

Software Architecture for Smart Cities: A Systematic Literature Review of Quality Attributes

¹Muhammad Shaheed Abdullahi, ²Muhammad Aminu Umar, ³Abubakar Isah, and ⁴Sheidu Salami Tenuche
Department of Computer Science, Ahmadu Bello University, Zaria-Nigeria.
¹shaheedabdullahi@hotmail.com, ²maumar@abu.edu.ng, ³sadiqrrw@gmail.com,
⁴sheidutenuche@gmail.com.

Abstract

Background: A Smart City leverages on Information and Communications Technologies (ICTs), and several other infrastructures for improvement of citizens' quality of life, efficiency in managing all aspects of city's operations and services. Having the right architecture in developing smart city applications is paramount to achieving the minimum set of Quality Attributes (QAs). Several architectures and frameworks were proposed that are aimed at satisfying different set of QAs. However, there is a little or no effort in developing a product line architecture that satisfies all QAs that are considered common and essential to smart city applications. **Aim:** This work is aimed at reviewing existing smart city architectures and frameworks to identify the QAs each of these architecture and frameworks satisfy, categorizing these QAs into high level QAs as well as proposing key QAs for smart city. **Method:** To achieve this objective, a Systematic Literature Review (SLR) was conducted and two research questions (RQs) were defined, and the result was analyzed using descriptive statistics techniques. **Results:** Sixteen (16) architectures/frameworks were reviewed, and identified eight (8) high-level QAs, among which four (4) were proposed as key Quality Attributes for smart city.

Keywords: Smart City, Internet of Things, Software Architecture, Systematic Literature Review, Software Quality Attributes.

1. Introduction

Smart City uses many infrastructures, which includes ICTs, leveraging on other smart technologies as well as data analytics technologies for optimization of city operations and service delivery, promoting economic growth and improving Quality of Life (QoL) for citizens. In addition to QoL, concept smart city is also about efficient and sustainable management of energy, efficient healthcare, smart education, transportation, efficient governance, and much more (Silva, Khan, & Han, 2018). Furthermore, components of smart city includes smart infrastructure, smart buildings, smart technology as well as smart citizens (Mohanty, Choppali, & Kougianos, 2006). Smart cities are complex due to heterogeneous nature of interacting objects (Bastidas, Helfert, & Bezbradica, 2018). It is a huge information system that comprises smaller, but efficient subsystems that are connected together. These subsystems need efficient and improved capabilities for data processing and storage, information retrieval, networking and communication (Bawany & Shamsi, 2015).

Smart City applications typically should achieve minimum set of Quality Attributes that are considered significant. For instance, all interacting object in the smart city ecosystem should be able to interoperate, components should be available when needed, the services and operations should be reliable, security and privacy of data should also be maintained. Achieving these and many more QAs is dependent on the Architectural decisions made. Software Architecture structures a system in form of elements or components, relationship among these components, and their properties (Bi, Liang, Tang, & Yang, 2018; Zhu & Gorton, 2007). How these elements are structured, the architectural pattern and styles being used has a profound effect on quality attributes of a system,

especially in complex system such as Smart City applications. Hence, there is a very strong link between software architecture and QAs of a system as mentioned by Ameller, Ayala, Cabot, & Franch (2012), also, as rightly stated by Zhu & Gorton (2007), that “the rationale behind each architecture decision is mostly about achieving certain Quality Attributes”. Several smart city architectures and frameworks were proposed by researchers, each focusing on certain quality attributes. There is however little or no effort in identifying and harmonizing QAs that are common and must be satisfied by all smart city applications. In this work, a systematic literature review was conducted on existing software architecture and frameworks for smart city applications. The work is aimed at identifying critical quality attributes that must be satisfied by smart city applications, which should serve as guidance to practitioners and researchers for developing product-line architecture for smart cities.

The rest of the paper is structured as follows: the methodology adopted in this research is discussed in Section 2. In section 3, we reviewed the existing architectures in an effort to identify the key QAs they aimed to meet, section 4 discusses high-level software quality attributes and summary of identified attributes in each of the reviewed architectures. In section 5, we presented the key quality attributes based on criteria mentioned in section 2. We concluded the paper in section 6 and discussed the future direction of this research.

2. Review of Software Architectures for Smart City

Several architectures for smart city were proposed in the literature. Each of these architectures aimed at achieving some quality attributes. In this section, we review these architectures and identified the QAs they aim to satisfy.

A survey conducted by Silva, Tomas, Dias, & Afonso (2013) reviewed several smart city architectures proposed in the literature. The aim is to highlight minimal set of architectural requirements of a smart city. The work identified and discussed eleven (11) essential requirements, i.e. Objects interoperability, real-time monitoring, sustainability, mobility, historical data, availability, privacy, service composition and integrated urban management, social aspects, distributed sensing and processing, as well as flexibility/extensibility.

Another survey conducted by Kakarontzas, Anthopoulos, Chatzakou, & Vakali (2014) identified important functional and quality requirements of smart cities, and proposed conceptual architectural framework based on identified properties. The result of their work identified interoperability, usability, authentication and confidentiality, availability and recoverability, as well as maintainability as the most important quality attributes. They applied Pattern Driven Architectural Partitioning (PDAP) method for selecting appropriate architectural patterns, then proposed conceptual architectural framework that could satisfy identified attributes.

A literature study by Kyriazopoulou (2015) discussed proposed architectures and requirements in the literature, specified those that are more useful in developing smart cities. The work categorized existing architectures into six (6) perspectives, the “Architectural Layers (AL)”, “Service Oriented Architecture (SOA)”, “Event Driven Architecture (EDA)”, “IoT”, “Combined Architectures”, and “Internet of Everything (IoE)”. The work deduced that AL is the most preferred architectural perspective due to the fact that features can be modified in different layers without changing the whole system. Also, SOA was the second most preferred due to its flexibility nature, service reuse. For the requirements, they deduced that data collection, data streaming and processing, as well as interoperability have the highest priority.

The work done by Bawany & Shamsi (2015) highlighted key challenges that relates to smart city adaptation, with emphasis on effective data storage and processing. The research proposed a “zone-based architecture” for “storage and management” of data to deal with the smart city’s information management challenges. The model adopts Service-Oriented Architecture for interoperability among components and application integration. It also proposed the use of open data model for third party applications development. The work identified scalability, availability, security and privacy of data, efficiency, heterogeneity and interoperability, as well as efficient data monitoring, storage and retrieval as critical attributes of smart city applications.

A cloud-based architecture of an application for smart sustainable tourism is proposed in Nitti, Pilloni, Giusto, & Popescu (2017). Although the architecture is specific to a tourism, the authors analyzed and proposed key IoT requirements the environment of smart city. The requirements addressed by proposed architecture includes end-to-end data privacy, authorization and access control; Use of open APIs for device flexibility, and remote device manageability; Data virtualization and flexible data definition tools, data scalability, and reusability of components.

A research conducted by Santana, Chaves, Gerosa, Kon, & Milojevic (2018) surveyed application platforms of smart city. The work examined 23 different platforms to identify the enabling technologies of these platforms, their requirements, and their main challenges. The authors categorized these platforms into Internet of Things, Big Data, Cyber-Physical Systems, as well as Cloud Computing. By combining the result of their research questions, a reference architecture was derived based on prevalent disruptive technologies, their requirements, and challenges. The architecture, according to the authors supports scalability, security, privacy, and interoperability.

An IoT-based smart city architecture proposed by Paul (2018) changed the conventional architecture of blockchain by making it more applicable to IoT applications. The authors argued that “conventional adoption of blockchain in IoT causes significant energy consumption, delay and computational overhead which are not suitable for various resource-constrained IoT devices.” The work focused on security and privacy attributes of smart cities, by preserving confidentiality, authenticity, availability, integrity and non-repudiation capabilities of blockchain technology.

