publishing journals and conference proceedings. At this level of the analysis, it was noted that IEEE Access contains the greatest number of publications targeting sustainable infrastructure.

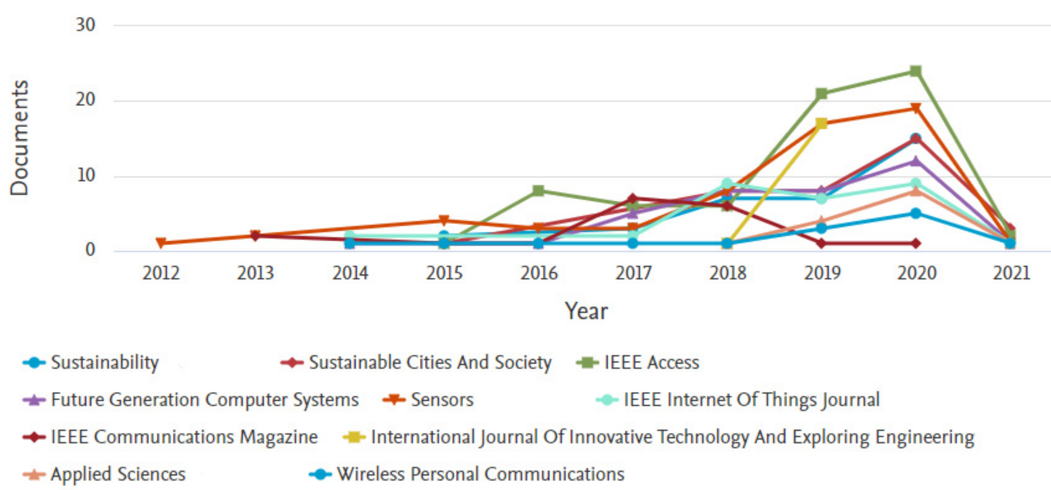

Figure 4. Sources of documents containing the keywords "smart city" and "infrastructure" from 2014–2021.

The GPS Visualizer software, an online utility created by Adam Schneider in 2002 in Minnesota, United States, was also utilized to create a map of the origins of the retrieved documents and their affiliations. Using BibExcel software, version 1.0, a tool-box developed by Olle Persson in Leuven, Belgium, it was possible to transform the (.csv) citation information retrieved from Scopus into localization information (latitude, longitude, name, and description). This information was then inserted into GPS Visualizer software, which read it, geocoded it and drew a map plotting the countries from which the Scopus documents originated. Since IEEE Xplore and Emerald Insight do not provide citation information documents in the required format to be uploaded into BibExcel, countries from those papers were added manually. Figure 5 presents the analyzed documents' countries of origin; to make visualization easier, Figure 6 presents Europe in greater detail.

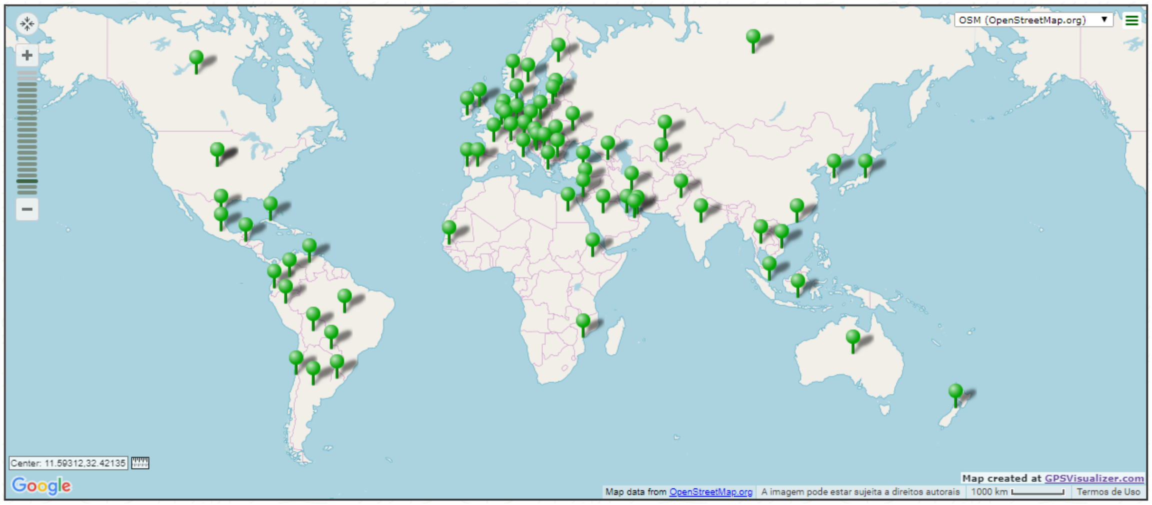

Figure 5. Documents' origins and authors' affiliations plotted with the GPS Visualizer tool.

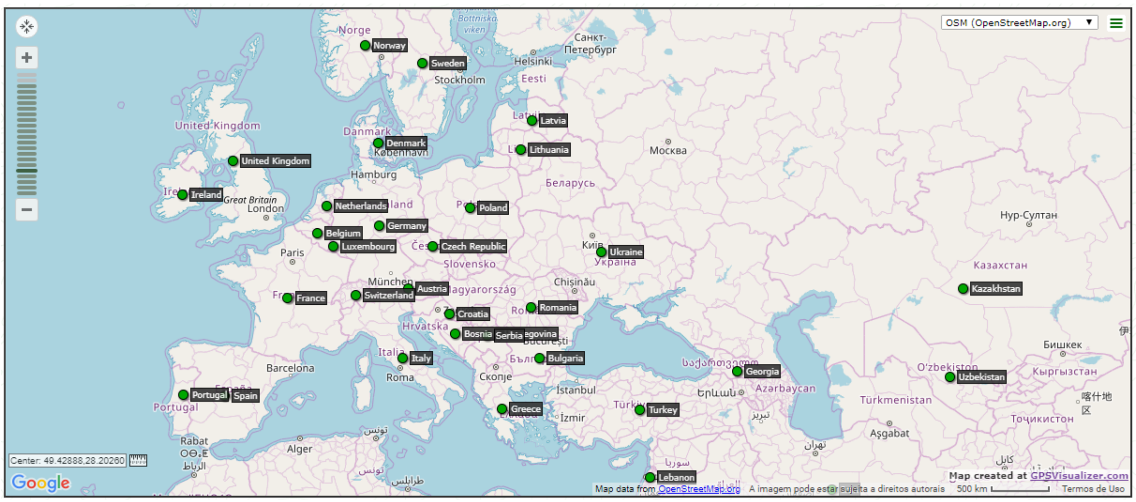

Figure 6. Europe in detail in the GPS Visualizer tool.

