A Unified Reference Model for Smart Cities

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Abstract. Smart city is a multi-faceted concept perceived in many different perspectives. Cities are multidimensional and highly complex interconnected systems of people, software, machines, and data, bringing new design, construction, and operational challenges. Work has been done on models and reference architectures for smart cities that can help to cope with those challenges. However, also because of the variability of concepts, arrangements of key components, and technology heterogeneity, a unique and universal smart city reference architecture for real world deployment is distant. This paper attempts to clarify the meaning of the concept smart cities, trying to reveal its mostly accepted dimensions and the best arrangement between them. Through an in-depth literature review of relevant studies from academia, international organizations, corporations, and standards development organizations, that gathered and analyzed contributions ranging from smart cities definition attempts and enunciations of their relevant dimensions, to already existing models and urban platforms, the paper proposes a classification for grouping the identified smart cities dimensions, exposed on a unified reference model for smart cities.

Keywords: Reference model · Reference architecture · Framework · Smart cities

1 Introduction

Cities are multidimensional and highly complex interconnected systems of people, software, machines, and data. Systems with this high level of complexity have been studied from diverse perspectives and are referred to by numerous different designations: system of systems (SoS) [1]; cyber-physical systems [2, 3]; cyber-physical-social systems [4]; socio-technical systems [5]; and multi-scale systems [6].

Besides smart cities have attracted extensive and emerging interest from both academia and industry with an increasing number of international examples emerging from all over the world, there is no unique and consensual definition for what constitutes a smart city, though the most common characteristic among all definitions is the strong recurrence to Information and Communications Technology (ICT).

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These emerging complex, interactive systems that constitute the cities ecosystem bring new design, construction, and operational challenges. A significant challenge of these types of evolving projects related to the improvement of the quality of life for cities, is how to manage complexity, including interoperability, in a SoS with many continuously changing components.

If there is still no single definition of what a smart city is, even less is there a unified reference model, a description of the basic arrangement and connectivity of the parts of the city. Still is missing a complete broad overview and skeleton of the interlinked items, which might constitute an all-encompassing architecture that provides guidance, design patterns, common vocabulary, and enables an end-to-end information flow, lowering barriers to interoperability, thereby enabling stakeholders of smart city projects to perform more and faster implementations.

The infrastructures of a city were often developed and provided through stand-alone (silo-vertical) systems. Enhance smart service interworking across domains in combination with data analytics is required to leverage the opportunities of digitalization. Current architectural standardization efforts have not yet converged, exhibiting a lack of consensus on a common language/taxonomy and architectural principles. The interworking across multiple urban infrastructures requires a coordinated approach avoiding that the different management systems are all dealing independently.

Dedicated domain specific systems are still required to operate the related urban infrastructures, thus such urban systems need to follow an open design approach, e.g. with open interfaces, supporting open standards for exchanging urban data and supporting new urban services extending the scope of the Smart City services over time by an increased use of digitalization. To provide this SoS like approach it requires interoperability on all levels as a core principle.

A reference architecture provides this common framework around which more detailed discussions can center. By staying at a higher level of abstraction, it enables the identification and comprehension of the most important issues and patterns across its applications in many different use cases. A universal and unified model would be important to take into not only the merging of those models and architectures into a single one by eliminating overlaps and clarifying their core part, but also for combining models and architectures specialized characteristics respectively for particular domains to fulfill diversified expectations at different levels. A unified smart city reference architecture will contribute to alleviate real-world deployment of smart cities, bringing notorious advantages like interoperability assurance, integration facilitation, reuse, risk reduction, better quality, and knowledge transfer.

Besides there is no single definition for smart cities, neither a single global and unified reference model, several models for understanding and conceptualizing smart cities have been developed, which aim to define their definition, scope, objectives, benefits, and architectures.

The aim of this paper is to analyze the existing smart city modelling approaches, ranging from conceptualization to the notorious cases of realization, contributing to the definition of the components that must be part of such models. First, the benefits of a reference model for smart cities are presented; next, it describes the literature research and analyses the gathered dimensions for smart cities proposing a twofold classification for grouping the technological and non-technological dimensions; finally, it proposes a smart cities reference model based on that classification and the degree of acceptance of each dimension.