Another architecture proposed by Khan, Abbasi, & Pervez (2019) also based on blockchain and edge computing model that provides “refined and secure management of data generated and processed in different geographical and administrative unit of a city.” The architecture uses blockchain technology for realization of open and traceable governance framework and uses edge computing for realization of green smart infrastructure by separating different levels of planning and decision making. Efficient citizen participation in data collection, storage and processing, transaction traceability and auditing, security and privacy are key attributes that the architecture aimed to achieve.

An architecture proposed by Saini, Zia, & Muhammad (2019) focuses on dependability, reliability and security of data in smart cities. The architecture is centered around attack analysis and attack exposure framework for monitoring information sensitivity in smart cities.

InterSCity is a smart city platform proposed in Del et al. (2019) based on microservice architecture. The architecture is aimed at providing modular, scalable and flexible infrastructure that is extensible and can be shared among smart city initiatives and research communities. In addition to horizontal flexibility/scalability of the platform, InterSCity is also designed with performance efficiency as core requirement, with the authors claiming that it is capable of handling more than 1 million complex requests in a span of 3 hours.

Snap4City architecture presented in Badii, Bellini, Difino, & Nesi (2020) is an architecture of a Snap4City platform developed as a result of research challenge launched by “Select4Cities Pre-Commercial Procurement H2020 research and development project of the European Commission” (SELECT for Cities, 2020). Their platform addressed all key requirements identified and presented in the challenge, with special emphasis on Security and Privacy, in addition to usability, interoperability, flexibility, scalability, open source, modularity and reliability.

SmartGC by Ramalho, Rossetti, Cacho, & Souza (2020) is a smart city application for garbage collection. The architecture is based on the concept Artificial Transportation System (ATS), which integrates artificial society methods and theory to transport simulation methods by applying high performance computing technologies and agent-based modeling to transportation system, according to Kong & Wang (2013). SmartGC architecture accommodated several QAs, according to authors including portability, modifiability, availability of data, security and access control, real-time and batch processing of data, and usability.

An Enterprise Architecture for smart cities based on “The Open Group Architecture Framework (TOGAF)” was proposed in Jnr (2020) The architecture aimed at efficient energy data distribution and storage to support energy presumptions in smart city buildings and electric vehicles using open, online, historic and real-time data. The architecture also leverages the openness of data to support interoperability among components.

A “big data driven multi-tier architecture” proposed by Jnr, Petersen, Ahlers, & Krogstie (2020) deploys Application Programming Interfaces (APIs) to process heterogeneous mobility data emanating from Electric Vehicle (EV) positions, usage, routes, charging stations, parking stations, public transport, etc. The architecture supports interoperability by offering flexible and scalable processing of real-time and historic mobility data in smart city.

An IoT-based System of System (SoS) software architecture is proposed in Aziz, Musharaf, & Sayyed (2021). The authors combined microservice architecture style (which is a variation of service-oriented architecture) with cloud computing to achieve important QAs. Applicability of the architecture was tested in smart city applications and evaluated with respect to scalability and maintainability quality attributes.

A hybrid architecture based on blockchain technology and Software Defined Network (SDN) for smart cities is proposed in Singh, Tripathi, Walia, Deepika, & Anju (2021). The architecture aimed at addressing challenges of smart cities, which includes privacy and security, scalability, latency and high bandwidth usage. Their result has proven effective in improving identified challenges.

From the reviewed works, it is evident that there is an integral relationship between quality attributes and smart city architectures. The work differs from the previously reviewed work because it reviews existing software architecture and frameworks for smart city applications with the aim of identifying critical quality attributes that must be satisfied by smart city applications. Therefore, this work reviews quality attributes for building effective product-line architecture for smart cities.

3. Review Methodology

The overall goal of this paper is to review existing architectures of smart cities to identify the QAs each of these architectures aimed to satisfy and propose the key attributes that could serve as guide for development of product-line architecture for smart city applications. This section details the approach adopted in searching and selecting relevant articles in the literature, identifying and categorizing the quality attributes, as well as analyzing and selecting the key attributes. This SLR was conducted according to the guidelines set out in Kitchenham & Charters (2007). The review was done in three (3) phases: Planning, Conducting, and Reporting phases, as shown in figure 1, and discussed subsections 3.1 to 3.7.

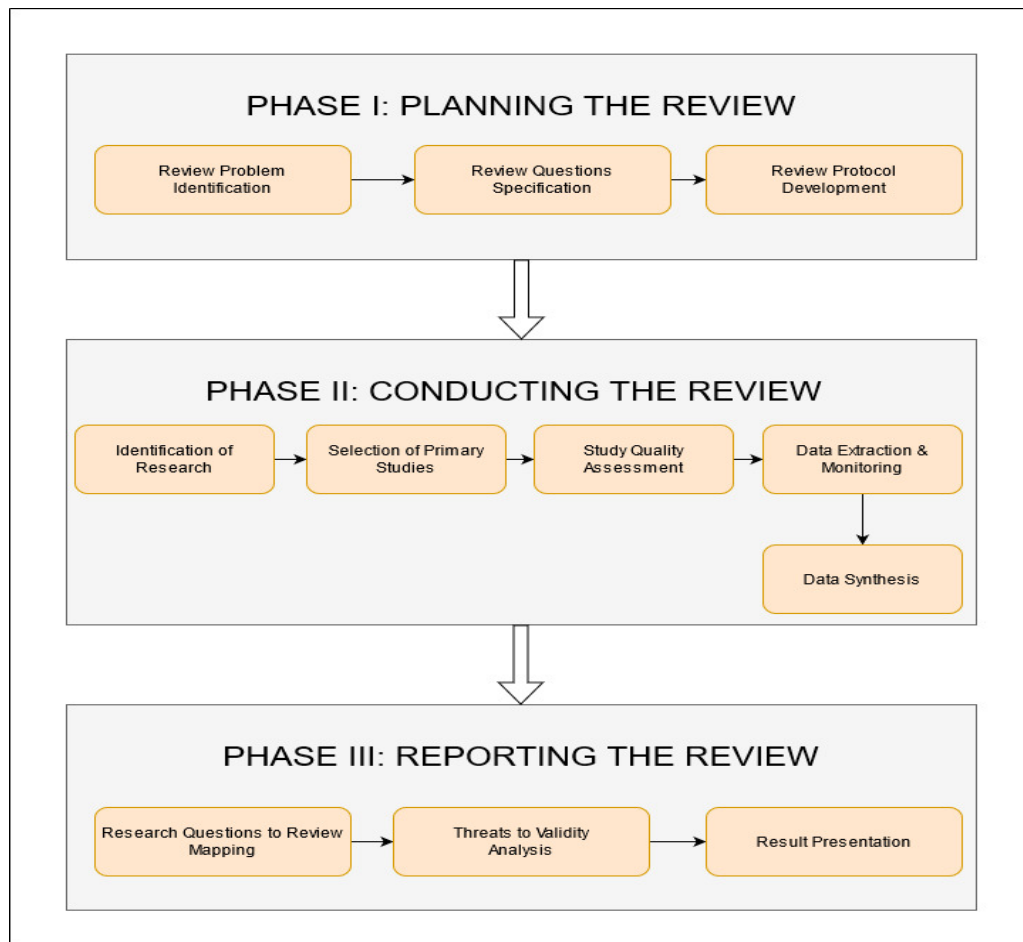


Figure 1 - The Systematic Literature Review Process

3.1 Research Questions (RQs)

This SLR was conducted to identify and understand the quality attributes that smart city architectures addresses, with the main objective of proposing key quality attributes that should be satisfied by all smart city applications. Hence, we defined two (2) RQs as follows:

RQ1: Which high-level QAs were addressed by smart city architectures?

