Recent Developments in Smart City Assessment: A Bibliometric and Content Analysis-Based Literature Review

Petr Hajek[a,*], Abdelrahman Youssef[a], Veronika Hajkova[a]

[a] Science and Research Centre, Faculty of Economics and Administration, University of Pardubice, Studentska 84, Pardubice, Czech Republic

* corresponding author

e-mail: petr.hajek@upce.cz, abdelrahmantaha.youssef@student.upce.cz, veronika.hajkova@upce.cz

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Abstract

Cities around the world are increasingly competing to upgrade their infrastructure and smartness levels to attract talent, become more effective and sustainable. However, assessing the progress of smart cities is often challenging due to the lack of theoretical foundation and consensus on an assessment methodology. These contradictions can pose major constraints on the development of the smart city concept and its implementation in practice. This paper analyzes a set of 164 articles published between 2010 and 2020 that deal with smart city assessment. The present study aims to identify the most influential research and key research themes, and suggests future research directions in the field of smart city assessment. A bibliometric analysis is used to reveal the most influential articles and their associations. Furthermore, a content analysis is performed to explore recent developments in the field of smart city assessment in terms of research hotspots and research themes. The analysis reveals the existence of 11 research themes and their timelines. The most influential research addresses (1) multiple-criteria decision-based performance measurement frameworks, (2) data connectivity challenges, (3) composite indexes for smart sustainable cities, (4) holistic performance evaluations of smart cities, and (5) the characteristics of indicator sets. Based on these results, current advances in smart city assessment are discussed, and future research directions in this field are suggested.

Keywords: smart city, assessment, framework, bibliometric analysis, content analysis, literature review.

1. Introduction

Following the rapid development of ICT, it appears that we are moving into a new era of infrastructure with more embedded technologies. Specifically, the recent digital transformation and developments in the Internet of Things (IoT), automation, and 5G have not only led to fundamental changes in industry (Industry 4.0), but smarter devices and environments have given rise to smart technology-driven ecosystems, including smart city, intelligent city, ubiquitous city, digital city, and other concepts (Rathore et al., 2018; Praharaj and Han, 2019). In regards to the characteristics of a smart city, the literature show three scenarios (Andreani et al., 2019): (1) a technology-centered scenario, in which technology is very visibly driving and shaping the development of a smart city through technological infrastructure both hardware and software such as digital networks, mobile technologies, and virtual technologies; (2) a human-centered scenario, in which there is an emphasis on people and human capital, such as the promotion of education and creativity; and (3) a combined scenario, which considers both technology infrastructure and a focus on people.

The concept and dynamics of creating a smart city have evolved over time. The first generation of smart cities, "smart city 1.0," was therefore driven more by technology companies, presenting use cases of smart city technologies and promoting their results to city officials. The second generation "smart city 2.0," followed a different approach, where cities were guided more by a vision of what a smart city was supposed to look like, such as implementing requirements for the needs, problems, and priorities of the city, in coordination with technology providers. More recently, the third generation of smart cities has come on the scene by considering citizens' opinions and encouraging their participation and engagement in smart city development (Yigitcanlar et al., 2019).

The need for smart cities is also increasing as more people move to urban areas, putting greater pressure on limited urban resources. This pressure is higher in regions where urban space is limited, such as Europe, where cities host an estimated two-thirds of the population. Cities therefore need to swiftly implement smarter ways of managing resources. Manville et al. (2014) came up with three recommended factors to make a smart city successful: (1) having a clear vision and communicating it; (2) seeing the opportunities from the perspective of city management and living citizens, who should also be encouraged to participate in the development of a smart city; and (3) having a standard process that connects ideas to projects and stakeholders.

The number of smart cities in the world, whether already developed, implemented, or planned, is growing. The global smart cities market is projected to grow from $411 billion in 2020 to $821 billion by 2025, attributed to the introduction of new government initiatives and the increasing adoption of smart technologies (Research and Markets, 2020). Cities across the globe are competing to be smarter and more efficient than others to improve the quality of life for their citizens and subsequently become recognized for their smartness. This strategy helps attract talent and investments that lead to a thriving economy with a sustainable future. With the rapid growth of smart city initiatives, smart city assessment is becoming an increasingly important factor in tracking their progress. One way to assess the effectiveness of a smart city and differentiate its position from others is shown by the IMD Smart City Index, which examines citizens' perception towards the smartness of their own city (IMD, 2020). The assessment is based on two pillars, the Structure pillar (existing infrastructure) and the Technology pillar (technology services). Within each pillar, five dimensions are measured, including health and safety, activities, mobility, governance, and opportunities. The result of the examination is a ranking of the evaluated 109 cities according to their overall rating and a rating for each pillar derived from the city's performance, as calculated relative to the other cities. The top-performing cities, which are seen as the leading cities against which to measure, are Helsinki, Zurich and Singapore.

The past decade has seen a rapid development of approaches for assessing smart cities. To compare these approaches, previous research has conducted comparative analyses of smart city assessment indicators (Huovila et al., 2019) and assessment practices (Caird, 2018). Only recently have smart city assessment approaches been comprehensively reviewed (Sharifi, 2019; Sharifi, 2020a). Sharifi (2019) conducted a critical review of 34 smart city assessment tools, examining their comprehensiveness, feasibility, flexibility, participatory development, context relevance, and alignment with strategic targets. Sharifi (2020a) substantially expanded the typology of smart city assessment tools by considering the main goals and dimensions of assessment, assessment formats (index/toolkit/scorecard), data types, and number of implementations. However, previous studies on smart city assessment have only focused on the categorizations of assessment indicators and schemes while neglecting to identify the most influential research and emerging research themes (see Table 1). In fact, research to date has tended to focus on the assessment schemes that provide freely accessible documentation, thereby overlooking many important academic studies available in scientific databases. Moreover, schemes covering only one assessment dimension have been excluded from previous review studies. As a result, previous research has not been able to provide a comprehensive understanding of research directions in this area.

Bibliometric analysis and science mapping can be effective in identifying well-established and emerging research themes. Clusters of research can be identified using these methods to reveal the intellectual structure and emergent study fields in the research domain. In addition, content analysis enables topical categorization of the published assessment schemes and investigations of the evolution of these themes over the years. More precisely, the bibliometric performance indicators allow us to identify the most important and influential authors, studies, and journals, while the science mapping serves to reveal the evolution of research in a given field through co-citation analysis. To further understand the structure of knowledge and avoid subjective bias, a literature review based on content analysis can be conducted by linking words in the publication text based on their collocations.

In light of the above, it is necessary to summarize the research on smart city assessment and explore its content. Without a thorough bibliometric and content analysis, identifying research hotspots and trends is more subjective and less accurate (Sharifi et al., 2021). To the best of our knowledge, this is the first study to perform a bibliometric analysis of the existing literature and reveal research hotspots and development trends in the field of smart city assessment. Taken together, this study provides a systematic mapping of the most recent developments on smart city assessment research, providing a broader overview, areas of current research interests. and potential future researcher directions in this domain. Hence, our study provides the opportunity to objectively identify the clusters of research streams within the smart city assessment literature. By exploiting the advantages of bibliometric and content analysis, existing systematic reviews are complemented with a more detailed roadmap for further research in this area.

To better understand global trends and deepen knowledge in this area, this study aims to conduct a content analysis of recent studies on smart city assessment. To achieve this goal, we analyzed 164 articles from the Web of Science (WoS) database, the IEEE Xplore database, and grey literature found in Google from 2010 to the end of 2020. Using standard bibliometric indicators, we identified the distribution of articles and the most influential authors, journals, and countries. Furthermore, by analyzing the content of these articles, we examined the evolution of research, which then allowed us to predict future trends in smart city assessment research. We identified three research development stages: the first stage, originating in 2011, concerned the development of sustainability measurement and smart city measurement frameworks; the second stage, originating in 2015-2016, concerned smart city indicators and standards, assessment frameworks and tools, and aspects of implementation; and the third stage, initiated after 2016, concerned smart sustainable cities, holistic assessment, citizen engagement, and data connectivity. The main contributions of this study are therefore twofold: (1) it presents the most influential theoretical foundations in smart city assessment research, and (2) the research development track is analyzed to better understand the research developments and identify future research directions.

The remainder of this paper is organized as follows. Section 2 introduces the smart city concept and related previous work on smart city assessment. Section 3 describes the methodology used, including the methods used for the content analysis. Section 4 presents the results of the bibliometric and content analysis. Section 5 discusses the results obtained. Section 6 summarizes our findings and suggests future research directions. Section 7 concludes with the limitations of the study.

Table 1: Comparison of earlier literature reviews with our study

Study	**Time period**	**Source of data**	**Dataset**	**Focus**	**Methodology**
Caird (2018)	2015	city authorities and city reports	5 UK cities	best practice in smart city assessment and reporting	interviews with local government authorities, review of city reports
Huovila et al. (2019)	2016-2018	international city indicator standards	7 sets of city indicators	develop a taxonomy of assessment indicators	input-process-output-outcome-impact typology for smart sustainable city indicators
Sharifi (2019)	2012-2019	WoS and grey literature	34 assessment tools	identify strengths and weaknesses of assessment schemes	typology study
Sharifi (2020a)	2012-2019	WoS and grey literature	34 assessment tools	analyze the structural features of assessment schemes	typology study
This study	2010-2020	WoS, IEEE Xplore and grey literature	164 articles	identify the most influential theoretical foundations and future research directions in smart city assessment	bibliometric analysis, content analysis

2. Theoretical Background

2.1. Definition of a Smart City

Although the concept of a smart city remains ambiguous, several definitions of what a smart city is have been presented. Here, we list those definitions presented in the most-cited studies to distinguish the main characteristics of a smart city. Giffinger et al. (2007) highlighted a combination of the six core dimensions and citizen amenities in a smart city:

Definition 1. "A city well performing in a forward-looking way in economy, people, governance, mobility, environment and living, built on the smart combination of endowments and activities of self-decisive independent and aware citizens".

Caragliu et al. (2011) and Bakici et al. (2013) took a broader perspective by emphasizing the concepts of sustainable development and quality of life:

Definition 2. "A city to be smart when investments in human and social capital and traditional (transport) and modern ICT communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance" (Caragliu et al., 2011).

Definition 3. "Smart city as a high-tech intensive and advanced city that connects people, information and city elements using new technologies in order to create a sustainable, greener city, competitive and innovative commerce, and an increased life quality" (Bakici et al., 2013).

Finally, Harrison et al. (2010) and Nam and Pardo (2011) emphasized information exchange as follows:

Definition 4. "A city connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city" (Harrison et al., 2010).