The descriptive analysis of this work involved a bibliometric analysis, which required uploading all citation information from the considered papers (title, abstract, author and keywords) into the VosViewer software and creating keyword clusters. Each map was created using the binary counting option, in order to remove any duplicated documents. After conducting the first analysis, VosViewer software identified how many keywords appeared in the title and abstract fields of all of the documents uploaded. By limiting results to a minimum number of occurrences, the number of keywords was drastically decreased. A relevant score was then calculated, and the most relevant terms were selected. Finally, the list of keywords was disclosed. General terms that did not relate to the issue such as "ease", "time", "place", and "thing" were deleted, before the cluster map was generated. Each map generated was examined and used in order to refine further research.

The first search conducted—which used the "smart city" term and retrieved 7122 documents, using the (.ris) documents in VosViewer—led to more than 60,000 keywords identified in the "title" and "abstract" fields. Limiting to a minimum of 250 occurrences, only 125 keywords met the threshold. In this field, 75 of them were considered more relevant, according to a relevance calculation from the software itself. After verifying the preliminary results and excluding generic words that did not relate to the issue, the first cluster analysis results were generated, as seen in Figure 7. The first and second clusters (in blue and green) highlight important aspects of the technological dimension of the smart city concept, e.g., internet and network, followed closely by IoT, sensor, and device. These keywords can be used to refine searches regarding the technological infrastructure of smart cities. The importance given to these terms leads to the conclusion that IT infrastructure is a big part of smart cities. The third cluster, in red, presents social and governance aspects of the smart city subject, highlighting keywords such as development, citizen, government, and strategy. Overall, the cluster map shows the three main dimensions presented in smart city discussions: technology, community, and governance. It can also be inferred that, although a holistic view is required to understand the subject entirely, each aspect must also be considered in its own particular way.

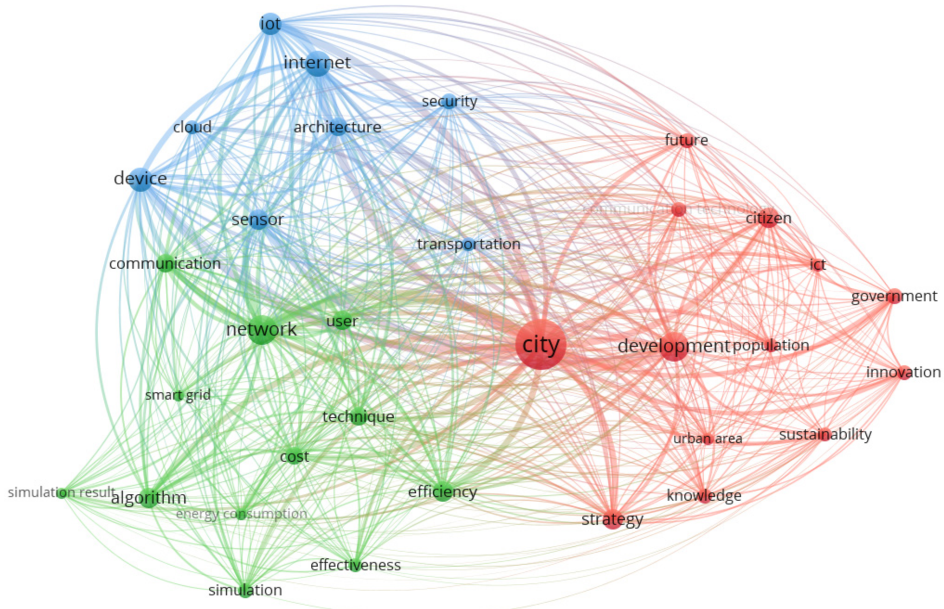

Figure 7. Cluster map generated by research results of the keyword “smart city”.

The second search, which used the terms “smart city” and “infrastructure” and retrieved 1848 documents, led to more than 15,000 keywords identified in the “title” and “abstract” fields. Limiting to a minimum of 50 occurrences, 122 keywords met the threshold. Within this pool, 73 of them were considered more relevant. After verifying preliminary results, the final clusters can be seen in Figure 8. Similarly, the second search highlighted the terms “network” and “internet'”, demonstrating the importance of IT infrastructure in smart city literature. It also denoted the keyword “system” as one of significant importance. Like the first map, it presented three clusters, each focusing on a different dimension of the subject.

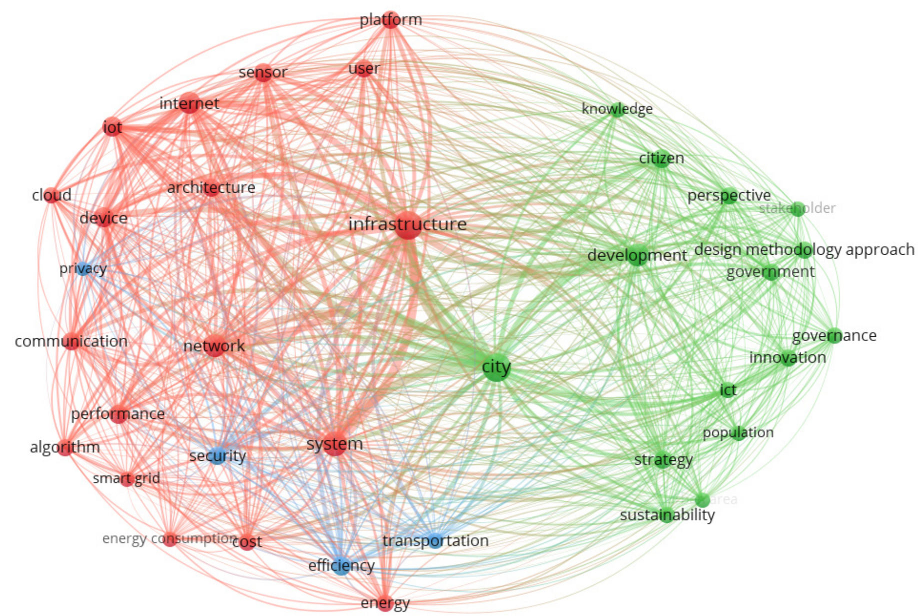

Figure 8. Cluster map generated by research results of the keywords "Smart City" and "Infrastructure".