RQ2: What are the key QAs for smart cities?

3.2 Data Sources

In order to identify digital sources of data, several discussions were held by authors. Several digital repository options were considered and explored with the aim of extracting relevant data to address the given RQs. The following repositories were finally selected based on authors’ discussions and SLR experience, and following the guidelines set out in Chen, Babar, & Zhang (2010): ACM digital library, Google Scholar, Springer, IEEE Xplore, and Science Direct.

3.3 Search Strategy

The RQs were analyzed by all authors to come up with appropriate search terms. Pilot search and selection was conducted using the following search strings: (“*Smart City*” OR “*IoT*” OR “*Internet of Things*”) AND (“*Architecture*” OR “*Quality Attributes*” OR “*Framework*” OR “*Software Architecture*” OR “*Quality Attributes*” OR “*Software Quality Attributes*” OR “*Non-Functional Requirements*” OR “*Requirements*”). Following the guidelines set out in Kitchenham & Charters (2007), these keywords were finally used to form the search strings: (*Smart City*” OR “*Internet of Things*”) AND (“*Architectures*” OR “*Frameworks*” OR “*Quality Attributes*”). The search terms were concatenated using Boolean “AND” and “OR” operators for building the search strings. A comprehensive search was completed in December 2021 using the combination of the aforementioned search terms interchangeably. A total of 78 studies were identified and retrieved, out of which 16 were finally selected following the inclusion/exclusion criteria and study selection criteria as discussed in the next sections.

3.4 Inclusion and Exclusion Criteria

In order to select the most relevant papers, the following inclusion and exclusion criteria presented in table 1 was followed, as proposed in Kitchenham & Charters (2007).

Table 1 - Study Inclusion & Exclusion Criteria

No.	Inclusion Criteria
InCriteria 1	A study that focuses on specifically on Smart city software architecture.
InCriteria 2	A study that focuses on Smart City Quality Attributes.
InCriteria 3	A study that is published in journal, conference proceedings, book chapters, and workshops.
InCriteria 4	Studies published in English language and whose full text is available.
InCriteria 5	Studies between 2010 to 2021
No.	Exclusion Criteria
ExCriteria 1	If a study on same wok is published in two places (e.g. conference and journal), we excluded the one that is less mature.
ExCriteria 2	Grey literature materials (e.g. technical reports, keynotes, editorials) were excluded.

3.5 Study Selection

We used the search strings discussed in section 3.3 for exploration of repositories discussed in section 3.2. The selection was conducted in three rounds as follows:

- In the first round, we searched the selected repositories and 78 papers were retrieved. We filtered the retrieved studies manually and selected 46 studies that seems more relevant based on their title and abstract, as seen in figure 2.
- In the second round, we applied the inclusion and exclusion criteria presented in section 3.4 on the 46 publications selected from the first round. This was done by reading and analyzing publications

thoroughly, and independently by two authors, after which a consensus was reached by all authors. 13 publications were finally shortlisted and retained for further assessment in the third round.

- In the third round, the 13 shortlisted papers from the 2nd round were studied and analyzed by different authors to avoid bias, and after a consensus by these authors, all the 13 papers were finally selected and retained as primary studies.
- Backward Snowballing was applied in the third round base on the guidelines set out in Wohlin (2014) to scan references of primary studies for potential addition. A total of 6 candidate papers were found to be most relevant, and we applied same inclusion/exclusion and selection criteria on these papers. Eventually, 3 papers were finally selected and included to our primary studies. This makes the total number of final studies to 16.

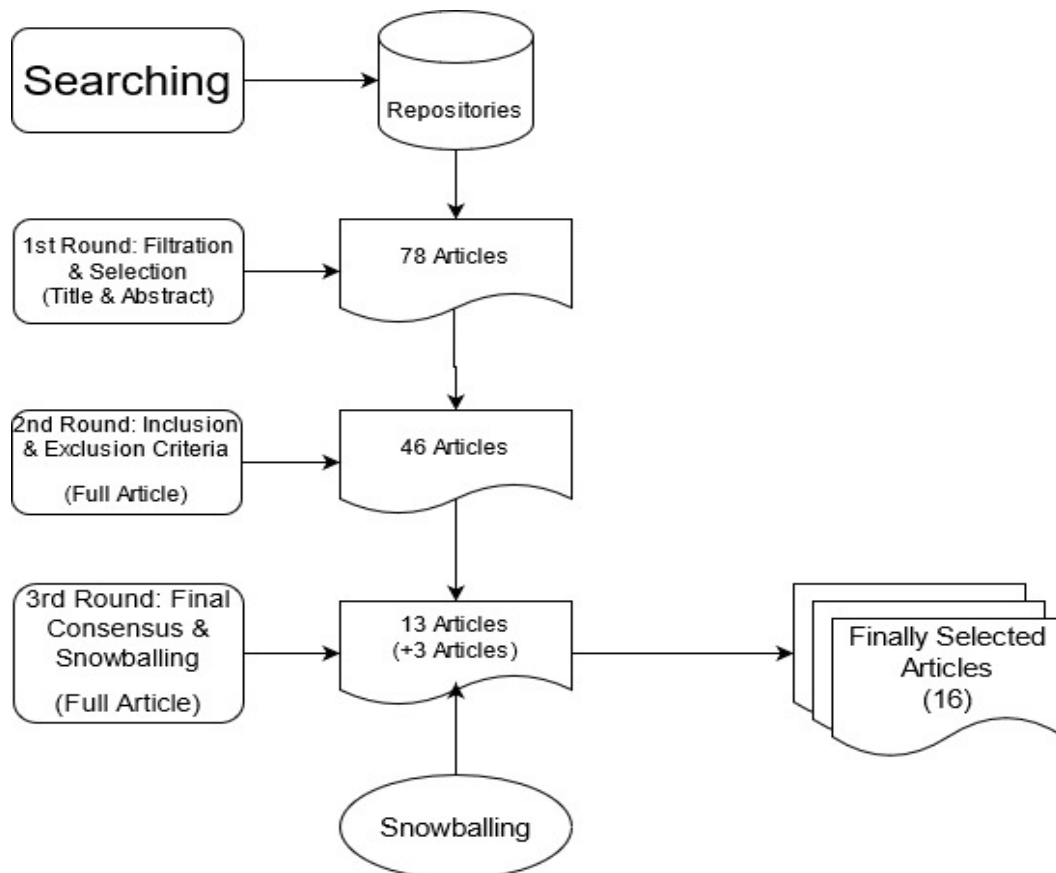


Figure 2 - Study Selection Process

3.6 Quality Assessment

We analyzed the quality assessment checklist as proposed Kitchenham & Charters (2007) and designed our quality assessment questions as presented in table 2. This is to avoid bias and also ensure completeness of the selected primary studies.

Table 2 - Study Quality Assessment Questions

ID	QUESTION
Q1	Has the aim/objectives of the research clearly stated?
Q2	Does the study address any of the defined research questions?
Q3	Has the proposed architecture in the study been implemented?
Q4	Does the study present explicit assessment of the result?
Q5	Does the conclusion of the study align with the stated aim and objectives?

We assigned scores to selected studies based on the quality assessment questions using three-point scale (Yes=1, Partial=0.5, No=0). We ranked the studies based on their scores as presented in table 4.