2 Reference Models, Frameworks, and Architectures

Models are abstractions of reality representing views of reality and, thus, allowing its users to focus only on the needed characteristics of the modelled reality. Models can minimize the complexity of reality they represent by including representations understandable and more easily handled by humans or machines. Models are also used to transfer pieces of knowledge between reality domains, namely from one organization into another, sharing a set of characteristics.

A conceptual model provides a common structure and definitions for describing the concepts of, and relationships among, the entities within systems.

A reference model is an abstract and easier to understand representation of a phenomenon in the world that is used or usable for reference, almost constituting a standard for. Reference models are abstract in the sense that they do not represent a particular phenomenon or organization.

An architecture is a description of the basic arrangement and connectivity of parts of a system (either a physical or a conceptual object or entity) [7]. The software engineering community considers that architecture is the fundamental organization of a system embodied in its components, their relationships to one another and to the environment and the principles guiding its design and evolution [8]. It is a set of conventions, rules, and standards employed in a system's technical framework, plus customer requirements and specifications, that the system's manufacturer or a system integrator follows in designing, or integrating, the system's various components (such as hardware, software and networks).

A reference architecture provides guidance for the development of system, solution and application architectures. It provides common and consistent definitions in the system of interest, its decompositions and design patterns, and a common vocabulary which allows to discuss the specification of implementations so that options may be compared [9].

A framework can be understood as a broad overview, skeleton, or outline, of interlinked items which supports a particular approach to a specific objective, and serves as a guide that can be modified as required by adding or deleting items.

The identification of proposed reference models for smart cities in literature, has led to consider all these terms and concepts which although conceptually can be distinguished, are closely intertwined and are together mentioned regarding the benefits and consensus around the necessity of such a definition of an all-encompassing high-level abstraction of architecture patterns and descriptions for the cities ecosystems.

The development and use of a general framework helps to identify the elements and relationships among these elements that one needs to consider for analysis [10]. A unifying high-level abstraction of these architecture patterns and descriptions has obvious benefits, since it provides common and consistent definitions, patterns, and a collective vocabulary, that facilitates easy sharing experience and know-how in designing, implementing and operating the systems [11, 12], in a way that encourages reuse of common system building blocks [11, 13], reduces the risk through the use of proven and partly prequalified architectural elements [11], provides better quality by facilitating the achievement of quality attributes [14], and contributes to the overall interoperability of the different systems [11, 13].

3 Reference Models for Smart Cities

When trying to identify proposed reference models for smart cities in literature, other terms and expressions that, more or less, refer to the same concept, must be perceived. That is the case of frameworks and reference architectures. The terms are really much intertwined as shown in the previous section.

Furthermore, they are subject to some misuse and lack of rigor. Although under the designation of architectures or models, some of the identified contributions are not proposing what can be considered an architecture, a reference architecture, a framework, or even a reference model for smart cities, but just describing an architecture of an ICT platform for cities, or the platform itself, particularly an open urban platforms (OUP), or even the simple depict of dimensions to consider in a city's ecosystem.

Rather than following a rigid systematic review methodology, this experience suggested that a more useful approach might involve a mixture of compliance and flexibility. Compliance with the broad systematic review principles of rigour, transparency and replicability, and flexibility to tailor the process towards improving the quality of the overall findings. We intended to increase the breadth of the research including urban platforms, and also works pointing out dimensions and components, most of them societal that need to be considered in a Smart City ecosystem.

Proposals of elements and their relationships to integrate on an overarching reference model for smart cities could come from diverse propositions, like obviously, already existing models for smart cities, but also from urban platforms, either working on practice or only conceptually projected, and even smart cities definition attempts, and enunciations of their relevant dimensions. Altogether, definitions of smart cities, models, and platforms, indicate the scope, the concepts, and the dimensions involved in smart cities.

Literature was surveyed not only about reference models, architectures, reference architectures, and frameworks for smart cities, but also searching for urban platforms, definitions, core concepts, attributes, indicators, key-performance indicators (KPI), and requirements for smart cities.

We surveyed literature using as sources SCOPUS and Google Scholar. Article search was performed since the year of 1997, the appearance of smart city concept, to early 2019. Works from government initiatives including EU, international organizations, corporations, and standards development organizations, were also taken into account. Screening citations on the examined articles left space for further exploration of papers missed in the initial search.