The third search, which used the terms "urban systems" and "development" and retrieved 1031 documents, led to more than 15,000 keywords identified in the "title" and "abstract" fields. After limiting results to a minimum of 40 occurrences, 113 keywords remained, of which 73 were considered more relevant. After verifying the preliminary results, the final clusters can be seen in Figure 9. The cluster map created shows two different clusters: the red one focuses on urban planning, highlighting keywords such as "urban planning", "urban development", "policy" and "planning"; the green one presents the technological aspects of urban planning, with "system", "network", "information" and "technology" in prominence. Since this work focused on smart urban systems within the infrastructure topic, this third search regarding urban systems was important to refine further searches. The prominence of the term "system" over others explains its use in the following research.

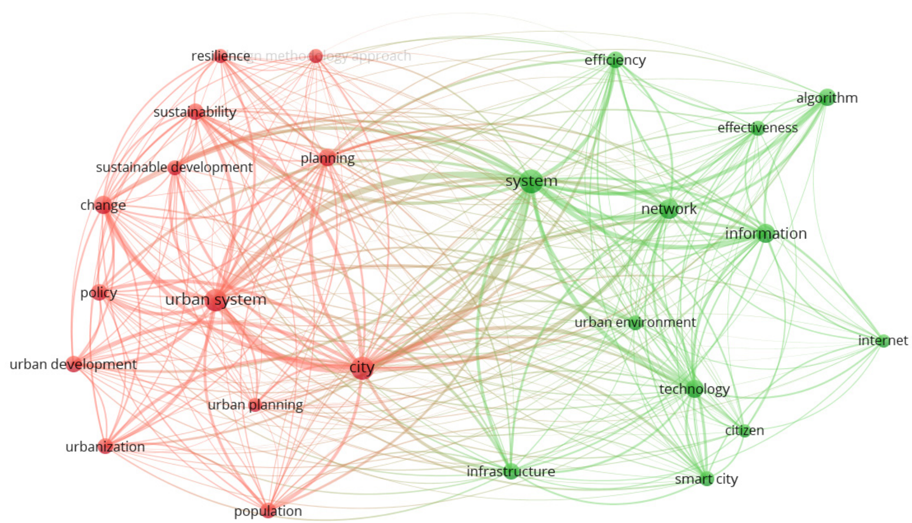

Figure 9. Cluster map generated by the research results of the keywords "urban systems" and "development".

After the creation of three cluster maps with the general/common wording of the search subject, it became clear that the technological aspect of smart cities' infrastructure appeared consistently. Therefore, the focus narrowed to more specific wording in order to deepen the analysis. Since the technological aspect is so prominent, it was the first to be tackled. Using the previously conducted research, the fourth search aimed to focus on this aspect. In order to do so, the key terms used were "smart city", "network" (due to its relevance in cluster maps 1 and 2) and "system" (due to its importance in cluster maps 2 and 3). Thereafter, the search retrieved 2001 documents that, in VosViewer, led to the results shown in Figure 10. The three clusters presented show different aspects of smart technology. In Figure 10, while the red cluster focused on energy (containing keywords such as "smart grid", "sensor" and "energy") the green one highlighted the importance of the technologies' architecture in maintaining everyone's privacy and security. Lastly, the blue cluster reminded us once again of the importance of bringing the population, the citizen, into this process. The importance of the keywords "communication technology", "knowledge" and "citizen" proved this point. This result can help refine further searches in the area of smart technology.

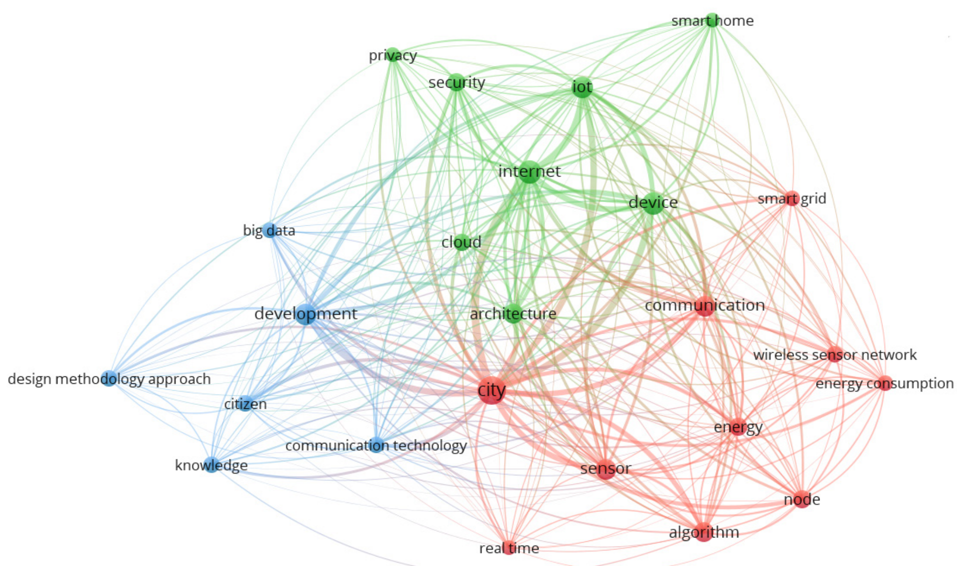

Figure 10. Cluster map generated by the research results of the keywords "smart city", "network" and "system".