Definition 5. "A smart city infuses information into its physical infrastructure to improve conveniences, facilitate mobility, add efficiencies, conserve energy, improve the quality of air and water, identify problems and fix them quickly, recover rapidly from disasters, collect data to make better decisions, deploy resources effectively, and share data to enable collaboration across entities and domains" (Nam and Pardo, 2011).

What is common to the above definitions, and we believe to most published definitions, are the following six dimensions: a smart city is based on ICT capabilities that (1) make resource management more efficient (governance); (2) impact human and social capital (people); (3) facilitate transportation (mobility); (4) provide a higher standard of living (living); (5) contribute to greater prosperity (economy); and (6) ultimately enhances sustainability (environment). We will shed more light on these dimensions in the following section, as we find that most approaches to assessing smart cities follow in the footsteps of these six core dimensions.

2.2. Smart City Assessment

The development of a smart city is often considered as a project that has its own objectives. For a project to be successful, it is essential to measure the achievement of its objectives, in this case the effectiveness and level of city smartness. A number of assessment frameworks and tools have been proposed to assess such smart city projects. In the following, in line with Sharifi (2020a), we will refer to assessment tools, frameworks, toolkits and indexes, and indicator sets as “assessment schemes”. The common feature of these schemes is a set of indicators, metrics, or standards related to smart city goals. Quantitative methods are part of a common assessment approach that helps city management focus their time, resources, and efforts while allowing them to develop and monitor long-term plans and communicate them to the various stakeholders they impact, including citizens (Berardi, 2013).

Most of the existing assessment schemes include six basic dimensions based on the above definitions of a smart city. One of the leading assessment schemes was conducted by the University of Vienna on 70 European cities to assess each of the six core dimensions. For example, in the case of smart mobility, the following sub-dimensions were defined: availability of ICT infrastructure, local/international accessibility, and sustainable and safe systems (Giffinger et al., 2007). Zygiaris (2013) proposed an assessment scheme by including an additional aspect, namely the green dimension. That is, the assessment scheme consisted of seven different dimensions, as follows: (1) the city dimension, as the site under assessment should have the characteristics of a city; (2) the green dimension, which considers environmental and sustainability elements in urban planning; (3) the interconnection dimension, which focuses on how economically connected the city is; (4) the instrumentation dimension, which focuses on how responsive the city is to the digital infrastructure of sensors powering its systems (it should be near real-time); (5) the open integration dimension, which assesses the overall integration of city applications, including data transfer and the availability of content and services across different applications; (6) the application dimension, facilitating overall city services and operations and their responsiveness; and (7) the innovation dimension, which emphasizes the readiness and creative environment of the city to support new business opportunities.

Other assessment schemes were inspired by the triple helix model, which considers three helices representing the key actors of a city, which are the university, government, and industry (Leydesdorff and Deakin, 2011). The framework was further developed by adding a fourth component, which is civil society. The four-helix framework was positioned as a suitable tool for complex urban environments where civic society, including cultural and social capital, will have a major influence on relationships across the traditional triple helix of university, government, and industry. These four helices can also be linked to the six dimensions of a smart city (smart economy, smart mobility, smart living, smart environment, smart people, and smart governance). Specifically, the developed frameworks included more than 60 indicators across the different dimensions, as revealed in a questionnaire aimed at the target groups of stakeholders (Lombardi et al., 2012).

Lee et al. (2014) focused on two leading smart cities, San Francisco and Seoul, and developed a specific framework based on those cities to guide the analysis of an effective smart city. The framework outlined six conceptual dimensions, with a total of 17 sub-items of what is considered best practice in building a smart city. The framework was supported by a thorough literature review plus several rounds of validation assessments with six focus groups (i.e., academics with experience in technology management, information technology and urban planning, IT industry experts, and city officials) representing different perspectives. The validation of the assessment resulted in the following six dimensions: (1) urban openness (design of smart city services and infrastructure in terms of interactions with citizens, data availability, distribution, and openness to external service development); (2) service innovation (assessment of the level of diversity of available services and the level of integration and interoperability of service); (3) partnerships formation (private-public partnerships in service development); (4) urban proactiveness (how smart are the technologies embedded in smart city services, such as sensing and analytics technologies, and how green are the services); (5) smart city infrastructure integration (availability of services on different device platforms, network infrastructure, and availability and inter-operability of data centers); and (6) smart city governance (leadership style and structure, maturity of smart city strategies, and efficiency of planning processes). Similarly, the lessons learned from San Francisco and Seoul suggest that smart embedded technologies facilitate broader innovation and support new value-added services, and that centralized leadership with comprehensive strategies strengthens smart city initiatives (Lee et al., 2014).

The Assessing Smart City Initiatives for the Mediterranean Region (ASCIMER) study, which believes in greater impact and visibility when analyzing multiple smart city projects, used a comprehensive framework to overcome the challenges encountered when examining the performance of a single smart city project. Although the framework was based on the same six core dimensions, it focused on the project viability rather than smart city effectiveness (Monzon, 2015; ASCIMER, 2017). More precisely, in order to be initiated, smart city projects must be (1) innovative (supporting technologies in platforms that help solve urban problems), (2) integrated (enabling the seamless sharing of information, materials, and energy between different parts of the city and stakeholders), and (3) inclusive (enhancing the ease of living in the city while managing complexity and acknowledging diversity).

Bosch et al. (2017) proposed a framework of key performance indicators to better track the progress towards smart city objectives. Social, economic, and environmental sustainability (dimensions of people, prosperity, and planet) were complemented by the implementation aspects of smart city projects (governance) and their application potential (propagation). Perhaps the most serious disadvantage of this assessment framework is that it does not provide an overall assessment score to compare and rank smart city projects. A few researchers have addressed the problem by aggregating multiple dimensions and indicators into a single score and ranking to help cities compare their performance with other cities and identify areas for improvement. A major difficulty in such aggregation is the assignment of weights (importance) to individual indicators in the overall assessment. To achieve an objective assessment, both multiple-criteria decision making (Shen et al., 2018) and multivariate statistical methods (Akande et al., 2019) have been used.

The above literature review is not exhaustive, but rather is intended to illustrate the complexity of assessing smart cities. Indeed, no consensus has been reached on which indicators and assessment dimensions should be considered and how and whether the values of the assessment criteria should be aggregated (see Table 2 for the most cited assessment frameworks).

Table 2: Top five cited assessment frameworks

Framework	**Reference**	**Dimensions**	**Method**
Smart cities Ranking of European medium-sized cities	Giffinger et al. (2007)	Quality of the health system	Cities grouped in five classes based on the quintile values
Assessing Smart City Initiatives for the Mediterranean Region (ASCIMER)	Monzon (2015)	Smart governance, smart economy, smart mobility, smart environment, smart people, smart living	Smart city projects assessment matrix showing potential and achieved effects of smart city actions on urban challenges
CITYkeys	Bosch et al. (2017)	People, planet, prosperity, governance, propagation	Key performance indicators measured on a ten-point scale
China Smart City Performance	Shen et al. (2018)	Smart infrastructure, smart governance, smart economy, smart people, smart environment	Entropy method used to assign weights to indicators, and TOPSIS decision-making method used to rank smart cities
The Lisbon ranking for smart sustainable cities in Europe	Akande et al. (2019)	Economy, environment, society	PCA used to extract a single quantitative index

In one of the few studies that have addressed this issue, interviews were conducted with five local authorities in the UK to explore their role in the assessment process and how smart city assessment helps them in their development decision-making (Caird, 2018). That is, the comparative analysis focused not only on cities' approaches to smart city assessment, but also on the effectiveness of these assessment efforts and their reporting by the city. The indicator standards for smart cities were compared by Huovila et al. (2019), and indicators were categorized in terms of city focus (sustainability/smartness), indicator type (input/process/output/outcome/impact), and city sector (e.g., natural environment, transport, energy, and economy). This comparative study suggested that sustainability and smartness should be balanced in the assessment scheme and the input, output and impact indicators used. More comprehensive comparative analyses have recently been carried out. Sharifi (2019) compared over 30 assessment schemes by examining the distribution of dimensions and indicators to assess the level of comprehensiveness of the schemes. Furthermore, the authors examined the extent to which stakeholder engagement, city context, and strategic needs were considered in the assessment schemes. The schemes were also compared in terms of their flexibility and the financial and technical feasibility of smart city projects. The remaining benchmarks were the reporting of assessment results and linkages with other action plans. Later, Sharifi (2020a) added criteria on the type of data, the methods used for scoring, and the scale of implementation to the benchmarks. The findings showed that secondary data such as urban yearbooks and census data were the predominant data sources, with about half of the schemes considering the indicators as equally important. Of the scoring methods, benchmarking and baseline assessments were the most commonly used, with assessments usually conducted by the scheme auditor or surveyor. However, previous literature has failed to reveal trends in smart city assessment. Unlike previous review studies in this area, which have focused on the typology of assessment schemes, we conduct a bibliometric and content analysis-based literature review to reveal research trends in this domain.

3. Research Methodology

A literature review on smart city assessment was performed to answer the following research questions (RQs):

RQ1: What are the most influential articles and associations among existing articles on smart city assessment?

RQ2: What are the most influential journals and countries of origin of knowledge production?

RQ3: What research themes are addressed in existing articles on smart city assessment?

RQ4: What is the evolution of research in smart city assessment?

RQ5: What is the intellectual structure of the research themes in smart city assessment?

To answer these research questions, we used a research methodology that can be summarized as follows:

1. Research preparation (selection of the unit of the analysis, definition of the search strategy).
2. Data collection from a reliable database and data cleaning to remove unrelated articles.
3. Obtain co-citation networks among articles from the cleaned dataset.
4. Select words and phrases from keywords, titles, and abstracts of articles according to their occurrence.
5. Project the networks into 2D space and use the generated cluster labels to obtain science maps based on co-citations and keywords (terms). For this purpose, we used the visualization tool VOSviewer 1.6.9 (van Eck and Waltman, 2010, 2017).
6. Identify research hotspots and trends using the time slicing strategy implemented in the visualization tool CiteSpace 5.7 (Chen et al., 2010).
7. Detect emerging topics using the FB-LDA (Foreground and Background Latent Dirichlet Allocation) model (Tan et al., 2014).