Besides recognizing that models and platforms can further contribute than the simple enunciations of dimensions, many of the latter were included on the evaluation through a selection process subject to the inherent subjectivity due to the particular appreciation we made about the validity and originality of the proposals. A total of more than forty contributions from literature were selected as proposing a reference architecture, a reference model, an urban platform, a set of KPI for cities, or at least a set of city dimensions.

3.1 Smart Cities Dimensions

Many authors dedicated work to point-out dimensions, domains, planes, process fields, viewpoints, and drivers for smart cities, in which, for standardization and simplification of concepts will be identified from now on as dimensions.

Anthopoulos [15] performed a literature review and identified seven major smart city dimensions. Giffinger et al. [16] identified six smart city characteristics. Glebova et al. [17] defend that the smart city concept can be divided into five constituent parts. Hancke et al. [18] advocate seven sensor areas in a smart city. Mahizhnan [19] identified four key dimensions of a smart city, defined for the Singapore Intelligent Island. Eger [20] defends four key dimensions of a smart community. Thuzar [21] advocates other different four key dimensions for a smart city. Barrionuevo et al. [22] identified five types of capital that contribute toward a city's intelligence. Kourtit and Nijkamp [23] argue that smart cities are based on a promising mix of four types of capital. Fromhold-Eisebith [24] based on the categorization of process fields that constitute a smart city made by several scholars and added further her own urban arenas proposing eleven fields that have the potential for CPS-driven processes. Neirotti et al. [25] advocate six smart city domains, which in turn include some subdomains. Albino et al. [26] sought the dimensions advanced by various scholars of the phenomenon and identified the four most common characteristics emerging from them.

The International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) Focus Group on Smart Sustainable Cities [27] identified also another group of four core themes related to smart cities. De Oliveira Fernandes et al. [28] advocate three levels of city smartness for city authorities' actions. Lee et al. [29] conducted a research study that identified six key conceptual dimensions and 17 subdimensions of smart city practices that form a theoretical foundation for classification of practices. And finally, the United Nations (UN) Habitat [30] identified five dimensions of city prosperity.

3.2 Models for Smart Cities

More interlinked approaches to the smart cities core concepts and requirements can be seen in what can be considered a model or equivalent. Desouza and Flanery [31] stated a model with five city components divided between physical and social spheres. Nam and Pardo [32] introduced a representation of smart cities with the three key factors: human, institutional and technological, applied to theirs more than six, key dimensions. Chourabi et al. [33] presented a framework with five outer and three inner factors that explains the integration of technology, organization and policy.

CISCO Systems Inc. [34] envisioned a smart city framework with four layers, a decision methodology that enables both the public and private sectors to plan and implement smart city initiatives more effectively. International Business Machines (IBM) [35] introduced the technological functionalities of a smart city and highlighted the role of the ICT infrastructure and the information services stating a theory founded on two main assumptions: the city is based on nine main pillars organized in three major categories, with each category pillar being an individual system and the city seen as a SoS; and IBM's '*3 Is Equation*' where the smarter city is the result of instrumentation, interconnection of data, and intelligence brought by software. Naphade et al. [36] also have a SoS perspective with a set of seven interdependent public and private systems that the city can integrate and optimize.

Leydesdorff and Deakin [37] proposed a neo-evolutionary perspective of the Triple-Helix model for smart cities and Lombardi et al. [38] come up with also a revised version of the triple helix model, for smart cities, as always, based on networks of universities, industry, and government, that proposes a novel framework for analysis and performance measurement.

Liu et al. [39] advocate a smart city value chain model with primary and supportive activities. Edvinsson [40] envisioned the city as a knowledge tool model. Yovanof and Hazapis [41] conceptualized the digital city architectural framework for smart service provision with three main dimensions. Zygiaris [42] introduced his smart city reference model in a form of a multi-tier model with several components and entities that smart city planners could use to define the conceptual layout of a smart city and describe the smart innovation characteristics. The Spanish standard [43] has five smart cities layers in a structure devoted to assuring Open Urban Platforms (OUP) interoperability requirements. Abu-Matar and Mizouni [44] multiple-view smart city reference architecture meta-model has nine views interrelated with each other, where the cyber views run and control the physical views. Batty et al. [45] defend the structure of FuturICTs Knowledge Accelerator smart city program that organize smart cities research directions into seven distinct but overlapping areas. Anthopoulos et al. [46] propose a unified smart city model that identifies six major dimensions on literature and discovered eight conceptual models of viewpoints that address smart cities.