The subsequent search focused more on the infrastructure aspect of the topic, rather than on the smart aspect. The keywords "urban system" and "infrastructure" were used in combination with "sustainability", bringing one of the biggest concerns of smart cities to light. It led to 4260 documents and the Figure 11 cluster map. It sorted out different aspects of green infrastructure, highlighting the need for urban and city planning in order to respond to the challenges that urbanization and the growing population of urban areas bring (red cluster). It also highlighted the role sustainability plays in this development (green cluster). Papers that wish to focus on urban ecology might use this data for further refinements.

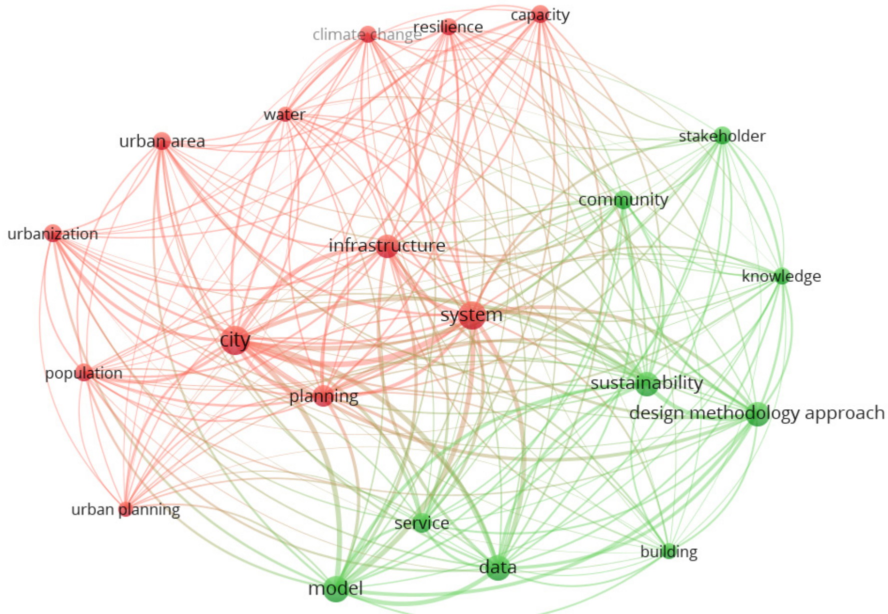

Figure 11. Cluster map generated by the research results of the keywords "urban system", "infrastructure" and "sustainability".

The last search considered the governmental aspect of implementing smart infrastructure. The keywords "citizen" and "government", both of which appeared in the same clusters on the first and second maps, were used together with "ICT"; results are presented in Figure 12. It is also of note that "citizen" appeared in all the cluster maps except the last one, as it focused on a more technical aspect of the topic. The results reflect the importance given to e-government and e-participation in today's smart cities. While the red and blue clusters present terms related to the governance aspect, the yellow and green ones sort out the technical issues of the topic.

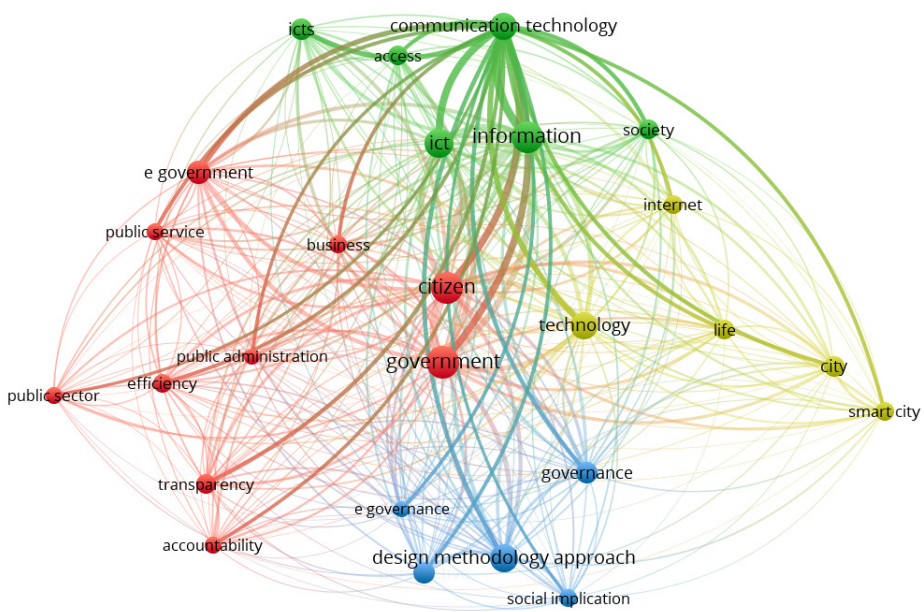

Figure 12. Cluster map generated by the research results of the keywords "ICT", "citizen" and "government".

2.3. Analysis of Papers

This section focused on the clustering of the selected body of work, based on the bibliometric analysis conducted. After retrieving more than 12,000 documents from the first three types of research, the keyword clusters generated by VosViewer software signaled how to refine smart cities' infrastructure further. Hence, the following three types of research were developed using these keyword enhancements, resulting in more than 7000 papers.

Out of the retrieved body of work, the 25 most relevant documents of each research cluster (identified from the bibliometric analysis) were chosen and expanded on in Tables 2–4. These tables present a summary of each one of the documents selected, based on their associated cluster.

Table 2. Documents that have "smart city", "network" and "system" as first clusters.