3.7 Data Extraction

We extracted relevant data from selected primary studies that addresses the research questions (RQ1 and RQ2) discussed in section 3.1. We recorded the extracted data in excel sheet. The quality of selected primary studies was assessed and graded according to the criteria set out in section 3.6 as presented in table 3, and details provided in appendix 1.

Table 3 - Extracted Data Items from Studies

Extracted Item	Description
Paper Title	The title of the paper been reviewed
Publication Type	The type of publication, i.e. journal, conference, book chapter etc.
Publication Year	The year of publication for selected primary study.
Aim of Study	Main goal of the study under review.
Focus of the Study	Scope of the study and information about proposed architecture
Quality Attributes	The quality attributes that the proposed architecture satisfy.
Obtained Result	Evidence of the effectiveness and applicability of proposed architecture.

Table 4 - Studies Quality Assessment Scores

ID	PRIMARY STUDY	Q1	Q2	Q3	Q4	Q5	TOTAL
PS-1	Silva <i>et al.</i> (Silva <i>et al.</i> , 2013)	1	1	0	0.5	1	3.5
PS-2	Kakarontzas <i>et al.</i> (Kakarontzas <i>et al.</i> , 2014)	1	1	0.5	1	1	4.5
PS-3	Kyriazopoulou (Kyriazopoulou, 2015)	1	0.5	0	1	1	3.5
PS-4	Bastidas <i>et al.</i> (Bastidas <i>et al.</i> , 2018)	1	1	0	1	1	4
PS-5	Santana <i>et al.</i> (Santana <i>et al.</i> , 2018)	1	1	0.5	1	1	4.5
PS-6	Paul (Paul, 2018)	1	0	1	1	1	4
PS-7	Khan <i>et al.</i> (Khan <i>et al.</i> , 2019)	1	0	1	1	1	4
PS-8	Badii <i>et al.</i> (Badii <i>et al.</i> , 2020)	1	0	1	1	1	4
PS-9	Nitti <i>et al.</i> (Nitti <i>et al.</i> , 2017)	1	0	0.5	1	1	3.5
PS-10	Ramalho <i>et al.</i> (Ramalho <i>et al.</i> , 2020)	1	0	1	1	1	4
PS-11	Singh <i>et al.</i> (Singh <i>et al.</i> , 2021)	1	0	0.5	1	1	3.5
PS-12	Aziz <i>et al.</i> (Aziz <i>et al.</i> , 2021)	1	0	1	1	1	4
PS-13	Saini <i>et al.</i> (Saini <i>et al.</i> , 2019)	1	0	0.5	1	1	3.5
PS-14	Del <i>et al.</i> (Del <i>et al.</i> , 2019)	1	0.5	1	1	1	4.5
PS-15	Jnr (Jnr, 2020)	1	1	0.5	1	1	4.5
PS-16	Jnr <i>et al.</i> (Jnr <i>et al.</i> , 2020)	1	0.5	1	0.5	1	4

3.7 Data Synthesis

We synthesized the data obtained in alignment with the data extraction form designed in order to answer the predefined research questions. Sections 3.7.1 and 3.7.2 discusses how the synthesized data was analyzed to categorize identified QAs and descriptive statistics performed on these attributes to obtain the answers to our research questions.

3.7.1 Quality Attributes Categorization

The identified quality attributes were categorized according to quality model of a product defined in “ISO/IEC 25010:2011” (“ISO/IEC 25010:2011(en), Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models,” 2011). The model categorized product QAs into eight (8) high level categories as follows:

- Functional suitability
- Performance efficiency
- Compatibility
- Usability
- Reliability
- Security
- Maintainability
- Portability

These categorizations consist of related subcategories each. Researchers in the literature used varying terms for the QA’s, for instance, terms like “modifiability” and “modularity” are associated with Maintainability; “response time”, “latency”, “speed”, “throughput” are associated with performance. We referred to (Hindle, Ernst, Godfrey, & Mylopoulos, 2011) for harmonizing the terms and categorizing them into appropriate high level category.

3.7.2 Selecting Key Quality Attributes

We analyzed selected architectures and identified the QAs they aimed to address. Descriptive statistics was used in analyzing quantitative data, in essences, the frequency of QAs appearance in reviewed architectures. We used concept matrix to compile the selected architectures against the QAs they address. QAs Frequency was calculated based on number of appearances in selected architectures, and four (4) QAs with highest frequency were considered key attributes for smart city architecture.

4. Results

The results of this SLR with the statistical representation of temporal distribution and publications type is presented in section 4.1 and section 4.2 respectively. The result with respect to two research questions defined in section 2.1, is presented in section 4.3 and section 4.4 accordingly.

4.1 Temporal Distribution

Figure 3 depicts the year-wise distribution of primary studies. As seen in the figure, out of the 16 primary studies reviewed, 1 is published in 2013, 1 in 2014, 1 in 2015, 1 in 2017, 4 in 2018, 2 in 2019, 4 in 2020, and 2 in 2021.

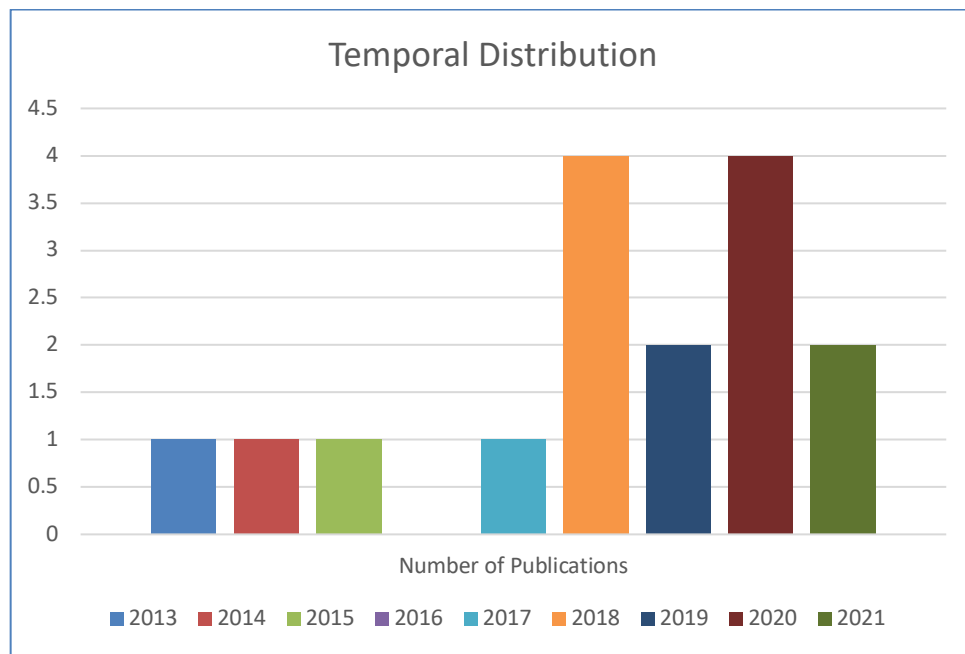


Figure 3 - Year-wise Distribution of Primary Studies

The data suggest that there is an increase in research on smart city architecture since 2018.

4.2 Publication Type

The primary studies reviewed were classified across three major publications types, i.e. Journal, Conference paper, and book chapter.