In the first step, we selected "smart city assessment" as the unit of analysis and performed the data collection. This step involved a comprehensive search of the WoS Core Collection database, which is recognized as a reliable source for bibliometric research (Bartolacci et al., 2020). To identify relevant articles and to include a wide range of relevant assessment schemes, we adopted the following search criteria used by Sharifi (2020a):

TS=((("evaluat*" NEAR/1 ("tool*" OR "toolkit*" OR "system*" OR "indicator*" OR "framework*" OR "index" OR "scorecard*" OR "scheme*")) OR ("assess*" NEAR/1 ("tool*" OR "toolkit*" OR "system*" OR "framework*" OR "indicator*" OR "index" OR "scorecard*" OR "scheme*")) OR ("measur*" NEAR/1 ("tool*" OR "toolkit*" OR "system*" OR "framework*" OR "indicator*" OR "index" OR "scorecard*" OR "scheme*"))) AND ("smart") AND (("city" OR "cities" OR "communities" OR "community" OR "neighbo*rhood*" OR "district*"))).

Data were chosen for the period January 2010 to December 2020 due to the exponential growth of smart city publications in the last decade (Zheng et al., 2020; Bajdor and Starostka-Patyk, 2021), driven by the emergence of theoretical approaches to performance measurement and advances in enabling technologies (e.g., big data, IoT, smart computing). Indeed, only a few articles had been published in the area of smart city research up to 2010 (Sharifi et al., 2021).

Only English-language articles were included in the research. A total of 705 articles (including review articles, proceedings papers, and book chapters) were found. After careful review of the retrieved records and the exclusion of unrelated WoS categories, 111 articles remained for analysis. To reach high coverage of articles on smart cities, we followed Oliveira et al. (2019) and performed the same search via the IEEE Xplore database, resulting in 37 more articles added to the analysis. Finally, in agreement with Sharifi (2020a), we also repeated the search in Google to find relevant grey literature (research practice), which led to the inclusion of 16 more articles (in this case, only their titles and abstracts/summaries could be included). Details on the study selection process are presented in Figure 1.

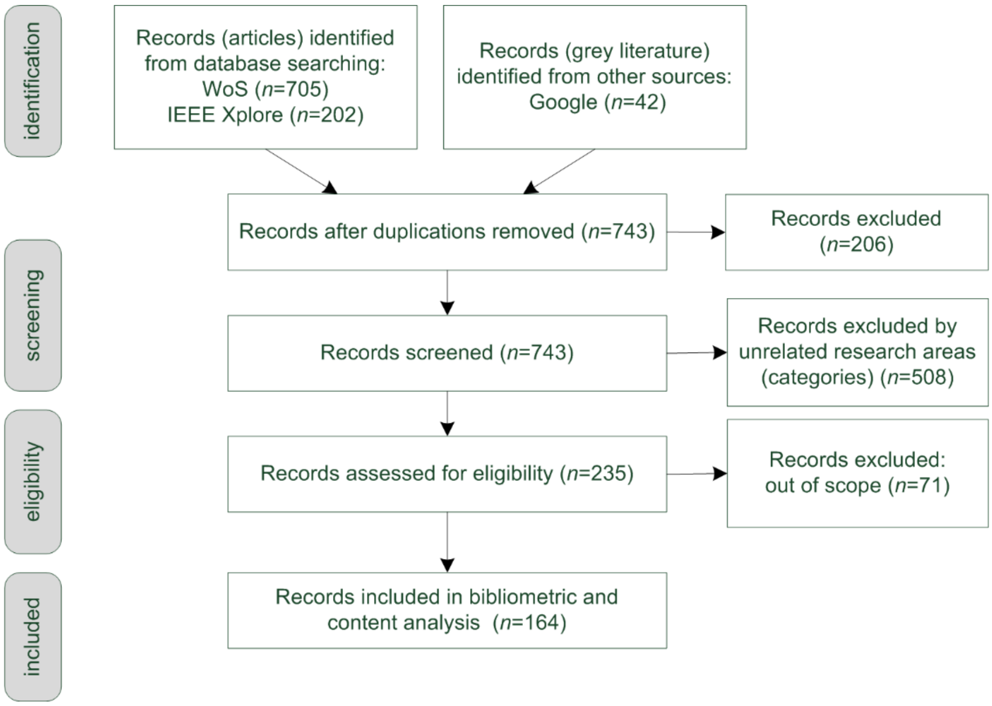

Figure 1: PRISMA flow chart of study selection process

A bibliometric analysis using performance indicators (co-citation analysis) and science mapping (Noyons et al., 1999) was conducted to evaluate academic research on smart city assessment. These methods allowed us to quantitatively and objectively analyze the articles obtained from the used databases. This approach was not only proven powerful for investigating the conceptual structure of a research area (Castriotta et al., 2019; Kumar et al., 2020) but it also benefits from a systematic and reproducible review process (Mora et al., 2017). The performance indicators allowed us to identify the most important and influential authors, studies, and journals, while the science mapping served to reveal the evolution of research in the given field through co-citation analysis. We chose these complex maps to visualize the conceptual and intellectual structure of the research field. We preferred a co-citation analysis of documents and journals because citations are considered a relevant indicator of scientific impact and interactions (Mora et al., 2019). For documents, intellectual proximity is measured using the number of co-citations, and it is this proximity measure that can be used to identify thematic clusters mapping interactions between the main research topics (De Bellis, 2009).

To further understand the structure of knowledge and to avoid subjective bias, a literature review based on content analysis was conducted by linking words in the text of publications based on their collocations. The general purpose of content analysis is to increase the understanding of a core phenomenon by describing it more concisely. In agreement with previous review studies (Mora et al., 2019; Sharifi et al., 2021), we complemented the bibliometric analysis with a content analysis to identify thematic clusters based on the co-occurrence of terms and to visualize the most important terms for specific research topics (Li, 2019). We used two major software tools, VOSviewer and CiteSpace, to perform the bibliometric and content analyses.

In order to visualize the structure and dynamics of the research in smart city assessment, we created science maps that can help classify existing knowledge by clustering the underlying research in terms of articles, authors, sources, or textual content (terms, keywords). Co-occurrence matrices were used to create the science maps. To create the matrices, the VOSviewer tool used association strengths based on the number of co-occurrences of items (see Van Eck and Waltman, 2009 for details). Subsequently, science mapping was performed to minimize the weighted sum of the squared Euclidean distances between all pairs of items, and items could be assigned to clusters based their density (Van Eck and Waltman, 2010).

To visualize the evolution in the research domain with respect to the temporal aspect, a progressive network analysis was performed using the visualization tool CiteSpace, which focuses on the most important nodes of network evolution over time. Thus, development trends in the domain were able to be identified. The progressive network method uses a time slicing strategy to synthesize a series of network snapshots (Chen et al., 2010). The most influential nodes in the network indicate ground-breaking articles that are crucial to the evolution of research over time (turning points in the intellectual structure of the research domain). Specifically, a document co-citation analysis was performed first, and then a semantic analysis of the extracted documents' content (title, abstract and keywords) was performed to label each research theme. This analysis was further complemented by the identification of newly emerging topics from the foreground after removing topics addressed in the research background. To this end, FB-LDA was used to extract foreground topics from the documents' content. Specifically, an LDA model was fitted using the Gibbs sampler separately for background and foreground documents. The FB-LDA-Master Python library was used to deploy the FB-LDA model.

4. Results

To answer *RQ1 (What are the most influential articles and associations among articles on smart city assessment?)*, we used two common science mapping techniques, namely co-citation analysis and bibliographic coupling, which are the most prevalent methods in related review studies (Li, 2019; Mora et al., 2019).

The co-citation network presented in Figure 2 shows that Caragliu (2011), Giffinger et al. (2007), and Albino et al. (2015) are the most cited and have the highest overall link strength. Giffinger et al. (2007) developed the European Smart City Model, an established approach to profiling and comparing European cities. Caragliu et al. (2011) defined the concept of smart city and conducted a review of various smart city performance factors. Albino et al. (2015) presented the main dimensions characterizing smart cities and reviewed urban smartness metrics. Thus, these studies (represented by the cluster marked in red on the map) provided the theoretical foundation for further research on smart city assessment.

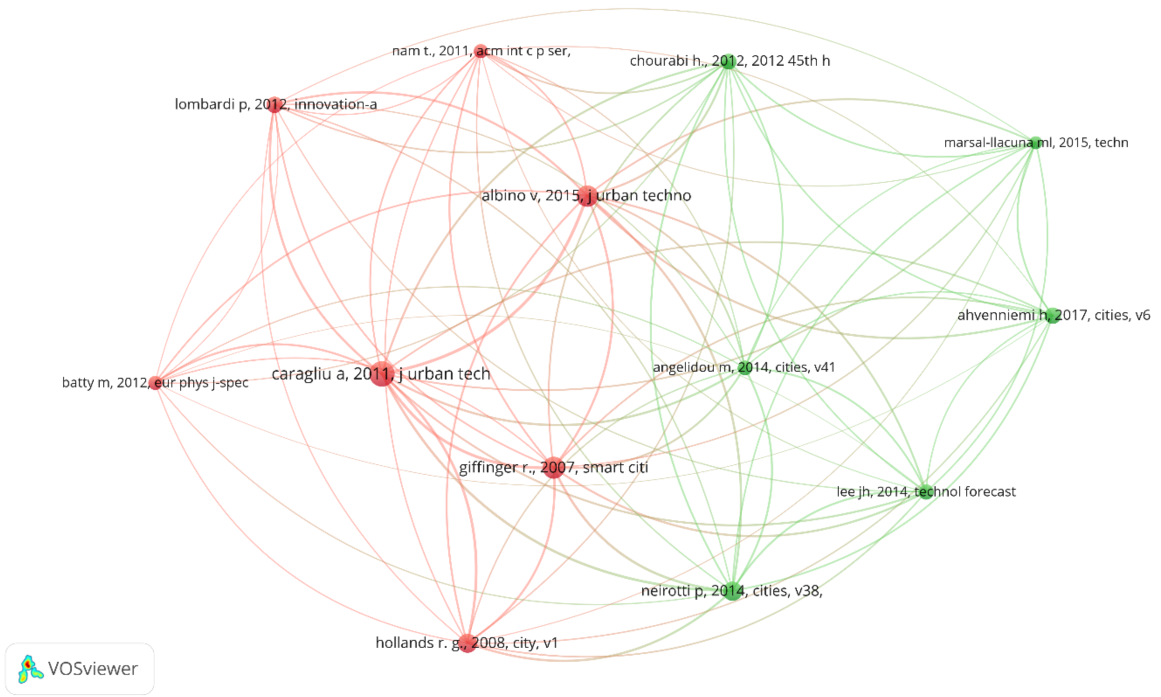

Figure 2: Co-citation map of cited references. The size of the node (vertex) indicates the strength of the co-citation (number of co-citations), and the edges (links) indicate that the two references are jointly cited by a third article. The minimum number of citations of a cited reference was set to 10.