Source	Description
[17]	Presents a hierarchical architecture to resolve interoperability issues regarding smart energy system infrastructure and services in smart cities.
[18]	Proposes a new traffic control system based on the integration of SDN (software defined networks) and IoT (Internet of Things) in the smart city environment in order to ease the movement of emergency service units.
[19]	Presents an idea of a traffic management system that helps drivers to reach their destination in optimal time with the use of 5G networks, RFID transponders, and cloud infrastructure.
[20]	Applies ANN (Artificial Neural Network) for automatic building detection process, to be applied on smart city infrastructure for lightning detection, in order to build protection.
[21]	Presents a security architecture for smart cities where social networks enable an adaptive sensing-as-a-service system. The smart city objects will have their reputation built on the feedback they receive from humans and other nodes in the network.
[22]	Discusses the design of information-centric cognitive radio-based networking for multimedia-based applications in smart cities. It also studies its capability for improving network connectivity and content search, distribution, and reliability.
[23]	Presents a collaborative experience between government and offering advantages in cloud services to improve the services of smart governments.
[24]	Proposes a multilevel IoT-based smart cities' infrastructure management architecture and evaluates the proposal through a case study related to the waste management problem.
[25]	Presents DistArch-SCNet, a new smart city network architecture, to address concerns about energy scalability, flexibility, availability and efficiency in the existing network.
[26]	Studies big data algorithms through the lens of the 3 Vs (veracity, volume, and velocity) in order to facilitate soft sensing within smart city applications.
[27]	Introduces the smart cities as an important example of sustainable interdependent networks. Moreover, presents the emerging challenges of these networks in terms of upgrading the existent infrastructure to more intelligent systems.
[28]	Identifies network characteristics and requirements for different smart city applications. It also identifies networking protocols that can support the data traffic flows between the different components of the system.
[29]	Proposes a heterogeneous network scenario to implement a real time video surveillance application in a smart city environment.
[30]	Presents a methodological framework for parking availability predictions.
[31]	Discusses the concept of a smart city based on ICT (Information and Communication Technology) and analyzes the goals of smart city development in Taiwan.
[32]	Proposes a new vehicle network architecture for the smart city environment, mitigating network congestion with the optimization of networking, caching and computing resources all together.
[33]	Proposes data-driven methodologies to increase data validity in a cellular network-based transportation data collection system.

[34]	Analyzes smart city security architecture and risk, in order to present insights on how to create an optimal smart city security platform.
[35]	Proposes an architecture design of green WSNs (wireless sensor networks) for smart cities, also listing the challenging issues raised by its design.
[36]	Proposes an energy- and congestion-aware routing metric for smart meter networks to be implemented in smart city scenarios. By minimizing power consumption, network lifetime will be enhanced.
[37]	Evaluates a thousand neural network architectures used for the automatic diagnosis of chronic social exclusion. It also presents the advantages of using a DL (deep learning) paradigm over ML (machine learning) alternatives.
[38]	Presents tests and experiments to demonstrate the potential of ZnO (zinc oxide) as highly transparent conductive materials and, thus, a suitable and greener alternative to ITO (indium tin oxide) for microwave applications.
[39]	Proposes a microgrid-based congestion management method to relieve transmission line congestion.
[40]	Presents a comprehensive literature review of key features and applications of the IoT paradigm supporting the sustainable development of smart cities.
[41]	Proposes a novel traffic management system by considering the gaps of previous research and what is yet to be explored in the current scenario.

Table 3. Documents that have "urban systems", "infrastructure" and "sustainability" as first clusters.

Source	Description
[42]	Defines the phrase "urban ecological infrastructure" and further proposes an integrated framework in which a city's infrastructure network provides sustainable urban systems and ecosystem services despite changing landscapes and climate.
[43]	Explores the barriers to green infrastructure implementation and suggests policies that can overcome these barriers and accelerate implementation.
[44]	Presents a framework for planning and managing urban green infrastructure in order to improve urban sustainability.
[45]	Conducts quantitative research on the imbalances of investment in urban infrastructure within China's cities.
[46]	Analyzes the urban infrastructure systems as if they are analogous to ecological systems. Presents the 12 guiding principles of infrastructure ecology and how they can change the decision-making process for urban development.
[47]	Examines the potential of big data analytics and context-aware computing to improve urban sustainability.
[48]	Documents the challenges and addresses their solutions in the water infrastructure planning and management domain.
[49]	Explores the synergy between the sustainable development underway in cities nowadays and the socioecological innovations in the current trend of sharing economy.
[50]	Offers strategies for mitigating greenhouse gas emissions from Chinese industrial parks.
[51]	Proposes a new economic geography model to simulate China's urban systems' evolution and to further predict the future development of the country's systems under different urbanization prospects.
[52]	Presents a geodesign method that facilitates a closed-loop urban system process through algae cultivation by making urban waste streams turn into renewable energy.
[53]	Uses an evaluative framework to determine to what extent sustainability initiatives led by local governments reflect what literature claims they can do.
[54]	Presents a systems-based framework to define how environmental, organizational and social aspects interact within an urban system in China.
[55]	Presents the results of a new indicator system to monitor the environmental quality of infrastructure. The 22-indicator system created accounts for socioeconomic development as well as the construction of sustainable infrastructure, applied to data from 2000 to 2010 in 277 Chinese cities.
[56]	Focuses on the debate concerning urban planning, highlighting the need for a novel approach and tools that could allow for the smartization of cities.

[57]	Proves that, regarding the whole-city level, the operating cost is intimately related to housing density and relative length of roads.
[58]	Examines to what extent urban densification policies contain an assumption that continual growth, expressed in per capita consumption of building stock and infrastructure, should be accommodated.
[59]	Examines the outcomes of a collaborative research project, EcoCities, and presents approaches to build adaptive capacity into environmental and spatial planning projects.
[60]	Provides an overview of the architecture required in the context of modelling Land Use/Land Cover change patterns.
[61]	Presents estimates of the changing exposure of urban infrastructure to floods and droughts due to urban land expansion from 2000 to 2030.
[62]	Proposes a stochastic theory of urban growth that considers some scaling; the predictions are confirmed by empirical data from the US and the Organization for Economic Co-operation and Development (OECD).
[63]	Proposes a new systemic model approach to the issue of adapting cities to climate change.
[64]	Offers a conceptual framework that expands the traditional transition model (industrial-sanitary-sustainable city) to include permutations of transition options.
[65]	Uses the multi-sectoral systems analysis tool to address questions of sustainability and to support the decision-making process for policy and investment.
[66]	Proposes a system-based framework to synthesize the connections between water use and energy consumption in an urban scenario.
[67]	Analyzes how (and to what extent they are indicators) benchmarking and dashboard initiatives are employed by cities, arguing that they make the city seem like visualized facts. It further indicates how this reshapes the way cities are governed.

Table 4. Documents that have "citizen", "government" and "ICT" as first clusters.