Yin et al. [47] state a smart city architecture proposal with four general layers and two planes based on what they observed in literature, a data-centric and multidisciplinary smart city. Santana et al. [48], based their analysis of several urban platforms and architectures and derived a novel reference architecture for software platforms for smart cities with four technological levels and an additional all-encompassing security vertical tier. Also Silva et al. [49] synthesize the commonalities of most of the works they have analyzed in a four layers architecture for a generic smart city, with a key concern on sensitive data protection.

Elhoseny et al. [50] performed an elicitation of requirements and capabilities for the ideal smart city service-oriented architecture (SOA) framework, proposing one of their authorship. Clement et al. [51] propose a reference architecture for smart cities incorporating the viewpoints of the traditional city infrastructure, services and business roles. The authors augment the traditional city architecture layers of environment, infrastructure, logistics and human elements, with a computing infrastructure based around SOA principals, traversing these computing elements and business roles across several levels of city architecture from the utilities through to the service provisions.

The smart cities model advocate by Clement et al. [51] is expected to utilize simulation so that the system can predict future outcomes and react accordingly.

ISO 37120 [52] defines and establishes methodologies for a set of indicators (a quantitative, qualitative or descriptive measure) to steer and measure the performance of city services and quality of life. The indicators are structured around seventeen themes. Recognizing the differences in resources and capabilities of cities worldwide, the overall set of indicators for city performance has been divided into core indicators (mandatory) and supporting indicators (recommended).

The ITU-T performed a components analysis for a smart sustainable city and derived a modular Smart and Sustainable Cities (SSC) ICT architecture approach [53] with six sub-systems organized in modules. For almost all the modules, a hypothetical assignment of standards is presented.

The International Electrotechnical Commission (IEC) city model presented in [54] synthesizes a set of city characteristics where smartness is applied. City subsystems surrounded by environmental context, city history and characteristics, societal context, and city governance.

ITU-T [53] and Anthopoulos [55] propose a generic multi-tier ICT meta-architecture for smart and sustainable cities (SSC) consisting of five layers (natural environment, hard non-ICT infrastructure, hard ICT-infrastructure, services and soft-infrastructure). The architecture meets existing standardization efforts [52, 56], and more specifically UN Habitat KPIs [57], can accordingly be the baseline for smart city standardization.

National Institute of Standards and Technology (NIST) and some international partners, convened an international public working group to compare and distil a consensus language, taxonomy, and framework of common architectural features for smart cities. First version of the IES-City Framework (Internet-of-Things-Enabled Smart City Framework) was recently released [58] introducing a reference framework for the development of architectures for incremental and modular smart cities. The framework provides the tools to evaluate the breadth of functional requirements, assess the readiness of the municipality infrastructure, and measure the benefits to the citizenry.

The ESPRESSO H2020 project [59] produced a smart cities reference architecture with three vertical layers formed by groups of services, and six horizontals layers topped by two services consumer layers for respectively, sectorial specific businesses and city stakeholders.

The ESPRESSO reference architecture joined with the results of the European Innovation Partnership on Smart Cities and Communities (EIP SCC) urban platform initiative, were on the basis of the German standard [60] for a reference system architecture of an open urban platform (OUP), with its multi-layered approach where each capability cluster is represented by a single layer, and three priority vertical areas.

3.3 Urban Platforms

It is also possible to identify the most recurrent components in existing OUPs. City Data and Analytics Platform (CiDAP) [61] is an analytics platform deployed into the SmartSantander testbed. The system architecture of CIDAP has four main modules and three layers. Modules to collect, store, process, intensive process and perform analytics to data, along with a CityModel server responsible for interfacing with external applications.

OpenIoT is an IoT platform used by the Vital project, with three planes: physical, virtualized, and utility-app [62]. Sii-Mobility architecture [63] is presently in place in the

Tuscany area. Is an evolved solution of the semantic aggregator and reasoner architectural pattern with two components: a semantic aggregation & big data processing based on the Km4City Ontology, and a smart city API.