The cluster marked in green represents more recent efforts to develop more comprehensive smart city assessment schemes. The most influential works are Neirotti et al. (2014) and

Ahvenniemi et al. (2017). Neirotti et al. (2014) elaborated a coverage index based on a taxonomy of smart city application domains, while Ahvenniemi et al. (2017) introduced the concept of "smart sustainable cities" and developed an assessment scheme considering three dimensions of sustainability, namely economic, social, and environmental sustainability.

Figure 3 shows the resulting bibliographic coupling map, which groups the underlying dataset into six categories. Ahvenniemi et al. (2017) highlighted the environmental aspect of sustainability and the need to include environmental indicators in smart city assessment schemes. This article represents the most influential research with a central position in the map. The critical review articles on smart city assessment by Sharifi (2019, 2020a) represent another cluster positioned in the center of the map. The cluster marked in green represents articles on smart city development, and the yellow cluster indicates assessment schemes based on multiple-criteria decision making (MCDM) methods. The cluster marked in dark blue elaborates on indicators for smart sustainable cities, while the last cluster concerns the civic and creative aspects of smart sustainability.

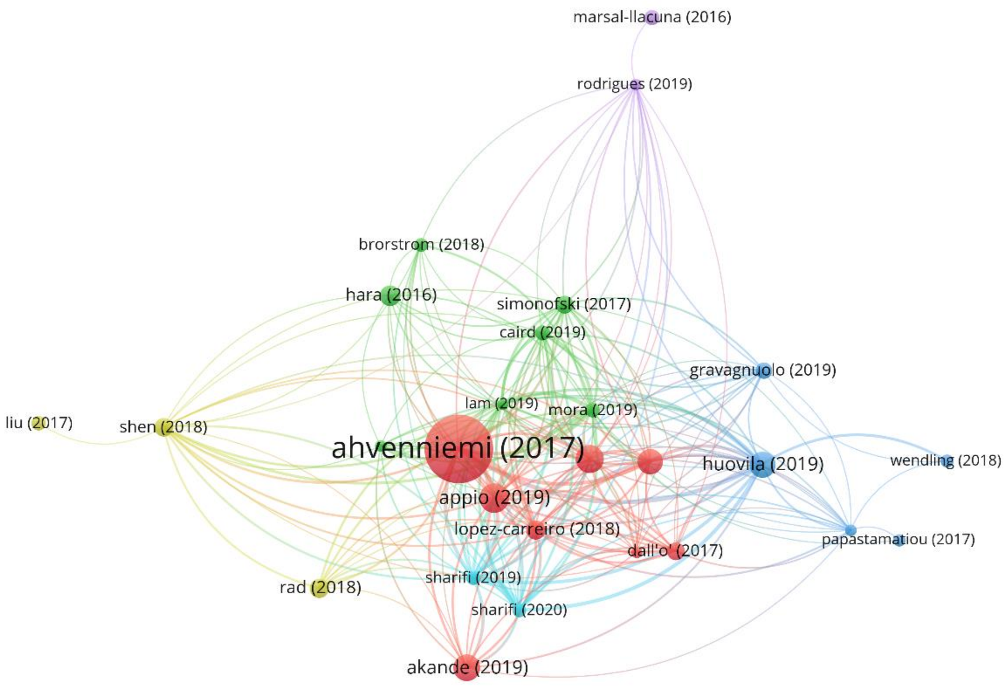

Figure 3: Bibliographic coupling of cited references. The size of a node indicates the number of shared references, and the edges indicate that two references share the same references. The minimum number of citations of an article was set to 10.

To address *RQ2 (What are the most influential journals and countries of origin of knowledge production?*), we performed a co-citation analysis of sources and a citation analysis using countries as the units of analysis.

The map of journal co-citations shown in Figure 4 represents the structure of scholarly sources. Related journals were divided into two main clusters associated with different scientific categories, namely urban studies (the cluster marked in red) and environmental sciences (the green cluster). Journals on the boundary between the two clusters bridge the gap between the two categories with a broader social science research perspective. The map also indicates the central position of the *Cities* journal, which is also the most-cited source, as indicated by the size of the node. The third cluster (marked in blue) represents the category of information science, which concerns smart city technologies.

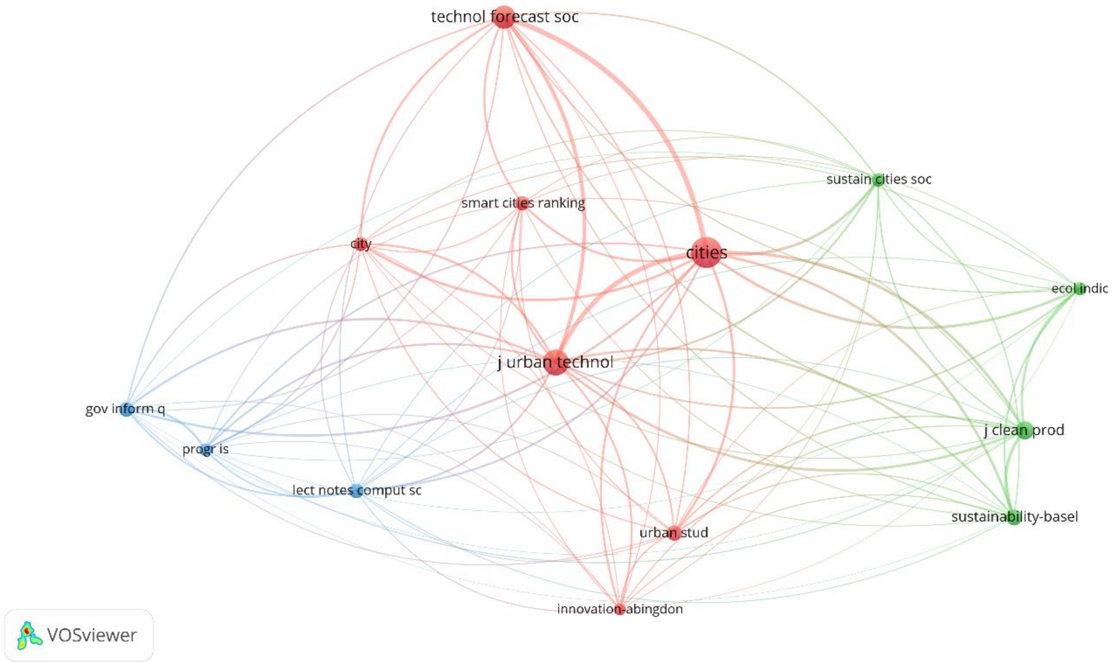

Figure 4: Map of cited sources. The minimum number of citations per cited source was set to 20.

To investigate the geography of knowledge production, Table 3 shows that the most influential research (in terms of total link strength and the number of citations) on smart city assessment originated from Finland. Altogether, Europe and China were the largest contributors to the development of the science domain. However, the impact of Chinese research is small given the large number of source documents. This finding is consistent with the results of bibliometric studies on smart city research (Mora et al., 2017; Sharifi et al., 2021).

Table 3: Ten top-ranked countries

Rank	Country	Total link strength	Documents	Citations
1	Finland	31	5	389
2	Japan	24	5	70
3	Spain	20	12	186
4	Italy	16	12	182
5	China	14	36	105
6	Portugal	13	10	102
7	Netherlands	10	2	55
8	Turkey	5	4	11
9	Germany	4	4	12
10	Greece	4	7	63

To answer *RQ3 (What research themes are addressed in existing articles on smart city assessment?)*, we used keyword and co-occurrence analyses.

To visualize the content of the articles, we extracted and analyzed the words associated with them. More specifically, we used both keywords as article descriptors and terms (words and phrases) extracted from article titles and abstracts. The science maps created based on the keywords (terms) allowed us to explore the concepts and topics addressed in the articles. The difference between the two maps is that the keywords were assigned by author, while the terms were automatically extracted from the titles and abstracts using text mining techniques.

The result of the co-occurrence analysis in Figure 5 shows the most-frequent keywords and their associations. The map can be broadly divided into two main clusters of keywords, one related to smart cities and indicators (clusters marked in red and blue) and the other related to evaluation frameworks and models and lessons for smart city development. However, it should be noted that keyword-based co-occurrence analysis can suffer from a human indexer bias, leading to inconsistent keyword classification.

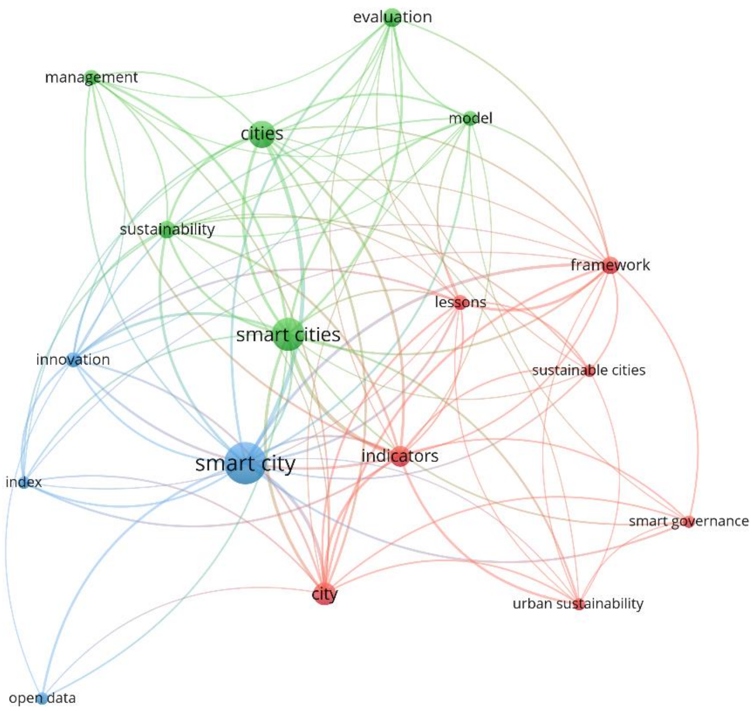

Figure 5: Keyword-based science map. A full count of terms extracted from title and abstract fields was used with a minimum number of occurrences of the keyword of 5.