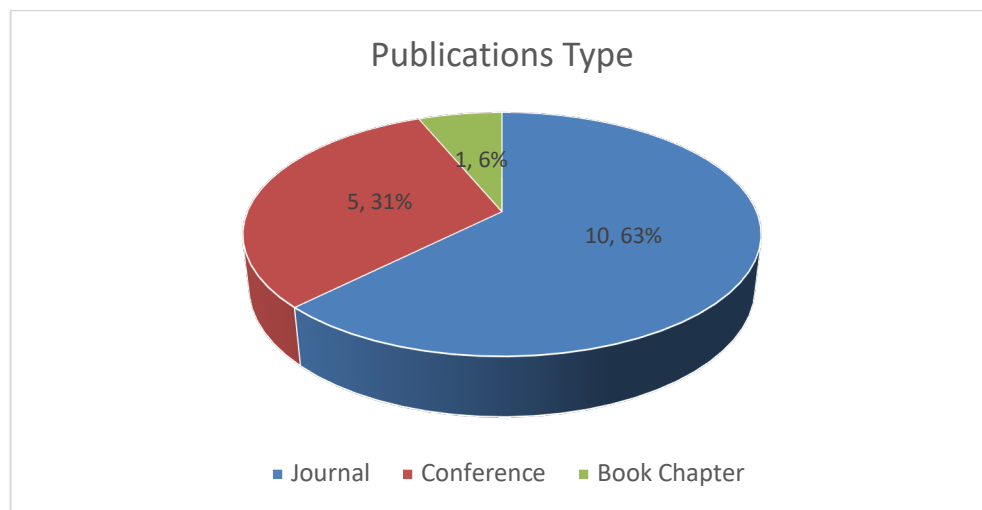


Figure 4 - Publication types of Primary Studies

Figure 4 shows 10 primary studies were published in journals, representing 63% of the total studies reviewed, 5 primary studies, representing 31% of total studies are conference papers, and 1 study representing 6% of total primary study is a book chapter.

4.3 High-level software Quality Attributes for Smart City (RQ1)

Quality attributes are part of the non-functional requirements of an application that capture the many perspectives of how the functionalities/functional requirements of an application are achieved (Gorton, 2011). This section discusses the QAs addressed by smart city architectures in the reviewed literature with respect to research question 1 (RQ1).

We categorized Software Quality Attributes reviewed into eight (8) high-level categories, with each category composing of several related subcategories, based on the high-level categories of QAs presented in (“ISO/IEC 25010:2011(en), Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models,” 2011) as follows:

- **Functional suitability:** This attribute represents a level at which a software achieves the specified and/or implied needs, i.e., the stated functionalities are achieved. It includes the level of functional completeness, correctness as well as appropriateness. Functional suitability has been expressed differently in the literature, for instance, “service composition and integrated urban management” as in Silva et al. (2013), “allowing citizen participation, data collection, storage and processing” (Khan et al., 2019).
- **Performance Efficiency:** Subcategories of Performance efficiency includes resource utilization, time behavior, and capacity. This QA has been expressed in literature as simply efficiency as in Bawany & Shamsi (2015), real time and/or batch monitoring and processing of data (Jnr, 2020; Kyriazopoulou, 2015; Ramalho et al., 2020; Silva et al., 2013) virtualization and flexible data definition tools Nitti et al. (2017), as well as low latency and low bandwidth usage (Del et al., 2019; Singh et al., 2021).
- **Compatibility:** Compatibility includes interoperability on one hand and co-existence on the other. Co-existence refers to a degree at which required functions can be performed by a product efficiently without undesirable impact on another product. On the other hand, Interoperability is concerned with the degree at

which information is exchanged and used among two or more components, products or systems. It has been expressed in the reviewed architectures as interoperability as in (Badii et al., 2020; Bawany & Shamsi, 2015; Jnr, 2020; Jnr et al., 2020; Kakarontzas et al., 2014; Kyriazopoulou, 2015; Santana et al., 2018; Silva et al., 2013), heterogeneity as in Bawany & Shamsi (2015), distributed sensing and processing Silva et al. (2013), or remote device manageability (Nitti et al., 2017).

- **Usability:** This attribute represents the degree at which a software can be used to achieve some specified objectives, by certain or specified users with efficiency, satisfaction, and effectiveness. Subcategories includes “operability”, “user error protection”, “user interface aesthetics”, and “accessibility”. It is mostly expressed as usability, as in (Badii et al., 2020; Kakarontzas et al., 2014; Ramalho et al., 2020).
- **Reliability:** Represents the level at which specified functionalities are achieved by the software under given conditions and over given period. Reliability involves availability, maturity, recoverability, and fault tolerance. It has been mostly expressed as availability as in (Bawany & Shamsi, 2015; Kakarontzas et al., 2014; Paul, 2018; Ramalho et al., 2020; Silva et al., 2013). It has also been expressed as reliability as in Badii et al. (2020), and recoverability as in (Kakarontzas et al., 2014).
- **Security:** This represents the level of data and information protection of a software, in which access is controlled and restricted to authorized party. Security involves confidentiality, integrity, non-repudiation, authentication, and accountability. These properties have been expressed differently in the reviewed literature, such as privacy (Badii et al., 2020; Bawany & Shamsi, 2015; Nitti et al., 2017; Paul, 2018; Santana et al., 2018; Silva et al., 2013; Singh et al., 2021); authentication and confidentiality (Kakarontzas et al., 2014; Paul, 2018); security (Badii et al., 2020; Bawany & Shamsi, 2015; Khan et al., 2019; Ramalho et al., 2020; Saini et al., 2019; Singh et al., 2021); integrity and non-repudiation, as in Paul (2018); traceability and auditing, as in Khan et al. (2019); authorization and access control (Nitti et al., 2017; Ramalho et al., 2020).
- **Maintainability:** This attribute represents the degree at which modification can be made on software effectively. Subcategories involves modularity, analyzability, reusability, testability, and modifiability. The properties have been expressed as extensibility and flexibility (Badii et al., 2020; Del et al., 2019; Nitti et al., 2017; Silva et al., 2013); maintainability (Aziz et al., 2021; Kakarontzas et al., 2014); modularity (Badii et al., 2020); open source or open APIs (Badii et al., 2020; Nitti et al., 2017); reusability (Nitti et al., 2017); modifiability (Ramalho et al., 2020).
- **Portability:** This attribute represents the degree at which a transfer of component can be made effectively from a certain platform or software to another. Its subcategories involve installability, adaptability, and replaceability. It has been expressed in form of scalability (Aziz et al., 2021; Badii et al., 2020; Bawany & Shamsi, 2015; Khan et al., 2019; Nitti et al., 2017; Santana et al., 2018; Singh et al., 2021); mobility (Silva et al., 2013); and portability (Ramalho et al., 2020).

4.4 Key Quality Attributes for Smart City (RQ2)

In this section, we address research question 2, (what are the key quality attributes for smart cities?). It is established from table 5, that different architectures were proposed to address different set of quality attributes, and there is hardly an architecture that addresses all quality attributes. This is reasonable, because cities have different characteristics, for instance government and political structure, economic model, social and cultural activities (Kyriazopoulou, 2015; Silva et al., 2013). Despite these differences however, some key quality attributes are very critical and should be satisfied by smart city architectures. In this section, we propose four (4) quality attributes based on the reviewed architectures that are key to smart cities, irrespective of city’s characteristics. We used the frequency of appearance of each QA in the reviewed architecture and selected top four that are addressed by majority of reviewed smart city architectures, as presented in figure 5, and discussed below.