The Open Machine Type Communications (Open-MTC) platform is an IoT/M2M middleware [64] with a backend assuring several functions and several gateways for vertical domains. The Fiware platform [65] provides a set of APIs that ease the development of smart applications in multiple vertical sectors, with its library of generic enablers.

4 Discussion

From the analysis of the above contributions, it was realized that there is a great variety in the way the elements of the smart cities models and the various dimensions perceived as intervening in the complex ecosystem of smart cities, are designated, and even enunciated. E.g., all the thematic dealing with the mobility of persons and goods in a city is designated in smart cities literature in several ways, like ‘transportation’, ‘smart mobility’, ‘smart transportation’, ‘intellectual transport system’, and ‘sustainable urban mobility’.

In addition to this taxonomic topic, the models do not agree on the same set of dimensions, and this is immediately visible in the more conceptual models that almost exclusively include human and institutional dimensions. If we observe the layers or tiers that constitute the more technological models, this scenario is even more evident, with a great diversity of ICT components with their functionality and designation.

Though there is abundant literature available on smart cities, there is no standardized and commonly accepted set of terminologies to aptly identify a set of univocal dimensions that a smart city must take into account. Given the lack of standardized terminologies, a comparative analysis was performed to map and compare the designations and definitions of the various smart city dimensions and organize the results to reveal commonalities and consensual dimensions. This section presents a study of the dimensions associated to smart and sustainable cities.

For this purpose, several papers were collected from academic literature, as well as reports and articles from other databases. These sources were reviewed and analyzed to help consolidate a wide range of dimensional perspectives of smart cities. These dimensions were obtained from a variety of sources comprising academic and research communities, government initiatives including EU, international organizations (like United Nations, ITU, European Commission, etc.), corporate/company profiles, and standards development organizations, briefly exposed in the previous section.

More than forty sources of proposals about the components or dimensions to be considered for a smart city were analyzed. All sources were scrutinized and a spreadsheet was used to collect the dimensions indicated by each one, what facilitated the subsequent aggregation.

The decomposition operated for the dimensions pertinent to the overall ecosystem of smart cities, showed a total of one hundred and one (101) dimensions, even after some depuration obtained from eliminating evident synonyms and aggregating obviously similar dimensions.

To sort and group all dimensions found, dimension categories have been defined. These categories were established taking into consideration the classification of Nam and Pardo [32] and Lea [66], that arranged the components of smart cities in three major aspects: institutional, human, and technological.

Some dimensions cross several boundaries just like Nam and Pardo [32] and Lea [66] conveyed in theirs overlapping classifications, so, two more categories were taken into account with purposes of univocity and intended and casuistic specialization: city component-related aspects, and environmental aspects. So, all the viewpoints of what a smart city is can be segmented into the following categories:

– **Human** viewpoint - pertains to human infrastructure and social capital, involving education and governance, lifestyle, historical legacy, culture, recreation, economics, finance, social equity, engagement, laws, division of power, and politics.
– **Institutional** viewpoint - relates to institutions, governance, government, policy, regulations/directives, planning, procurement, safety, emergency response, security, healthcare, city infrastructure.
– **Technological** viewpoint - concerns all topics related to ICT, namely software, mobile and virtual technologies, and digital infrastructure and networks.
– **City Component-related** viewpoint - is used to denote cities specific resources and processes like transportation, hard infrastructures, buildings, waste management, water, energy, and some city functions and services in general.
– **Environmental** viewpoint - indicating environmental management, protection, and sustainable usage.

This classification provided the first grouping level and more noticeable than the five categories is the underlying distinction between technological dimension and all the others. Each non-technological dimension perceived in literature was uniquely identified as belonging to one of the categories above, although ambiguity occurred for some of them.

A second grouping level would have to detail this segmentation, particularly for the yet not segment technological dimensions. TOGAF [67], the Open Group standard for enterprise architecture includes four different architectural domains, which are accepted as sub-sets of an overarching enterprise architecture. A complete enterprise architecture should address all four architecture domains: data, application, and technology architectures that build on the business architecture. An "enterprise" is any collection of organizations that have common goals. Could be partnerships and alliances of businesses working together, such as a consortium or supply chain.