Therefore, to avoid the indexer effect, we also performed an automatic term extraction from article titles and abstracts (Figure 6). Sequences of words (called *n*-grams) were extracted based on the number of occurrences. Figure 6 shows four clusters of related terms. Cluster 1 (marked in red) represents the assessment model, index, and evaluation system, and their dimensions and construction. China was the most common geographic region used for the application of the assessment models. Cluster 2 (marked in green) includes smart city projects, tools, solutions, initiatives, and approaches highlighting the process of implementing smart city assessments along with implications for policy makers. The keywords included in cluster 3 (blue) refer to the assessment methodology and its objectives, while cluster 4 (yellow) refers to technologies, their use, and their impact on governance and citizens' lives.

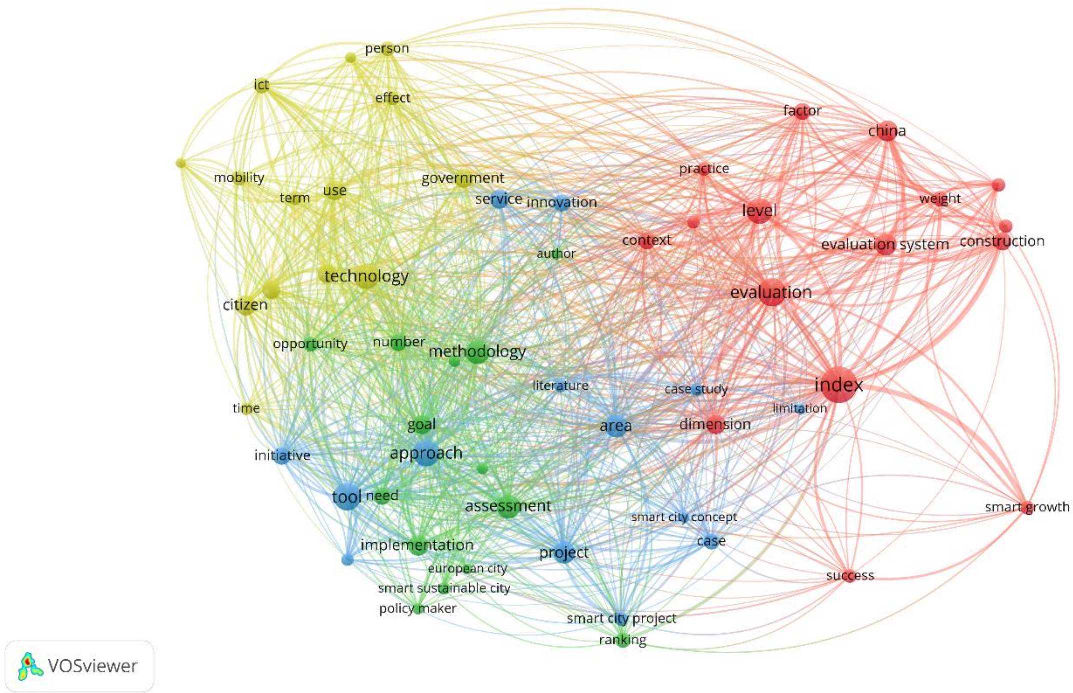

Figure 6: Term-based science map. A full count with a minimum number of term occurrences of 10 was used; unigrams, bigrams, and trigrams were considered.

To answer *RQ4 (What is the evolution of research in smart city assessment?)* and *RQ5 (What is the intellectual structure of the research themes in smart city assessment?)*, we conducted a progressive network analysis based on the co-citations as obtained using the CiteSpace tool.

To visualize the evolution of the science domain, Figure 7 shows the results of the progressive network analysis. As can be seen in Figure 7, 11 clusters were created on the thematic science map. The timeline also shows the length of the cluster history, its evolution, and the representative terms for highly cited years. Each cluster reflects a hotspot (hereinafter referred to as a “theme”) in smart city assessment research over the past 11 years.

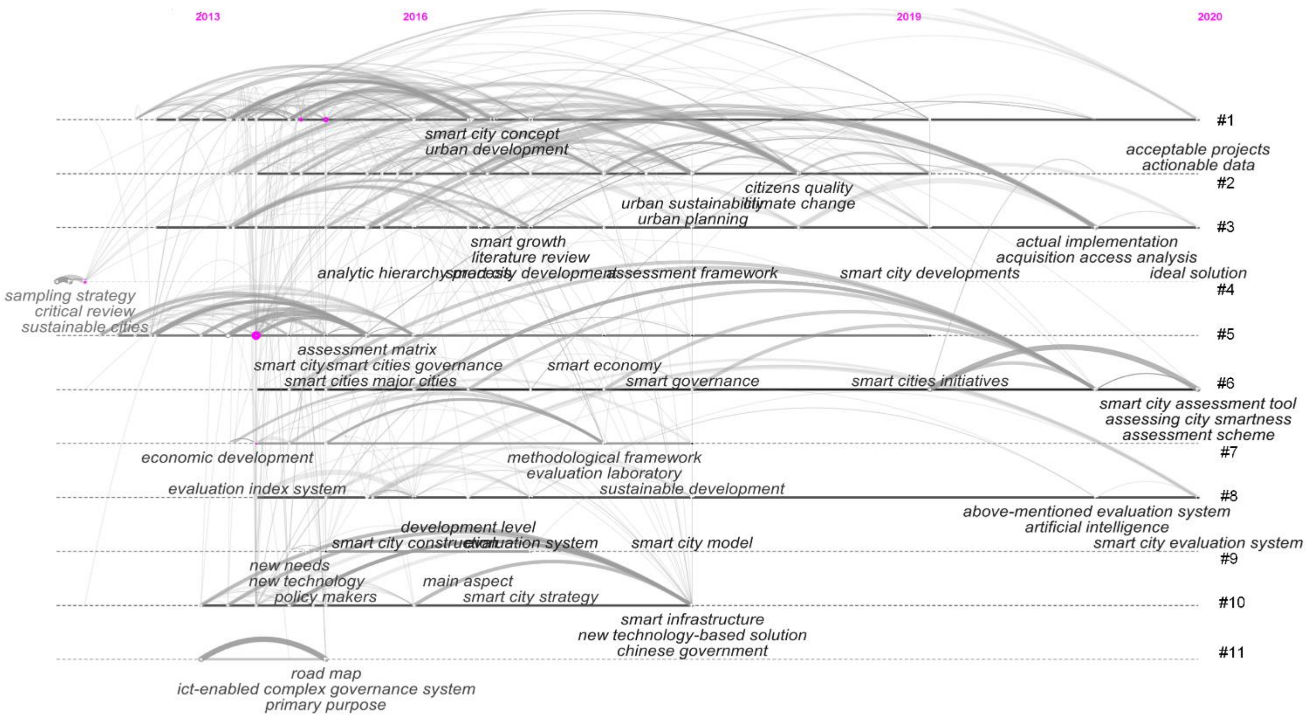

Figure 7: Timeline of research themes. Cluster labels were assigned to themes ranked using the log-likelihood ratio from article titles (providing us the best coverage of themes compared to mutual information and latent semantic indexing); the time slice was set to one year; the source of terms were titles, abstracts, and keywords; nodes represent terms and articles; the cosine link similarity measure was used; and the *g*-index with a scale factor of *k*=25 was used as the selection criterion. The merged network included 284 nodes and 982 links.

Table 4 shows the number of articles in each cluster as well as the corresponding cluster quality silhouette value and the mean value of the year. The results in Table 4 show high silhouette values for all clusters (the overall weighted mean silhouette index was *S*=0.895), with differences observed for cluster sizes and time spans. For example, the research theme of cluster 1 was “smart city performance measurement framework”. This cluster included 22 articles, and the average year of cluster 1 was 2015 (when the cluster was formed). However, as shown in Figure 7, this theme emerged intensively in 2017 but lasted until 2020. Cluster 10 (“ranking sustainable cities”) was created in 2009, whereas the most recently created research themes were clusters 2, 3, 5 and 6, labeled “connecting challenge,” “smart sustainable cities (composite index),” “indicator set,” and “evaluation system,” respectively. Interestingly, two different clusters, namely 6 and 8, were assigned similar labels (“evaluation system” and “evaluation index system”) but were formed in different years. The vertical connection between the two clusters in Figure 7 also suggests that the themes are closely related. To better understand the range of themes included in the clusters, Table 4 also shows the top five keywords in terms of their degree centrality (sum of co-occurrence counts).

Table 4: Description of the clusters extracted from the science theme map

Cluster	Size	Silhouette	Mean year	Label (equally ranked labels)	Top five keywords (with highest degree centrality)
1	22	0.843	2015	Smart city performance measurement framework	Smart city concept, environmental indicators, urban development, sustainability assessment, smart city framework
2	19	0.847	2016	Connecting challenge	Assessment framework, literature review, citizens participation, analyses comparison
3	18	0.753	2016	Smart sustainable cities (composite index)	Local context, urban sustainability, composite index, smart sustainable cities, impact indicators
4	16	0.888	2014	Holistic evaluation	Smart city, active participation, assessing urban participatory policy, smart cities governance, major cities
5	12	0.911	2018	Indicator set	Action plan, analysis target audience, addressing interlinkages, indicator set, assessment scheme
6	10	0.805	2016	Evaluation system	Smart city construction, evaluation system, smart city evaluation system, appraisal index system, appraisal outcome
7	8	0.961	2015	Smart city performance	Smart city dimension, Chinese government, new technology-based solution, smart infrastructure, smart city program
8	7	0.899	2015	Evaluation index system	Evaluation index system, decision-making trial, evaluation laboratory, methodological framework
9	5	0.957	2015	New technologies	Available technology, assessment tool, bests way, policy makers, different technology
10	3	0.995	2009	Ranking sustainable cities	Critical review, collecting data, economic triangle ideology, identifying measurement indicators, ranking methodology
11	2	1.000	2014	Advancing performance measurement	Advancing performance measurement, brief comparison, critical challenge, emergent phenomenon, institution actors interactions

In addition to the above description of the clusters, Table 5 lists both citing articles with the highest citation coverage of a given theme to identify emergent research concepts (the so-called research front) and the top-cited references to identify the intellectual base of the research themes.