1. **Security:** Smart city applications involves different devices and gadgets supporting everyday lives of citizens. These devices collect and process personal and often confidential data that should not be disclosed to unauthorized party. For instance, e-voting system requires personal data as well as sensitive information about voting that must be protected. Security attribute includes privacy, confidentiality, authentication, and non-repudiation. Security has been the most common concern in reviewed architectures as seen in figure 5, with all but four (4) architectures aimed to meet security attribute. Privacy in particular has been the major concern in most architectures, as in (Badii et al., 2020; Nitti et al., 2017; Paul, 2018; Santana et al., 2018; Silva et al., 2013; Singh et al., 2021). This is because privacy is important not only for protecting sensitive data, but also building confidence and trust of citizens to accept the smart city systems (Bawany & Shamsi, 2015; Hakak, Khan, Gilkar, Imran, & Guizani, 2020). Another security property widely addressed by reviewed architectures are non-repudiation, authorization and access control as in (Khan et al., 2019; Nitti et al., 2017; Paul, 2018; Ramalho et al., 2020). It is therefore important for smart city architectures to include mechanisms for ensuring security as a key quality attribute, as this will boost citizen’s confidence and promote general acceptability of smart city applications.
2. **Portability:** Existence of wearable devices, handheld devices, smartphones, tablets and many more gadgets and devices make portability an important attribute in the smart city domain. Additionally, rapid and frequent change in operational environment, hardware and software platforms makes it necessary for smart city to be able adapt to new setting and respond to frequent changes in the environment (Fahmideh et al., 2021).

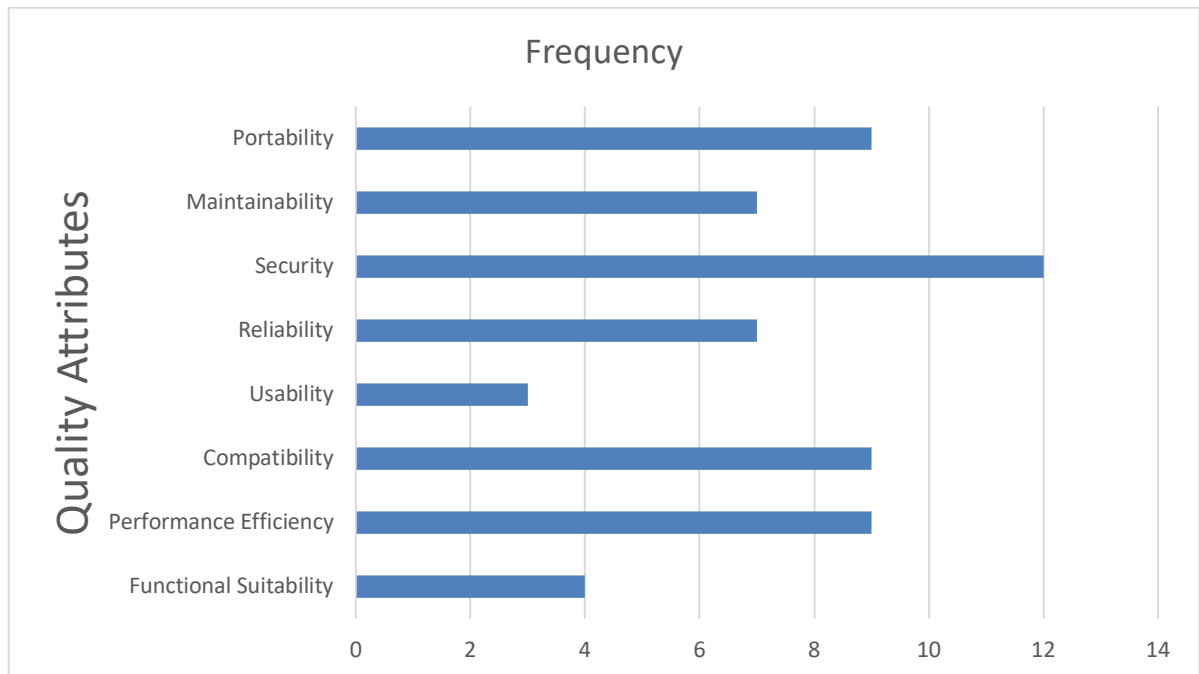


Figure 5 - Frequency of Appearance of QAs

In smart city ecosystem, sensor data flows in large volume, the data stored in databases increases, the devices handled by the system increases frequently, the application and users in the ecosystem also

increases often, hence the need to design a scalable architecture for smart city (Bastidas et al., 2018). This is supported in the literature, with nine (9) architectures considering portability as essential attribute in smart city. Scalability in particular has been the major attribute of concern as seen in (Aziz et al., 2021; Badii et al., 2020; Bawany & Shamsi, 2015; Khan et al., 2019; Nitti et al., 2017; Santana et al., 2018; Singh et al., 2021). It is therefore important to design an architecture with portability as a major QA.

3. **Performance Efficiency:** Sensors are integral part of smart city operations, with real-time monitoring and processing of data at the center of this ecosystem. Efficient time behavior, capacity and utilization of resources including memory and bandwidth cannot be overemphasized. Real-time monitoring and processing of data help smart city users in making predictions of various situations that may influence prosperity of the city (Purushothaman et al., 2013; Razzaque, Milojevic-jevic, Palade, & Clarke, 2015). Performance efficiency is an important attribute for smart city, as shown in figure 5, nine (9) smart city architectures consider it as a key requirement for its success. Particularly, real-time data streaming and processing (including batch) has been integrated in these architectures as in (Kyriazopoulou, 2015; Ramalho et al., 2020; Silva et al., 2013).
4. **Compatibility:** Smart city is centered around heterogeneous objects and components that share data and communicate with each other. These objects are often developed by different vendors, applications running these objects are implemented in different languages, and run under different platforms (Bastidas et al., 2018). How these objects coexist and interoperate has been a major concern of reviewed architectures, with nine (9) out of these architectures proposing mechanism for implementing this attribute. Interoperability in particular is a major QA that is widely proposed in the literature as in (Badii et al., 2020; Bawany & Shamsi, 2015; Jnr, 2020; Jnr et al., 2020; Kakarontzas et al., 2014; Kyriazopoulou, 2015; Santana et al., 2018; Silva et al., 2013). Ensuring compatibility among objects and components in the smart city domain is critical for the success of the system. Therefore, smart architecture should include compatibility as a key quality attribute and provide mechanism for its implementation.

Table 5 - Software Quality Attributes for Smart City

REFERENCES	QUALITY ATTRIBUTES							
	Functional Suitability	Performance Efficiency	Compatibility	Usability	Reliability	Security	Maintainability	Portability
Silva <i>et al.</i> (Silva et al., 2013)	✓	✓	✓		✓	✓	✓	✓
Kakarontzas <i>et al.</i> (Kakarontzas et al., 2014)			✓	✓	✓	✓	✓	
Kyriazopoulou (Kyriazopoulou, 2015)	✓	✓	✓			✓		
Bastidas <i>et al.</i> (Bastidas et al., 2018)	✓	✓	✓		✓	✓		✓
Santana <i>et al.</i> (Santana et al., 2018)			✓			✓		✓
Paul (Paul, 2018)		✓			✓	✓		
Khan <i>et al.</i> (Khan et al., 2019)	✓					✓		✓
Badii <i>et al.</i> (Badii et al., 2020)			✓	✓	✓	✓	✓	✓
Nitti <i>et al.</i> (Nitti et al., 2017)		✓	✓			✓	✓	✓
Ramalho <i>et al.</i> (Ramalho et al., 2020)		✓		✓	✓	✓	✓	✓
Singh <i>et al.</i> (Singh et al., 2021)		✓				✓		✓
Aziz <i>et al.</i> (Aziz et al., 2021)							✓	✓
Saini <i>et al.</i> (Saini et al., 2019)					✓	✓		
Del <i>et al.</i> (Del et al., 2019)		✓					✓	
Jnr (Jnr, 2020)		✓	✓					
Jnr <i>et al.</i> (Jnr et al., 2020)			✓					
FREQUENCY	4	9	9	3	7	12	6	9

5. Threats to Validity

In this SLR, we analyzed validity threats according three validity threat types as discussed below.