Source	Description
[68]	Explores the drivers behind what makes citizens engage in social and political participation on the internet.
[69]	Presents a multicriteria methodology to evaluate e-government using eight criteria built on four points of view: infrastructure, investments, e-processes and user attitude.
[70]	Develops a new approach to e-participation based on passive crowdsourcing by government agencies.
[71]	Discusses the use of government social media for openness and accountability in order to improve citizen participation.
[72]	Analyzes practices of citizen involvement in smart city initiatives and to what extent it is the goal of a smart community to involve citizens in governance.
[73]	Examines how the use of e-government websites by citizens relates to their satisfaction and perception of public sector trustworthiness.
[74]	Proposes a framework that integrates processes, resources, back offices and front offices of online systems for E-Government 2.0 implementation.
[75]	Introduces the main features of the Internet-Enabled-Services (IES) Cities platform, whose aim is to facilitate the creation of citizen-centric apps that exploit urban data from different areas of knowledge.
[76]	Analyzes the mechanisms through which e-government can influence corruption in a nation and tests the direct and mediated effects of e-government on corruption in national institutions and stakeholder service systems.
[77]	Examines the evolution of ICT technology in the public sector throughout time.
[78]	Focuses on how to work with imperfections during information retrieval and data integration in a smart city's systems.
[79]	Presents the findings of a survey conducted in Taiwanese cities regarding citizens' willingness to accept and use ICT services.
[80]	Examines how patterns of technological chance in using Geographic Information Systems (GIS) and ICT are impacting local governments' process efficiency.

[81]	Investigates different ways through which open data, together with innovative visualisation techniques, can be used to provide new services to cities.
[82]	Provides an integrated model regarding ICT projects that identifies factors that can influence the adoption of e-government services.
[83]	Highlights the gaps in current e-government maturity and stage models.
[84]	Proposes a multiple-mediation model that examines the technology-organization-environment factors that affect the government's willingness to implement e-participation.
[85]	Develops the concept of ICT as an influencer of how citizens view civic roles by testing relationships between social media use, political identity, and citizens' views of government service provision and spending.
[86]	Proposes a practical framework structure to organize, promote and implement e-participation.
[87]	Presents and examines the effects on service delivery outcomes of a novel ICT platform where citizens can send free and anonymous messages to the local government.
[88]	Examines the key determinants of mobile government attractiveness.
[89]	Determines the criteria important for both teachers and citizens in using video-to-video (V2V) communication in municipality services for ICT education of senior citizens.
[90]	Proposes a conceptual framework for e-government implementation in a low infrastructure situation.
[91]	Presents a checklist for use by designers and city planners to identify key outcomes of a user-centric mobile initiative from the government.
[92]	Presents the outcomes of a survey regarding data collection in Iran, including aspects of technical and communication infrastructure, business environment, culture, and society.
[93]	Analyzes the development of the digitalization process of the Italian Public Administration, through the adoption of well-suited ICT solutions.

2.4. Smart Cities' Infrastructure Research Dimensions and Themes

The framework that is proposed in this study for smart city infrastructure relies on organizing the retrieved papers based on a number of research dimensions. These dimensions can then be broken down further into themes that define the research areas examined in smart city infrastructure. By observing Figures 7–12, three main dimensions are derived: technical, community, and institutional, as seen in Table 5. The technology dimension encompasses smart city infrastructure studies that examine the use of technologies such as SDN (Software Defined Networks) [23], IoT (Internet of Things) [23], 5G [94], RFID (Radio Frequency Identification) [95], big data [96] and cloud infrastructure [97] as essential to make cities smarter. For the institutional dimension, subjects such as e-governance [98] and ICT services for administration are discussed [99]. Finally, for the community dimension, e-participation of citizens and the use of ICT services to enhance citizens' user experience are frequently examined in smart city infrastructure [100].

Table 5. The three main dimensions of the "smart city" concept and commonly seen subjects regarding each one of them.

Dimensions	Frequent Subjects	References
Technology	AI	[13,101–103]
	Traffic Real-time control	[104]
	Sensor network	[105]
	RFID technology	[106]
	5G	[107]
	IoT	[102,108–110]
	Big Data	[111]
Institution	E-governance	[112,113]
	ICT services	[103,114,115]
Community	E-participation	[102,116]
	ICT services with a user-centric approach	[117]

Narrowing down the dimensions further, a list of 10 themes highlights an appropriate classification mechanism for the studies examined. The proposed classification framework of smart city infrastructure studies is shown in Figure 13. Associated references with each theme and the further refinement of studies based on classes of research targeted is presented in Table 6. The ten themes of classifying smart city infrastructure studies include energy, security, transportation, smart city network architecture, health, construction, land use, hydrology, government, and population.