Table 5: Top citing/cited articles for the identified research themes

Cluster	Top citing articles (with highest coverage >5)	Top cited references (with highest degree centrality >10)
1	Ahvenniemi et al. (2017), Sharifi (2020a), Mora et al. (2019), Sharifi (2019), Appio et al. (2019), Warnecke et al. (2019), Bilbil (2017), Airaksinen et al. (2017), Dall'O' et al. (2017), Lam and Ma (2019), Battara et al. (2017), Akande et al. (2019)	Albino et al. (2015), Ahvenniemi et al. (2017), Angelidou (2014), City Protocol Society (2015)
2	Simonofski et al. (2017), Simonofski et al. (2019), Feizi et al. (2020)	Networking Society Lab. (2016), Manville et al. (2014)
3	Huovila et al. (2019), Mora et al. (2019), Rodrigues and Franco (2019a), Garau and Pavan (2018), Sharifi (2019)	ISO 37122 (2018), Akande et al. (2019), Bosch et al. (2017), Garau and Pavan (2018), Vanolo (2014), Dameri (2017)
4	Shen et al. (2018), Castelnovo et al. (2016), Branchi et al. (2017), Fernandez-Anez et al. (2020)	Neirotti et al. (2014), Chourabi et al. (2012), Batty et al. (2012), Lee et al. (2013), Nam and Pardo (2011)
5	Sharifi (2020a), Sharifi (2020b), Wang et al. (2020)	Sharifi (2019)
6	Yan et al. (2020), Rui (2016)	NDRC (2015, 2016)
7	Shen et al. (2018)	Lee et al. (2014), Ben Letaifa (2015)
8	Qu and Wang (2014), Rad et al. (2018)	Caponio et al. (2015), Elmaghraby and Losavio (2014)
9	Branchi et al. (2015)	-
10	Pan (2010)	CABE (2009)
11	Zhang and Chen (2015)	Xinhua News Agency (2013)

To validate the research themes extracted from the science theme map and identify emerging themes among them, we then conducted an analysis of background and foreground topics using the FB-LDA model (Tan et al., 2014). More precisely, in agreement with Nagariya et al. (2022), we analyzed separately the content of articles published in 2010-2017 (background period) and articles published in the last three years 2018-2020 (foreground period). Tables 6 shows the top foreground and background topics from the FB-LDA model. The lowest word entropy was applied to detect the top 5 foreground topics. Top keywords for each topic allowed us to associate topics with cluster labels from the science theme map. As illustrated, foreground topics detected using FB-LDA are emerging research themes.

Table 6: Foreground and background topics from FB-LDA

Topic category	No.	Top ten FB-LDA topic keywords	Corresponding cluster label from the science theme map
Foreground	1	smart city framework assessment projects application results implementation used data	Smart city performance measurement framework
	2	social public citizens economic goal focus stakeholders local life patterns	Holistic evaluation
	3	smart environmental city solutions resilience performance tools nbs sdg waste	Smart sustainable cities
	4	urban study performance evaluate economy indicators environment selected including assets	Indicator set
	5	cities new innovation technology make open data services ict approach	Connecting challenge
Background	6	evaluation city index development construction method based level model urban	Evaluation index system
	7	smart city evaluation system indicator framework aspects policy current criteria	Evaluation system
	8	urban sustainable sustainability use indicators cities framework energy quality ranking	Ranking sustainable cities
	9	assessment technologies mobility methodology case assess environmental order ict	New technologies
	10	smart city data information indicators concept monitoring governance proposed implementation	Smart city performance
	11	technology assessment system new solutions consequence strategy social levels application	Advancing performance measurement

5. Discussion on Identified Research Themes

In what follows, we discuss the identified research themes with a particular focus on establishing future research directions in these areas. We restrict ourselves to the top five themes in terms of the size of the clusters covering them. Note that these clusters include the most recently emerged research themes, as found by FB-LDA.

5.1. Cluster 1 – Smart city performance measurement framework

During the past 10 years, a large body of literature has investigated smart city assessment frameworks, as outlined in subsection 2.2. Table 5 shows that various approaches have been recently put forward to develop comprehensive assessment frameworks. However, this research theme was formed around the year 2015 and is largely based upon an intellectual base that highlights urban development and sustainability assessment.

In her seminal article, Angelidou (2014) discussed different strategic choices arguing for diverse smart city development policies that should consider synergies, selectivity, and prioritization as guiding principles. This implies that smart city assessment should be tailored to the integrated urban strategy. The City Anatomy framework (City Protocol Society, 2015) provided a guide to implementing smart city projects by consistently aligning all smart dimensions with the city's systems as well as the specific nature of urban development. To differentiate smart cities from traditional cities, the main dimensions characterizing a smart city were identified by Albino et al. (2015) as follows: (1) a city's networked infrastructure, (2) emphasis on urban growth, (3) social inclusion and social capital, and (4) the natural environment. Similar to Angelidou (2014), the authors argued against a universal assessment framework, stressing the variety and complexity of smart cities' visions and characteristics worldwide.

Inadequate sustainability assessment and the lack of environmental and energy indicators were identified as major drawbacks of existing smart city frameworks by Ahvenniemi et al. (2017). Indeed, the introduced concept of "smart sustainable cities" is not only a key intellectual base for this research theme, but the study by Ahvenniemi et al. (2017) also represents the research front with the highest citation coverage. One implication of the study findings is that smart city assessment frameworks should be integrated with sustainability assessment, and that impact indicators should be considered to evaluate the contribution towards the sustainability goals.

This intellectual base was further expanded in several directions. Following Angelidou (2014) and Albino et al. (2015), Dall'O' et al. (2017) proposed an assessment methodology designed specifically for small- and medium-sized cities. In this methodology, different stakeholders participate in a technical committee established to develop a smart city protocol, taking into account existing indicator standards and defining smart city goals. Field testing is used to verify the availability and reliability of the indicators. More recent studies have suggested that the technical efficiency of a city should be considered as a benchmarking methodology and that a citizen perception survey should be conducted to include citizen satisfaction in the assessment scheme (Warnecke et al., 2019; Patrao et al., 2020; Ramirez et al., 2021). Automated analyses of social media can alternatively be used to assess community perceptions on smart city projects (Yigitcanlar et al., 2021). Another important aspect of smart city assessment highlighted in this cluster is the linking of assessment to action plans, which is needed to prioritize policy measures and interventions (Sharifi, 2019). Only a quarter of existing assessment schemes reportedly include action planning (Sharifi, 2019). Sharifi (2019) also proposed a set of qualities and criteria for assessment schemes, concluding that existing assessment schemes do not adequately consider (a) technical and financial feasibility, (b) interoperability between indicators, (c) scenario making, and (d) stakeholder engagement (participatory implementation and development). Sharifi (2020a) discussed the policy implications of the strengths and weaknesses of existing assessment schemes, suggesting potential areas for improvement.

Recent developments in this research theme also reflect the climate change mitigation challenges in smart cities. The assessment scheme developed by Gargiulo et al. (2017) evaluated a combination of medium-term initiatives to achieve a sustainable energy future, considering the impacts of energy flows on sustainable development criteria. To evaluate the contribution of smart city initiatives to environmentally sustainable urban systems, Ipsen et al. (2019) used an assessment scheme integrating metabolic flows in cities with a life cycle assessment method. A global warming potential indicator (focusing on CO2 emission) was used to assess the overall performance of the city. The results of these studies suggest that special attention in this line of research will be given to targeted smart city interventions and technologies aimed at climate change mitigation and climate resilient cities.

Figure 7 shows that the cluster has recently focused on integrating smart city assessment schemes into smart city actions. Three research directions were identified, namely smart city initiatives, smart city strategies, and open data initiatives. Bilbil (2017) explored the operationalization aspects of smart cities to identify the limitations of policy action plans. In addition, best practices and roadmaps for achieving smart projects were identified by analyzing previous policy reports. Three key dimensions of successful smart city initiatives were pursued, namely infrastructure (including the legal and coordination framework), policy scope, and appropriate performance indicators. Mobile applications were also identified as a key tool for communicating the smart city strategy to its citizens (Bilbil, 2017). Warnecke et al. (2019) developed a web-based application allowing city authorities not only an assessment of their competitive position but also an actionable guide on how to improve it. To facilitate the design and measurement of smart city programs, Appio et al. (2019) introduced a visual diagram linking the physical infrastructure of smart cities with the quality of life and innovation in smart cities. In reality, cities have adopted different strategic approaches to implement smart city strategies, as illustrated by numerous case studies in the literature (Brorström et al., 2018; Shamsuzzoha et al., 2021). In general, cities engage in smart strategies to manage budget constraints and often conflicting urban development objectives, and assessment schemes are introduced to enhance their effectiveness. The final theme of this cluster is open data initiatives and their impact on complex smart city ecosystems and sustainable development (Neves et al., 2020).

5.2 Cluster 2 – Connecting challenge

The research agenda of this theme relies on two practical assessment schemes. Manville et al. (2014) devised a procedure to identify the characteristics of successful smart cities and smart city projects in Europe, stressing the role of ICT in optimizing the effectiveness of urban processes by connecting diverse city elements into an interactive collective intelligent system. The Networked Society City Index introduced by the Networked Society Lab (2016) seeks to rank smart cities based on their performance in terms of sustainable urban development and ICT maturity. ICT reportedly emerged as an engine of change with a substantial potential to promote sustainable urban growth. To achieve a more connected society, cities need to adapt their infrastructures, strategies, and urban planning by exploiting innovative ICT. The characteristics of the future networked society include resilience, collaboration, mobility, and participation.

This cluster was established in 2016 in response to new needs triggered by the revolution in digital and communication systems. A comprehensive smart city assessment system was proposed by Yan et al. (2020) to demonstrate the self-organization capabilities of a highly complex smart city system. In this system, three dimensions were included: ICT (technical support for smart city operations), smart cells (smart devices), and developmental mechanisms (coordination of operations between elements of the smart city system).

Smart city testbeds equipped with thousands of IoT devices and other sensors have been developed to evaluate smart city solutions. For example, the well-known SmartSantander testbed implements use cases, such as environmental and traffic monitoring, participatory sensing, and augmented reality, to explore the deployment and operation of smart city infrastructure (Sotres et al., 2017). It is also one of the few assessment schemes that allows evaluating deployed technologies through interaction with real end-users. Feizi et al. (2020) proposed a multifaceted assessment scheme for measuring transportation performance by including four categories of indicators, namely network performance, environmental impact, traffic safety, and physical activity.

This cluster also includes research on several aspects related to citizen participation. Specifically, it explores in a broader sense of how citizen participation is valued and enabled in smart cities (Simonofski et al., 2017). Assessing citizen participation in smart city decision-making has only been emphasized since 2015, although citizen engagement and participatory governance were considered key concepts in earlier smart city frameworks (Castelnovo et al., 2016). Since then, various indicators have been developed to assess citizen-centricity, such as performance in protecting citizens' rights (Marsal-Llacuna, 2016, 2017) and aspects of social and technological innovation (Paskaleva and Cooper, 2018). Simonofski et al. (2019) proposed CitiVoice, a framework for engaging citizens as democratic participants, co-creators, and ICT users in smart cities design. A set of indicators was developed for each category of citizen participation.