5.1 Construct Validity

In order to mitigate construct validity threat, which focuses on ensuring that data was collected correctly, we conducted a pilot search with multiple search strings. We developed the final search strings based on the returned string of the pilot search. The above measure helps in reducing the possibility of having large amount of irrelevant primary studies, that may be as a result of inappropriate search strings. In addition, to mitigate the possibility of missing some relevant primary studies, we conducted backward snowballing on the already selected primary studies, this helped in identifying addition relevant studies for our SLR.

5.2 Internal Validity

To ensure rigorousness of the SLR process, we thoroughly followed the guidelines presented by Kitchenham & Charters (2007), as presented in section 2. We developed three (3) research questions and based on that, five major digital repositories were explored in order to retrieve relevant primary studies, using carefully thought search terms. We developed four (4) inclusion and two (2) exclusion criteria for study selection. We also applied backward snowballing to include relevant studies that may be missed.

5.3 External Validity

To ensure generalizability of our findings, we reviewed 16 primary studies, including those obtained after snowballing that are directly relevant to smart city architectures, and we summarized our findings based on these studies.

6. Discussions

This section discusses and analyze the findings of the review based on stated objectives and research questions.

6.1 The High-level Software Quality Attributes for Smart City (RQ1)

In this research, we identified several quality attributes for smart cities that are addressed by reviewed architectures. These QAs were discussed in the reviewed literature, expressed differently by researchers and practitioners. However, we classified these QAs according to quality model defined in “ISO/IEC 25010:2011” (“ISO/IEC 25010:2011(en), Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models,” 2011), which classified software quality attributes into eight (8) high-level categories, which are functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability.

The finding suggests that citizen participation capability, services composition and integrated urban management, data collection, storage and processing are the major subcategories of functional suitability quality attribute. Performance efficiency means performance that relates to amount of resources utilized under certain condition (“ISO/IEC 25010:2011(en), Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models,” 2011). In the reviewed literature, performance efficiency has been expressed in form of time behavior such as real-time or batch processing of data, low latency; resources utilization such as low bandwidth usage, efficiency; capacity such as virtualization and flexible data definition tools. Compatibility attribute in the literature mainly deals with co-existence of heterogeneous objects and interoperability. This QA has been expressed in the reviewed literature mostly as simply interoperability, heterogeneity, distributed sensing, and processing, as well as remote device manageability. Usability attribute, which is the degree at which a software can be used to specified objectives has been expressed in the reviewed literature as simply usability, and sometimes operability or ease of use. Our result also shows that attributes such as availability, fault tolerance, recoverability are associated with Reliability high-

level QA. The Security QA has been a major concern among the high-level QAs that were identified, with studies expressing it in form privacy, authentication and access control, confidentiality, integrity and non-repudiation, as well as traceability and auditing. Maintainability is another high-level QA that was identified in the review, which represents the degree at which software can be effectively modified without significant effect on its operation. This QA has been expressed as extensibility, flexibility, modifiability, reusability, modularity, as well as open source or open API. Another high-level QA that was identified in the literature is portability, which represents that level at which a software or software component can be effectively transferred from one platform to another. It was expressed mostly as scalability, adaptability, installability and replaceability.

6.2 The Key Quality Attributes for Smart City (RQ2)

Among the eight high-level quality attributes identified in the literature, our finding shows that four QA are more critical and considered key to all smart city applications, due to the frequency of their appearances in reviewed architectures. These QAs are Security, portability, Performance efficiency and Compatibility.

Our result suggests that Security is the most critical QA that should be achieved by smart city applications. As shown in figure 5, 20% of reviewed architectures considered security as a key attribute for smart cities. Specifically, privacy has been the major security focus of these architectures, with 6 (representing 50%) out of 12 studies that deals with security focusing on privacy. As stated in section 4.4, protecting sensitive and private data of citizens is an enabler for general acceptability of smart city applications. In addition to privacy, non-repudiation and access control is another security aspect that most architectures aimed to address. This is not surprising considering the different stakeholders that are involved in daily operations of smart city applications, as unauthorized parties should not be allowed access to sensitive data and every transaction and/or change in citizen's information should be traced back to the initiator. It is therefore important design a smart city application with security at a center stage, as this will help in boosting confidence of all stakeholders in accepting these applications.

Portability is another QA considered critical and key to smart city applications. 15% of reviewed architectures considers portability as key attribute, with scalability representing a significant percentage among portability concerns. Scalability in this context means the ability of smart city platforms to be accessed by variety of devices without affecting the functionalities or performance. A scalable application can cope with increasing number of functionalities, simultaneous connections from variety of smart devices, and can be deployed on different devices and platforms. Considering the dynamic nature of smart city ecosystem, with wearable and handheld smart devices being integral part of daily lives, developing a portable smart city application is important.

Another quality attribute that receives attention in significant number of reviewed architectures is performance efficiency. Our result shows that 15% of these architectures considers performance efficiency as important QA for smart city applications. With the amount of data that is stored and processed by these applications, which often require real-time monitoring and processing, as well as existence of sensors in the ecosystem, it is unsurprising that performance efficiency is at center stage of smart city architectures. Irrespective of city of operation, domain of use and stakeholders involved, smart city applications should have efficient resources utilization as well as efficient time behavior.

The fourth high-level QA that is considered key is compatibility. Our result suggests that 15% of reviewed architectures considers compatibility QA at a center stage of smart city platforms. The concept of smart city is centered around heterogeneous object exchanging some data, with each of these objects or components often developed by different vendors. Designing an architecture and implementing this architecture in a way that these heterogeneous objects interoperate is a major concern to smart city developers. Compatibility, specifically, interoperability is a critical attribute for all smart city applications, irrespective of city and domain of operation.

7. Conclusion and Future Work

This work reviewed existing smart city architectures with the goal of identifying quality attributes these architectures aimed to achieve. This is towards identifying and categorizing these QAs into high-level QAs and propose key minimum QAs that are common to all smart city systems, which is a step towards developing product-line architecture for these systems. We adopted the quality standard model of ISO/IEC 2510:2011 ("ISO/IEC 25010:2011(en), Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models," 2011) for categorizing QAs into eight (8) high-level attributes. We identified and proposed four (4) quality attributes as key and should be implemented in all smart city applications, irrespective of the domain of use. These attributes are Security, Portability, Performance Efficiency, and Compatibility. Security is a serious concern, this is because citizen's private and government's sensitive data

is integral part of smart city ecosystem, and ensuring security not only protect these data but also boost citizen's confidence in accepting smart city systems. Portability is widely considered a key quality attribute due to rapid and frequent change in the operation setting of smart city environment. Existence of wide range of devices, increase in data volume and rapid increase in users and applications in the smart city ecosystem are other factors that make portability a key attribute, irrespective of domain of operation. Performance Efficiency is considered due to reliance of sensors and other monitoring devices for data monitoring and processing, which is often in real-time. The need for efficient utilization of resources such memory space and bandwidth for efficient operation of these sensors and other components are additional factors that makes performance efficiency a key attribute in any operational domain of smart city systems. For the compatibility attribute, the heterogeneous nature of devices and components in the smart city makes it an important attribute for any smart city application. These devices often share data and communicate with each other and ensuring efficient coexistence and interoperability of these devices cannot be overemphasized, hence the need for any architecture to provide mechanism for achieving this quality attribute. This review is a step towards proposing a product-line architecture for smart city applications. The future direction of our research is to investigate the most appropriate architectural pattern for smart city applications, and using these results, we aim to develop a product-line architecture that could be adopted by developers and researchers in building smart city applications.