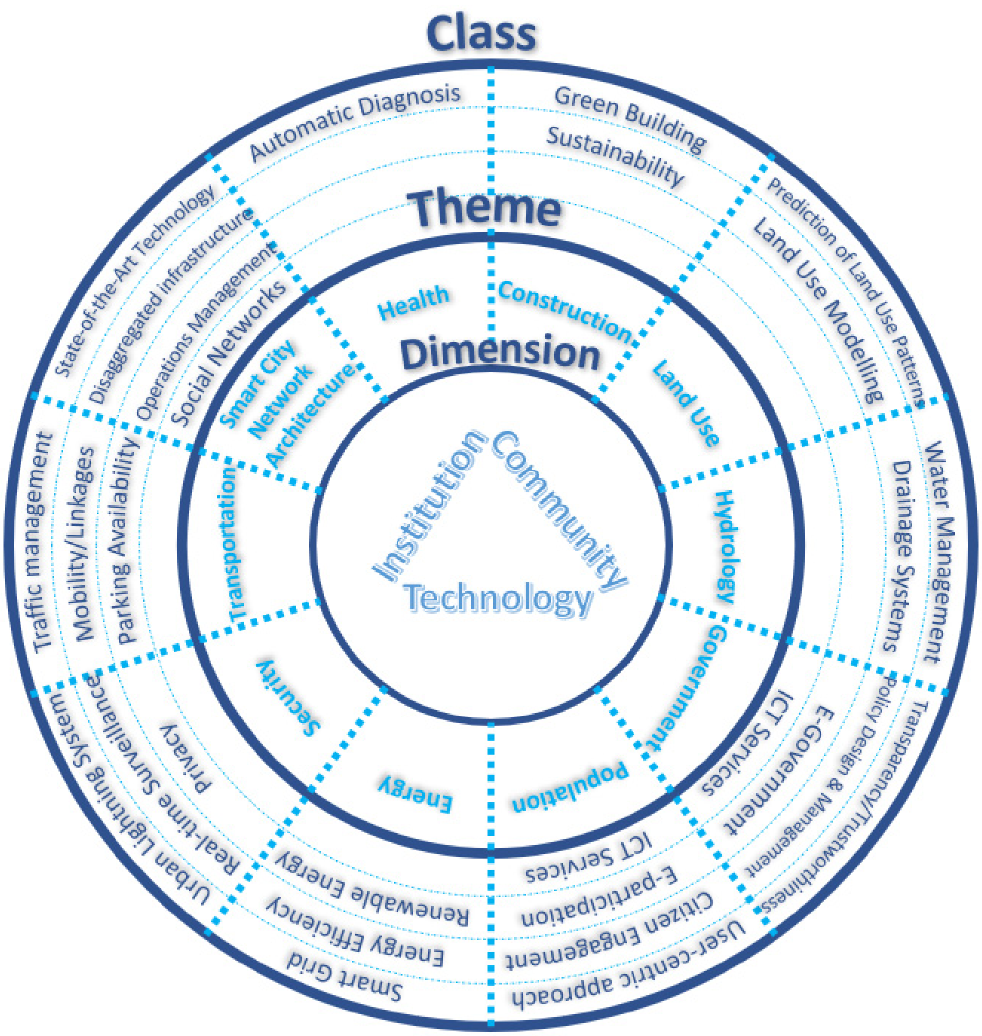

Figure 13. Classification framework proposed for smart city infrastructure.

Table 6. Classification of literature based on themes and associated classes.

Themes	Classes	Articles
Energy	Smart Grid	[17,66]
	Energy Efficiency	[35,36]
	Renewable Energy	[50]
Security	Privacy	[34]
	Urban Lighting System	[20,57]
	Real-time Surveillance	[29]
Transportation	Traffic management	[18,19,33,36,39,41]
	Mobility/Linkages	[45,62]

	Parking Availability	[30]
Smart City Network Architecture	State-of-the-Art Technology	[25,26,31,32,40,47,93,118]
	Social Networks	[21,22]
	Operations Management	[27,28,38,51,67,78]
	Disaggregated infrastructure	[119–123]
Health	Automatic Diagnosis	[37]
Construction	Green Building	[42–44]
	Sustainability	[46,47,49,124]
Land Use	Prediction of Land Use Patterns	[60,61,64]
	Land Use Modelling	[56,59]
Hydrology	Water Management	[48,52,66]
	Drainage Systems	[61,125]
Government	Transparency/Trustworthiness	[53,71,73,76]
	E-Government	[73,83,84,90,93,126]
	ICT Services	[70,71,76,77]
	Policy Design and Management	[58,65,80]
Population	User-centric approach	[75,91]
	ICT Services	[68,81,85,87,89,92]
	Citizen Engagement/E-participation	[68,81,100,116]

3. Results and Discussion

In this section, the questions posed at the start are answered after having reviewed the literature.

a. What are the various dimensions that smart city infrastructure research focuses on, and what are their associated frequent subjects?

There are three main focal points when it comes to smart city research dimensions: technology, community and institution (i.e., government) [127]. What can be noticed is that research articles tend to focus on one or two of these dimensions without regard to all dimensions. That means that most documents are either very technical (focusing on the technological aspect), or very social (focusing on how the government and the citizens are related to urban infrastructure). When it comes to review papers, this issue occurs less frequently. Frequent subjects reported in the literature for each dimension are shown in Table 5.

For technology, the most prominent subjects seem to be sensor networks [105], IoT [108] and real-time traffic control [104]. It is important to note that the issues of big data and IoT seem to lack a broad perspective when it comes to smart city infrastructure, without cross-mapping and a clear initiative for implementation to go with proposed methods of addressing associated challenges. For the institutional aspect, the subject of e-governance and how it impacts decision making—in terms of infrastructure maintenance, operation and risk management—are hot topics in the realm of smart city infrastructure [128]. Nam et al. [129] conducted a literature review on the impact of blockchain technology on smart cities and discussed the major issues related to that technology, including some misconceptions. Krishnan et al. [84] reviewed several papers on e-government literature and assessed the mediation effects of the government's willingness to implement electronic information sharing, electronic consultation and electronic decision-making, as well as the maturing relationships of e-government. Within the community focal point, e-participation and how it impacts decision-making for investment in smart city infrastructure is heavily studied, as are issues associated with boosting community participation in public life. For instance, Allen et al. [116] conducted a literature review about e-participation in monitoring service performance and open government, with a focus on citizens' contribution to e-monitoring. Additionally, Yigitcanlar et al. [102] proposed a social media analysis approach that contained descriptive, content, policy, and spatial analyses. Recent studies have tended to focus on the technology and institutional dimensions, but there are subjects in all three dimensions that stand out, as presented in Table 5.

b. What are the research themes and classes associated with these dimensions?

This research question's main aim was to further filter down the dimensions identified in smart infrastructure research, based on a set of themes and interrelated classes of research themes. One of the fastest growing themes investigated is associated with smart city network architecture and transportation, with a large number of papers focusing on the state-of-the-art technologies implemented in smart infrastructure, operations management of smart infrastructure, and issues related to disaggregated infrastructure, traffic management, or mobility. Construction and governance are the next most highly active research themes, with emphasis on the following: ensuring sustainability in the construction of smart infrastructure; methods and approaches for linking ICT services to enhance governance of smart infrastructure; the notion of e-governance and its use for the operation and maintenance of infrastructure. It is also important to point out that many themes—e.g., energy, transportation, security, smart city network architecture, hydrology, construction, and land use—present papers that largely deal with the technological aspect, as follows:

- Energy-themed studies focus mainly on the smart grid [130], with articles tackling the issue of how to make the urban electricity system greener [131] and more efficient [132].
  Security-themed studies focus on issues related to privacy, associated with infrastructure monitoring [133], methods of enhancing security of the infrastructure for the community via real time surveillance [134], and enhanced smart lighting at night time [135].
- Transportation-themed studies discuss traffic management via smart approaches [136], safety enhancement of the infrastructure system [137], and improving the operations of the system [138].
- Smart city network architecture covers papers regarding the installation of sensors throughout the city for diverse reasons [139], including big data analysis of urban systems to enhance their performance [140], communications technology, and mobile signal. There is also the issue of fragmented infrastructure [67].
- Health-themed studies focus on automated tools and technology embedded in the infrastructure for diagnosing defects, structural issues and maintenance requirements [141].
- As a theme, construction is associated with studies that target green construction of smart city infrastructure systems [111], along with the sustainability of the construction and maintenance of the systems [124].
- The land use theme focuses on studies that examine patterns of urban sprawl [142] and how to optimize smart infrastructure in saturated spaces such as densely habited urban areas [143].
- The hydrology theme covers studies that examine smart infrastructure water management systems [6] for clean water provision, sewage, sanitation, and drainage [115].
- The government research theme contains papers that examine e-governance of smart infrastructure systems [90], ICT services used to administer systems [144] and policy-making associated with systems [145].

- Lastly, under the population theme, articles that discuss smart communities (e.g., their participation in key decision-making regarding infrastructure systems, or enhancing their contributions via user-centric approaches) are categorized [146]. Studies that motivate citizens by utilizing transparent and accessible management models of smart city infrastructure are also grouped under this theme.

c. What are the main shortcomings of current approaches, and what would be a good research agenda for the future in smart infrastructure development?

A holistic view (involving all three dimensions of smart city infrastructure) is fundamental for a deeper understanding of smart city infrastructure. Some studies continue to focus on only one or two of the dimensions identified, while others fail to present a clear road map of technology implementation in smart city infrastructure that guarantees the involvement and consideration of the other two dimensions. This review of smart city infrastructure studies indicates that a possible blind spot continues to exist in ICT services, information systems, and e-government models available for smart cities. This may prevent unity within the infrastructure system, exaggerating Frankenstein urbanism in smart cities. For example, Cugurullo [119] discusses how smart cities fail to fulfill their philosophical and sustainable ideals, often replicating traditional capitalist urbanization strategies. Additionally, Yigitcanlar et al. [147] proposed that smart cities' lack of progress can be attributed to strong techno-centricity.

The main shortcomings identified in the current literature are as follows:

- A more comprehensive understanding of the impacts of socio-technological practices on the future roadmap of smart city infrastructure development is needed.
- Most of the studies tend to focus on how to transform, ameliorate or create smart infrastructure and do not necessarily sufficiently tackle the issue of how to maintain and conserve it.
- Topics that collectively examine how smart infrastructure impacts economic growth and politics in the region are rare. There is an urgent need for studies that evaluate the realization of these aspects through quantitative comparisons or in-depth case analysis.

Once these shortcomings are acknowledged, recommendations for a future research agenda can be as follows:

- Smart city infrastructure must be conceptualized as an emergent socio-technological topic that will only be fully understood if a comprehensive view is studied and well-contextualized, such that Frankenstein urbanism is avoided.
- Future studies must focus on both the transformation and subsequent maintenance of urban infrastructure. Most current studies focus on one of these without exploring the other. Empirical research needs to done to investigate what is required in order to conserve everything well.
- Sound evaluation studies of the impact of smart city infrastructure on economic growth and politics are necessary. The underlying assumption is that a smart city makes life better for everyone, and there is a lack of attention to the politics of technical choices. Artifacts do have politics. Specific choices about (technological) infrastructure have consequences for power distribution in the city—and thus need to be studied accordingly.
- Scaling up the search for socio-technological synergy—from the level of enterprises and organizations in general to the level of urban systems—has merits. However, research into these issues must avoid oversimplifying the new connections between technology, government, and population. Research into smart city infrastructure and its governance must learn from the success of factors already identified for e-government and build upon it. It should consider existing theories of socio-technological transformation and study urban systems' development as an evolving process of institutional change.

4. Conclusions and Future Direction

Using content analysis, over 100 journal articles were examined in this paper to highlight the main dimensions and topics involved in the sphere of smart infrastructure. Three main research questions were addressed in this review, namely: (i) What are the various dimensions that smart city infrastructure research focuses on? (ii) What are the categories and classes associated with these dimensions? (iii) What are the main shortcomings in current approaches, and what would be a good research agenda for the future? Through the proposal of a classification framework and performance of comprehensive bibliometric and bibliographic analyses on papers published over the past six years, different smart infrastructure research trends were revealed. The bibliometric analysis presented seven major keyword clusters around which smart infrastructure research revolved: "smart city", "network", "urban system", "infrastructure", "sustainability", "citizen", "e-Participation", "government" and "ICT". On the other hand, the bibliographic analysis reflected major aspects of smart city infrastructure, including: IT infrastructure, sustainable and ecological buildings, urban systems, smart initiatives, and applications that stimulate e-governance and e-participation.

The knowledge disseminated in this study serves to suggest a path for future research, aligning smart city infrastructure with a set of well-defined dimensions, categories and classes of research. One limitation associated with the proposed categorization framework in this work is subject bias due to the framework's interpretative nature. In addition, there is a lack of focus on intertwined and holistic approaches to the framework presented; aspects of smart cities unrelated to infrastructure but which could impact infrastructure indirectly—such as social dimensioning and education—were not covered.

Based on the recommendations derived from the developed framework, the study herein predicts that future research will focus on subjects such as IoT, 5G networks, and ANNs (artificial neural networks) to help form a deeper understanding of the technical aspects of smart infrastructure and smart cities. Another expanding future direction relates to green infrastructure and how technology can be utilized to achieve environmentally friendly solutions. There will also be increased focus on e-governance, e-participation, and ICT (information communication technology), in order to help build knowledge on smart infrastructure planning, construction, operation and maintenance. Finally, the issue of Frankenstein urbanism and the challenges surrounding disaggregated infrastructure systems—and methods to avoid them in smart cities—will be an important research direction in the future of smart city infrastructure.

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