Within this cluster, problems related to data connectivity are addressed. Sharifi (2019) highlighted the role of IoT and big data analytics in assessing the complex dynamics of cities, as various urban services are interconnected. These technologies also provide an important source of information for decision makers and provide platforms for information exchange, thereby increasing the availability of urban services. However, Sharifi (2019) also pointed out that the potential of these technologies is not currently being exploited. The above connecting perspectives are summarized in Table 7.

Table 7: Summary of connecting perspectives

Study	**Assessment framework**	**Connecting perspective (variables)**
Networking Society Lab. (2016)	Networked Society City Index	➢ Triple bottom line (social, economy, environment) ➢ ICT maturity (infrastructure, affordability, usage)
Paskaleva and Cooper (2018)	SmartiP Co-evaluation Framework	➢ Citizens as co-decision-makers and co-producers of innovative services (open innovation processes)
Simonofski et al. (2019)	CitiVoice	➢ Democratic participation (competent facilitators, citizen-oriented objectives, influence on priority setting) ➢ Citizen co-creation (citizen-centric requirements, living lab strategy, use of online platforms) ➢ ICT usage (use of open data and ubiquitous computing)
Yan et al. (2020)	Self-organizing system-based assessment framework	➢ ICT (IoT, cloud, smart grid, AI, mobile internet) ➢ Smart cells (performance, quantity, penetration rate) ➢ Developmental mechanism (social system innovation, information promotion, rules and laws, industry-university-institute integration)

5.3 Cluster 3 – Smart sustainable cities (composite index)

As shown in Figure 6, this cluster highlights the role of smart city development and sustainable urban development as key concepts for smart city assessment. In terms of the assessment methodology used, the main focus of this cluster is on city ranking. The ranking is usually based on a composite index constructed using multivariate statistical methods. The ranking for smart sustainable cities proposed by Akande et al. (2019), as the most-cited intellectual base in this cluster, combined hierarchical clustering with principal component analysis (PCA) to identify a set of indicators selected from the underlying dataset and to synthesize the indicators into four components. The factor scores of these components were used to calculate a ranking of European cities. In fact, ranking is reportedly the most common method of communicating smart city assessment results to end users (Sharifi 2019).

This cluster also emphasizes international standards for smart and sustainable city indicators issued by ISO (e.g., ISO 37122 (2018)), ETSI, UN, and ITU. The first attempts of standardization initiatives by international normalization organizations were presented by Marsal-Llacuna (2016). Recently, a summary of existing indicator standards for smart cities was presented by the most influential reference of this cluster, Huovila et al. (2019), who argued that when evaluating smart sustainable cities projects, the use of indicator standards should examine the relationships between inputs, outputs, outcomes, and impacts, and should take into account the interdependencies between the economic, environmental, and social dimensions of sustainable development.

This research theme was developed between 2013–2017 with a focus on the smart cities aggregate index. When different indicators measured at different scales are combined, data normalization methods are usually used to transform them into a single scale (Garau and Pavan, 2018). The different importance of indicators can also be incorporated into the aggregate index by assigning different weights to the indicators. Pairwise comparisons between indicators were used to calculate the weights of the indicators, as is common in the Analytic Hierarchy Process (AHP) method (Shi et al., 2018). The weights are assigned based on experts' opinions, resulting in a hierarchical system of indicators grouped according to the dimensions of the assessment. One source of weakness in AHP is that consistent pairwise comparisons must be made by multiple experts (decision makers). Moreover, this method does not allow for interrelationships between indicators. To overcome this limitation, considerable effort has been devoted to modelling the interactions between smart city indicators using the Analytical Network Process (ANP) (Ozkaya and Erdin, 2020) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) (Rad et al., 2018). By comparing the six dimensions of smart and sustainable cities, it has been found that smart living was the most important dimension, while smart governance was identified as the least important (Ozkaya and Erdin, 2020). The ANP and DEMATEL methods were used to assess ubiquitous cities by considering the relationships between the cities' main components (Rad et al., 2018).

Another current research topic was presented by Rodrigues and Franco (2019a, 2019b, 2020), who emphasized that cities should be sustainable, creative, and incorporate intelligence in order to efficiently implement their strategies and policies. Composite indexes for sustainable development (Rodrigues and Franco, 2020), creativity (Rodrigues and Franco, 2019b), and the intelligence dimension (Rodrigues and Franco, 2019a) have been developed to assess the performance of cities with respect to these requirements. PCA was again used to create the composite indexes (for a comparison of assessment methods used to construct composite indexes in previous studies, see Table 8).

Table 8: List of assessment methods used in existing assessment schemes

Study	# Variables	Data pre-processing	Method	Composite index	Ranking
Shi et al. (2018)	16	min-max normalization	AHP + extreme learning machine	Weighted sum (weights determined using AHP)	✓
Garau and Pavan (2018)	38	×	Rating system based on 5-point scale	Sum of points for 6 rating categories	×
Rad et al. (2018)	99	min-max normalization	ANP + DEMATEL	Weighted sum (weights determined using ANP)	✓
Akande et al. (2019)	32	min-max normalization	PCA + hierarchical clustering	Sum of the first four principal components	✓
Rodrigues and Franco (2019a)	19 for governance dimension, 10 for ICT dimension	Z-score normalization	PCA	Average of governance and ICT dimensions	×
Rodrigues and Franco (2019b)	36	Z-score normalization	PCA	Weighted average of culture, creative economy and favorable environment dimensions	×
Rodrigues and Franco (2020)	21 for economic, 25 for social and 16 for environmental sustainability	Z-score normalization	PCA	Weighted average of economic, social and environmental dimensions	×
Ozkaya and Erdin (2020)	31	min-max normalization	ANP + TOPSIS	Weighted sum (weights determined using ANP)	✓

5.4 Cluster 4 – Holistic evaluation

This cluster highlights the need for a more comprehensive and holistic approach to smart city assessment. The intellectual base of this research theme relies on: (1) the smart communities movement highlighting shared interests and partnerships in governance (Nam and Pardo, 2011); (2) the critical factors of smart city initiatives identified by Chourabi et al. (2012); (3) the need for holistic systems, services, and technologies integrating data acquisition and analytics for better supporting stakeholders' decisions (Batty et al., 2012; Lee et al., 2013); and (4) the role of smart city initiatives in urban living with respect to different functional domains (Neirotti et al., 2014). All these studies emphasize the importance of a holistic view integrating technology and human dimensions as critical factors of successful smart city initiatives.

Branchi et al. (2017) elaborated the technology assessment matrix of Branchi et al. (2015) to simulate the potential impact of new technologies on urban scenarios. Castelnovo et al. (2016) presented the first holistic approach to assessing smart city governance and policy decisions. This holistic scheme consisted of a central component assessing stakeholder engagement and four related components, namely vision and strategy, asset management, financial sustainability, and public value creation. It is therefore proposed to shift the focus from the assessment of smart city projects to the city's ability to create public value, with citizen engagement playing a central role. Other scholars have based their holistic assessment schemes on an appropriate selection of indicators to maximize the effectiveness of public policies in practice (Shen et al., 2018). In order to provide cities with a holistic scheme for assessing smart city projects and their effects on urban challenges, Fernandez-Anez et al. (2020) proposed a Smart City Projects Assessment Matrix intended to facilitate the understanding of smart city projects as tools categorized into smart city dimensions and combined using the holistic scheme.

5.5 Cluster 5 – Indicator set

A theoretical background for the construction of indicator sets was presented by Sharifi (2019). While earlier comparative studies examined indicator sets with respect to only a limited number of assessment schemes and focused on classifying indicators into thematic dimensions, Sharifi (2019) made considerable progress in this line of research by incorporating a large number of schemes and accounting for a variety of indicator qualities. To this end, a comprehensive list of indicators was compiled based on the review of existing assessment schemes and classified into themes and sub-themes to evaluate the distribution patterns of indicators and their variations among assessment schemes. The other indicator qualities included the comprehensibility of indicators to stakeholders, their context sensitivity, and their alignment with the city's strategic needs. In addition, the flexibility of indicator sets was underlined to allow for tailoring the assessment schemes to cities' specific needs and priorities. The major weaknesses of the existing indicator sets were identified, such as a lack of balanced distribution and a lack of context sensitivity and flexibility.

The follow-up research front has mostly used the same criteria as Sharifi (2019) to select the relevant indicator sets. Sharifi (2020a, 2020b) complemented the intellectual base by providing a dataset covering the existing indicator sets while examining the maturity level of assessment schemes, including different scales of indicator sets (project/community/city), geographic focus, data type (primary/secondary), data source, and indicator weighting. The main weaknesses of existing indicator sets were identified as follows: (1) there is a lack of customized indicator sets for developing countries, and (2) indicators based on real-time open data are rarely used.

The selection of a set of appropriate indicators was recognized as a challenging problem, as the specific needs of each city should be taken into account and the selection is influenced by the spatial and temporal scale of the assessment, the purpose of the assessment, and the phase of smart city development (plan/operation). In addition, the selection of indicators also depends on their qualities, including their documentation and data quality (e.g., transparency and reliability), which in turn influence the quality of decisions based on these indicators.

6. Findings and Future Research Directions

In this section, our findings are summarized, limitations of current research are identified and future research directions are suggested.

6.1 Main findings

To map the knowledge structure of the domain, we analyzed the extant literature on smart city assessment from 2010 to 2020. The bibliometric analysis revealed the leading articles, journals, and countries of knowledge production in smart city assessment research from 2010 to 2020. The content analysis shed light on the knowledge being studied by the researchers in the field. The results of the bibliometric and content analysis enabled us to answer our five RQs and to present the main findings as follows:

(1) The articles by Caragliu (2011), Giffinger et al. (2007), and Albino et al. (2015) were the most cited, thus providing a theoretical basis for further research in the domain, while the article by Ahvenniemi et al. (2017) on smart sustainable cities was the most influential (RQ1).

(2) The *Cities* journal was the most influential outlet, and Finland was the most influential source of knowledge production (RQ2). What might appear surprising is that the US authors did not have a major influence on the advancement of the science domain, which can be attributed to their techno-centric (ICT) and corporate orientation within smart city research (Mora et al., 2017; 2019).

(3) Current research on smart city assessment was mainly on the dimensions and indicators of assessment schemes. Indeed, existing academic debates consistently focus on the typology smart city assessment tools. Therefore, the guidelines for their structural features have evolved over the past 11 years. The other research themes addressed in existing research are the implementation aspects of smart city assessments and the impact of technologies on cities' development (RQ3).