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Appendix 1: Detailed Data Items for Selected Studies

Paper ID	Paper Title	Publication Type	Publication Year	Aim of the Study	Focus of the Study	Quality Attributes	Obtained Results
PS-1	Smart Cities Software Architectures: A Survey	Conference	2013	Presents fundamental requirements that smart city architectures addresses	Surveys architectural projects in the literature with emphasis on the requirements they address	Functional suitability, performance efficiency, compatibility, reliability, security, portability, maintainability.	The study showed that no single architecture is applicable to all smart cities. But, each architecture should at least address the minimal set of requirements.
PS-2	A Conceptual Enterprise Architecture Framework for Smart Cities – A Survey Based Approach	Conference	2014	The aim is to identify QAs for smart cities, then propose an architecture that addresses the discovered attributes.	Pattern Driven Architectural Partitioning (PDAP) was applied for selecting appropriate architectural patterns that satisfies discovered quality attributes.	Interoperability, usability, confidentiality and authentication, availability, recoverability, and maintainability.	Conceptual architecture was presented based on architectural pattern that addresses identified quality attributes.
PS-3	Architectures and Requirements for the Development of Smart Cities: A Literature Study	Conference	2015	The aim is to discuss architectures and requirements that are in the literature and specify most useful ones in developing smart cities.	Focus is on existing software architectures and requirements in the literature.	Compatibility, Performance Efficiency, functional suitability and security.	Presented a set of requirements that reviewed architectures satisfies by categorizing these architectures into six (6) perspectives.
PS-4	A Requirements Framework for the Design of Smart City Reference Architecture	Conference	2018	The aim is to determine requirements for design of reference architecture for smart cities.	Focuses on exploring and defining set of requirements for standardization of reference architecture design for smart cities	Performance Efficiency, Functional Suitability, Compatibility, Security, Reliability and Portability.	The paper identified and proposed 12 “functional requirements” and 16 “non-functional requirements” that should be adopted by practitioners in designing reference architecture for smart cities.
PS-5	Software Platforms for Smart Cities: Concepts,	Journal	2018	The aim is to develop a reference architecture as a	Focused on analyzing 23 projects on smart cities emphasizing	Scalability, security, privacy, and interoperability.	A reference architecture was derived based on

	Requirements, Challenges, and a Unified Reference Architecture			guide for development of next generation smart city platforms	on most used technologies, functional and non-functional requirements, and classifying them in “cyber-physical systems”, “cloud computing”, “big data”, and “internet of things”.		identified technologies, requirement and challenges.
PS-6	IoT based Secure Smart City Architecture Using Blockchain	Conference	2018	The aim is to propose IoT architecture based on blockchain that is lightweight with respect to computation and resource usage, with decentralized security and privacy attributes.	Focus is on tackling security and privacy concerns with low computation and resource usage by adopting lightweight security measures including symmetric key cryptography in smart blocks.	Security, privacy, confidentiality, availability, authentication, non-repudiation, and integrity.	Lightweight architecture was proposed that is more suitable for smart agriculture applications and smart homes in comparison to existing literature.
PS-7	Blockchain and edge computing-based architecture for participatory smart city applications	Journal	2019	The aim is to develop novel blockchain and edge computing-based architecture for open and auditable governance with tightly coupled evidence-based communication mechanisms.	Focus is on utilizing blockchain technology for realization of open and auditable governance framework, as well as edge computing for realization of green smart technology by segregating districts and city level decision making.	Efficient citizen participation in data collection, storage and processing, transaction traceability and auditing, privacy and security.	Smart city architecture is proposed based on edge computing and blockchain. Smart citizen participation use case was used to develop proof of concept in evaluating the proposed architecture.
PS-8	Smart City IoT Platform Respecting GDPR Privacy and Security Aspects	Journal	2020	The aim is to design an IoT framework in response to a research challenge which identified several requirements identified as essential for modern smart city platforms.	Focus is on security and privacy related to design of Snap4City that is GDPR compliant.	Security, Privacy, Interoperability, Flexibility, Scalability, Open source, modularity and reliability.	The Snap4City architecture was developed and implemented. The solution addresses all challenges presented with special emphasis on security aspects.

PS-9	IoT Architecture for a sustainable Tourism Application in a Smart City Environment	Journal	2017	The aim is to propose an architecture of a platform for management of smart sustainable tourism.	Focus is on sustainable tourism operation with specific focus on Cagliari, Italy as a case study.	End-to end data privacy, authorization and access control, flexibility, remote device manageability, data virtualization, scalability, and reusability.	A Smart city platform was developed based on proposed architecture with evaluation conducted based on simulations of 67 points of interest, real transportation data and optimization algorithms.
PS-10	SmartGC: a software architecture for garbage collection in smart cities	Journal	2020	The aim is to present and discuss an architecture of a garbage collection System management application (SmartGC) based on the concept of artificial Transportation systems.	The main focus is on smart mobility perspective.	Portability, modifiability, data availability, security and access control, real-time and batch processing of data, and usability.	SmartGC platform was developed based on the architecture which was integrated into smart city agenda of Northeastern Brazilian city of Natal.
PS-11	Blockchain and IoT integrated Smart City Architecture	Journal	2021	The aim is to propose hybrid architecture for intelligent city using software defined network and blockchain technology.	The focus is on achieving low latency, reduced bandwidth usage, privacy and security.	Privacy, security, scalability, and performance efficiency.	The architecture was implemented and evaluated with a simulated data based on various performance metrics.
PS-12	Towards a Software Architecture for Internet of Things based System of Systems	Journal	2021	The aim is to propose novel architecture for IoT-based system of systems to achieve certain quality attributes	The focus is on combining microservice architectural styles and cloud computing for scalability, interoperability, maintainability and performance of smart city platforms.	Scalability, maintainability, Interoperability and Performance Efficiency.	The efficacy of the architecture was evaluated by implementing it using a case study based on scalability and maintainability attributes.
PS-13	Software Architecture for Smart Cities and Technical	Book Chapter	2019	The aim is to address dependability and reliability of	The study focuses on attack analysis and attack exposure	Dependability, Reliability, and data security.	The smart city platform was proposed based on the

	Solutions with Emerging Technologies' Internet of Things			smart city platforms.	framework for monitoring information sensitivity in smart cities		architecture for Oman.
PS-14	Design and Evaluation of a scalable smart city software platform with large-scale simulation	Journal	2019	The aim is to propose an architecture for microservice based and open source smart city platform named InterSCity.	The focus is on developing a platform the allows collaboration in development of large-scale applications, systems and services for city of the future	Flexibility, scalability, and performance efficiency	The InterSCity platform was implemented based on proposed architecture. Experiments were also conducted to evaluate scalability and performance efficiency.
PS-15	Smart city data architecture for energy prosumptions in municipalities: concepts, requirement, and future directions	Journal	2020	The study aimed at proposing architecture based on The Open Group Architecture Framework for efficient energy data distribution and storage to support prosumptions of energy in smart city building and electric vehicles.	Focus is on leveraging open data to support interoperability among components.	Interoperability, open and real-time time prosumptions.	Case study was used by implementing smart city platform based in proposed architecture for evaluation.
PS-16	Big data driven multi-tier architecture for electric mobility as a service in smart cities: A design science approach	Journal	2020	The aim is to propose multitier smart city architecture that supports collection, processing analysis and use of mobility data.	Focus is on using Application Programming Interface to enable interoperability among infrastructure that is needed for Electric mobility as a service (eMasS).	Interoperability, flexible processing of real-time and historic data.	Case study was used in evaluating the proposed architecture.