The purpose of enterprise architecture is to optimize across the enterprise the often fragmented legacy of processes (both manual and automated) into an integrated environment that is responsive to change and supportive of the delivery of the business strategy [67]. An intent that is not far from the main objective of smart cities if we take strategy in a much broader sense than just the business.

This paper's proposed aggregation and classification of the technological smart cities dimensions identified in the overall literature, used the TOGAF architecture domains and influences from the OSI reference model [68] suggesting the following categories:

Type A – Consumers (include any smart city stakeholder who wishes to interact with and consume smart city services) and the business services themselves which are demanded from the non-technological smart cities dimensions. Represents the application and presentation levels of the OSI reference model and are contained in the TOGAF application architecture domain, but also in some extent, in the business architecture domain.

Type B – Includes data services for data management, processing, exploitation and dissemination capabilities, and the software applications that manipulate that data, to support the forth Type A application and business services. Modelling & Analytics, Integration, Data Management, Reporting, Visualization, Systematization, Choreography and Orchestration, Technology and Supporting Services (Transaction Management, Orchestration, BI, Collaboration). Represents the TOGAF data architecture domain.

Type V – Supporting and common services. Some layers shall be 'vertical' as they cut across various other layers within the overall architecture. E.g. sensitive data protection is a key concern, thus security modules shall be integrated into each layer.

Type C – Includes communications, network & transport capabilities. Represents the TOGAF technology architecture domain and the session, transport, and network levels of the OSI reference model.

Type D – Includes the operation and management of physical devices, sensors, actuators. Represents the TOGAF technology architecture domain and the data link and physical levels of the OSI reference model.

5 Proposed Reference Model

Given the various contributions, definitions and the 100+ dimensions or layers for a smart city, there was a need to perform some more in-depth analysis to determine what would be a comprehensive and inclusive proposal of a smart city reference architecture.

In the above literature survey, there are divergent visions of smart city architectures. Through these different expressions, we can still find some common characteristics, evidenced by the way they were grouped in the categories described above.

The need to have a second level of grouping for non-tech dimensions, such as the classification presented in the previous section for the technological ones, led to sort all these dimensions taking into account their similarity. Therefore, groups become apparent.

Excluding the technological components addressed below, we identified thirteen main dimensions in the literature (the most referred to), which although mentioned by different designations as shown in Table 1, fairly represent the same principles and seem more than consensual given the profusion of citations.

The number of times each dimension is referred to in the selected literature is presented in parenthesis and contributes to the perception of which dimensions are considered as most important and inescapable. The table shows the exact designations used by the selected scholars and professionals, to the right of the aggregating designation that represents them.

Outside of this unification attempt were placed dimensions that occurred seldom, such as innovation, only advanced by Zygiaris [42] that dedicates to the cities' fertile innovation environment with new business models and opportunities pushed by the emerging technologies, an entire layer in the top of his smart city conceptual reference model. However not itemize as an individual dimension, this aspect is not forgotten by the rest of the authors that prefer to spread it over the remaining dimensions.