(4) Using the progressive network analysis, we revealed the evolution of research themes in smart city assessment research over the period 2010-2020 (RQ4). We find that five research themes (smart city performance measurement framework, connecting challenge, smart sustainable cities (composite index), holistic evaluation, and indicator set) dominate the discourse in the field. Our findings show that much of the research focuses on developing comprehensive assessment frameworks customized to the city requirements with appropriate sustainability assessments. This research focus seems logical as it is rooted in the need for better city governance and reflects the underlying purpose of smart cities, namely their potential to deliver sustainable prosperity for their citizens.

(5) By analyzing the background and foreground research in the field, we also find that the five dominating themes represent the foreground topics that have gained the attention of researchers in the last three years, while the remaining research themes (evaluation (index) system, ranking sustainable cities, new technologies, and advances in smart city performance) constitute the research background (RQ5).

6.2 Limitations of current research

Despite continued progress in smart city assessment, several factors are hindering growth in this area:

(1) *Lack of robust assessment schemes*. Existing assessment schemes fail to evaluate the impacts on economic opportunities, governance transparency, public decision-making, and participatory capacity of smart cities.

(2) *Lack of the assessment of risks associated with the development of smart city programs, such as those arising from the exponential growth of data and sensors*. The most frequently reported risks in this regard are cybersecurity threats, ideological manipulation, corporatization, and the tendency towards surveillance normalization (Appio et al., 2019). However, these risks are not adequately addressed in current assessment schemes.

(3) *Lack of focus on the dynamics of interactions in smart city assessment dimensions and indicators*. Even though existing research explored the hierarchical and network structures of the dimensions and indicators (Shi et al., 2018; Ozkaya and Erdin, 2020), these assessment schemes are static, not allowing to consider dynamic interactions among assessment factors. This shortcoming hampers current research in assessing short- and long-term effects of smart city dimensions on urban development.

(4) *Lack of universal reference architectures for smart cities*. Too little effort has been devoted to reference architectures and models for smart cities to achieve smart integration of urban systems (Kasznar et al., 2021). These limitations and other barriers, such as data ownership and bureaucracy, underline the difficulty of fully exploiting the large volumes of real-time data streams available from sensor networks, satellite data, or social media (Caird, 2018; Vandercruysse et al., 2020).

(5) *Lack of stakeholder participation in the assessment process*. Prior studies show that traditional citizen-centric smart city initiatives that rely on a top-down approach are often ineffective. Community-led approaches, such as blockchain, are an alternative and are currently being highlighted in this stream of research because ICT and decentralized technologies are expected to play an essential role in trusted and transparent communication with citizens, data processing and providing intelligent decision support (Oliveira et al., 2020; Marsal-Llacuna, 2020). In this case, mobile apps and wallets are used to enable citizen participation.

(6) *Linear composite indexes*. A serious weakness of PCA-based composite indexes is that the reduction of the dimensionality of the original set of indicators to one (or a few) components preserves only some of the data variance. PCA is a widely used dimensionality reduction method due to its simplicity, but its results can be adversely affected by outliers, missing data, and nonlinear relationships between variables. Indeed, these problems are common in real applications because reliable data may not be available for some variables (Sharifi, 2020a), and nonlinear interactions may be present between variables (Castanho et al., 2021).

(7) *Insufficient consideration of conflicting views of stakeholders*. Existing solutions are insufficient to capture the often-conflicting views of different decision makers and stakeholders (Deveci et al., 2020). Moreover, current research inadequately models positive (synergies) and negative (trade-offs) interactions between smart city dimensions and their indicators.

(8) *Lack of holistic evaluation*. The focus of previous research has been to develop a methodological framework for holistic evaluation to serve as a basis for future studies assessing smart cities in practice. All the studies above suffer from the fact that only existence or the absence of the effect of smart city initiatives on urban development was considered. The effect size of smart city initiatives on different dimensions of urban development has not been taken into account.

(9) *Insufficient assessment of smart city pitfalls*. The following pitfalls have been identified (Lam and Ma, 2019): (1) system information insecurity, (2) privacy leakage (information exposure), (3) information islands (leading to resource waste), and (4) digital divide (widening inequality). Unfortunately, existing research does not take into account these smart city pitfalls, thus hindering the assessment of potential negative impacts on smart city development.

6.3 Future research directions

Our thoughts on the limitations of current research in this field suggest that several areas of research deserve further work. The following are some research gaps that researchers could explore in the future:

(1) Our results show that there is a trend toward actionable data based on open secondary data. It is an evaluation of the impact open data has on urban development that presents potential opportunities for further research.

(2) Cities are seeking integration of resilience, leadership, health recovery, and sustainability of social infrastructure in light of the current pandemics. These challenges serve as a stimulus for future assessment frameworks, especially given the growing importance of cities to address these threats.

(3) To further enhance the robustness of assessment schemes to the specific needs of cities, more work needs to be done to adapt assessment schemes to: (1) the economic level of the national/local spatial unit, (2) the level of development of the smart city, and (3) different smart city strategies.

(4) We envision, as a promising direction for further research, the evaluation of the dynamics of interactions between different smart city dimensions and their respective indicators to assess their full impact on urban development.

(5) To address the problem of overlooking real-time data in existing assessment schemes, Candela and Mulassano (2021) showed how real-time data can be adopted to assess various dimensions of urban development, using data on traffic, pollution, cultural website activity, financial markets, and the activity of citizens on social media. Therefore, indicators based on real-time big data should be included in assessment schemes to complement those based on static historical data.

(6) Further work is needed to develop appropriate assessment schemes for community-led approaches. Similarly, future development of 5G-enabled smart cities (Guevara and Auat Cheein, 2020) poses another challenge in assessing benefits to smart city

transportation and other urban services, while considering the environmental impacts of these enabling technologies.

(7) Future research should explore and combine the dimensions of urban sustainability, creativity, and intelligence to construct composite indexes of urban performance. To overcome the problems of lack of reliable data and nonlinear interactions between assessment indicators, we recommend using robust PCA or kernel PCA (Ayesha et al., 2020), rather than the traditional PCA method.

(8) To preserve the variance of the data and account for the different weights of the components found, it is also suggested to integrate the PCA results with MCDM methods, such as TOPSIS or PROMETHEE, for city ranking. Future work could consider methods used for group decision making under multiple criteria by aggregating the preferences of different decision makers. It is worth noting that MCDM methods represent an alternative to multivariate statistical methods in generating an overall score of smart city performance. Therefore, future studies are recommended on assessment schemes integrating the above methods for establishing criteria weights with methods suitable for ranking smart city projects. Further research on ranking schemes is also needed to consider the contribution of indicators to the Sustainable Development Goals (SDGs) (Omer and Noguchi, 2020).

(9) Qualitative and quantitative assessment methods need to be developed to complement holistic approaches. In future investigations, it might be possible to use causal graphical models to represent the observed complex system under various hypothetical interventions needed for more effective decision making. The challenging task of constructing causal models is that stakeholders and experts need to define underlying assumptions and causal relationships, respectively. Alternatively, sufficient time series data must be available to learn such models. To address this issue, we recommend modeling the dynamics and the inherent uncertainty in complex causal relationships between smart city projects and the affected dimensions by using fuzzy cognitive maps, a causal graphical model using descriptive and interpretable linguistic terms.

(10) It is proposed to pay special attention to indicators related to smart city pitfalls, such as cybersecurity strategy, vulnerability assessment, assessment of standards for ICT services and governance, and data quality and digital inclusion. We recommend that these data are used in the construction of future indicator sets.

The suggested future research directions for the above emerging research themes are summarized in Table 9.

Table 9: Summary of the proposed future research agenda

Research theme	Further research suggestions
Smart city performance measurement framework	− Evaluate the impact of open data on urban development − Adapt assessment schemes to different levels of smart city development − Assess risks and threats associated with the development of smart cites
Connecting challenge	− Develop universal reference architectures for smart cities to achieve smart system integration − Exploit and assess the real-time big data streams − Assess community-led smart city initiatives
Smart sustainable cities (composite index)	− Composite indices based on robust dimensionality reduction methods − Integrate dimensionality reduction with group MCDM methods − Assess synergies and trade-offs between smart city dimensions and their contribution to SDGs
Holistic evaluation	− Assess the effect of smart city initiatives on urban development − Model causality within complex smart city systems under different hypothetical interventions − Model the dynamics and uncertainty in complex causal relationships between smart city projects and affected dimensions
Indicator set	− Assess the operational feasibility of indicator standards and their use in real decision-making − More research on indicators related to cybersecurity strategy, vulnerability assessment, assessment of standards for ICT services and governance, and data quality and digital inclusion − Utilize real-time open data in assessment schemes

7. Conclusion

The growth of smart city projects has been staggering over the past decade, and we expect it to be even greater in the coming years, especially as we see the maturity of technologies such as 5G. With more than 1,000 smart city projects implemented worldwide as of 2017 alone (Yan et al., 2020) and considering that the global smart city market is expected to double by 2025, the demand and urgency for effective smart city assessment schemes is increasing rapidly.

The aim of this study was to uncover recent developments in the field of smart city assessment by identifying the most influential research sources, research hotspots, and potential research themes. Using science mapping, we identified the theoretical foundations of smart city assessment and the most influential recent efforts to develop comprehensive assessment schemes. These trends particularly highlight the concept of smart sustainable cities with a growing body of literature in environmental science categories. A content analysis revealed that the articles covered four related sets of keywords, revealing the articles' orientation towards designing an assessment scheme, outlining the methodology used, validating the scheme on smart city projects and initiatives, and evaluating the impacts of smart city technologies on citizens' lives. Evidence from the progressive network analysis also suggests further research directions in the identified research areas. Specifically, recent developments suggest that future assessment schemes will address issues of data connectivity assessment and citizen participation, with an emphasis on holistic evaluation and more advanced assessment schemes.

We believe that by identifying five prevalent foreground research themes, this study provides an agenda for future research in smart city assessment.

Finally, a number of important limitations need to be considered. The most important limitation lies in the fact that the assessment schemes covered in the grey literature (not published in WoS or IEEE Xplore) could not be investigated in terms of science mapping that requires references linking research articles. However, the results of the science mapping should be treated with caution, as the findings may be influenced by the authors' decisions to select specific references. Moreover, a common shortcoming of science mapping is that all citations are given equal weight regardless of their impact on the citing article. It would therefore be interesting to combine our approach with a critical analysis of the assessment schemes to gain further insights.

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