Table 1. Non-technological dimensions

Dimensions	Alternative designations and sub-dimensions
Government and Governance (17 + 2)	Government [15, 25, 33, 35, 39, 42, 52, 54]; Smart governance [16, 24, 46]* [59]; Government services [36]; e-Government [53]; City governance for the smart city & decision support and participation [45]*; *sub-dimensions*: Urban planning [52]; Smart procurement [39]
Economy and Business (17 + 3)	Economy [15, 25, 33, 52]* [46]; Smart economy [16]; Economic development [20]*; Sustainable economic development [21]; Economic capital [22]; Socio-economic development [58]; Urban economics and commerce [60]; e-Business [53, 59]; Intelligent services layer [43]; Domain application layer [47]; *sub-dimensions*: Job growth [20]; Finance [52]; IT economy [19]
Transportation (16)	**Transportation(16):** Transportation[15, 25, 35, 36, 46, 51, 52, 58, 59]; Smart mobility[16, 24]; Smart transportation [18, 32, 53]; Intellectual transport system [17]; Sustainable urban mobility[60]
Environment (15 + 10)	Environment [25, 26, 33, 35, 38, 46, 51, 52, 54, 59]; Smart environment [16, 32]; Environmental capital [22]; Smart metabolism [24]; Green city layer [42]; *sub-dimensions*: Environmental protection [17]; Smart consumption [24]; Solid waste [52, 58]; Waste management [53]; Water and sanitation [52, 53]; Water and wastewater [58, 59]
People (13 + 3)	People [25, 26, 33, 46, 51, 59]; People (social) [31]; Smart people [16]; People - human factors (learning) [32]; Human capital [22, 23]; Actors [54]; Civil society [38]; *sub-dimensions*: Entrepreneurial capital [23]; Society and entrepreneurship [40]; Coherency [15]
Urban infrastructure (11)	Urban infrastructure [15, 33, 35, 42]; Smart infrastructure [18, 26, 39, 51]; Infrastructural capital [23]; Infrastructure [54]; Integrated infrastructure & processes [60]
Safety and Security (11)	Smart safety [32, 52, 53, 59]; Public safety [35, 36]; Public safety policing and emergency response [58]; Public security [17, 60]; Smart security [24]; Smart surveillance [18]
Smart Buildings (10)	Smart buildings [18, 25, 35, 53, 59]; Smart construction [24]; Shelter [52]; Facilities and buildings [54]; Built environment [58]; Sustainable district and built environment [60]

(*continued*)

Table 1. (*continued*)

Dimensions	Alternative designations and sub-dimensions
Energy (10 + 3)	Energy [25, 46, 51–53, 58, 59]; Smart energy [24, 32]; Energy consumption management and control [17]; *sub-dimensions*: *(paired with Water)* Smart electricity and water distribution [18]; Energy and water [35, 36]
Healthcare (9)	Healthcare [36]; Smart healthcare [18, 32, 53]; Health [46, 52, 58, 59]; Health and welfare [60]
Institutions (8)	Institutions [31]; Community - institutional factors [32]; Institutional capital [22]; Activities [54]; Social capital [22, 23]; Societal context [54]
Education (8 + 3)	Education [36, 52, 53, 58–60]; Smart education [24, 32]; *sub-dimensions*: University [38, 40] IT education [19]
Smart Living (8 + 3)	Smart living [15, 16, 25, 38, 46]; Quality of life [19–21]; *sub-dimensions*: City history & characteristics [54]; Recreation [52]; Knowledge cafes/cathedrals [40]

Almost forgotten seems to be the Industry subject. Only three works from the ones selected defend a smart industry dimension in the context of smart cities. Leydesdorff and Deakin [37] and Lombardi et al. [38] in the scope of their evolutionary perspectives for the triple-helix model for smart cities, and Fromhold-Eisebith [24] that considers the industry an obvious process field for the potential use of CPS-driven processes. Factories have their existence in cities, at least in the broader concept of cities adopted by smart cities, best embodied by regions or territory, and share many resources and restrictions with cities. ICT has the exactly same role in smart cities and initiatives aiming digital industries, conducting factories to the fourth industrial revolution, like Platform Industrie 4.0 [69], Industrial Internet Consortium (IIC) Industrial Internet [9], and NIST Smart Manufacturing [70], behaving has a key factor and acting as an enabling technology. For production and manufacturing in industry and also to assure an integrated city, ICT is a tool, not an end in itself. Noticeable key information that needs to be shared between factories and smart cities are for example traffic, energy needs, energy consumption or waste-handling. This survey shows the failure to perceive and establish an explicit link between these two domains that are not even disjointed, but overlapping.

Table 1 shows only the non-technological dimensions. ICT is one additional and inescapable dimension of smart cities. According to the particular classification of technological layers discussed in the previous section, that incorporates influences of TOGAF [67] and the OSI reference model [68], all layers proposed by the studied reference models, architectures, and platforms for smart cities were identified and organized by type in Table 2, that displays each proposed technological layer identified by its original designation and in-text citation.

Table 2. Technological dimensions grouped by type

Type A Dimensions
Applications [48], Application Layer [43, 49, 50, 59], Applications (ICT) [53], Services and Business (ICT) [53], External Applications [61], Application View (Cyber) [44]
Business Process View [44], Business Roles Viewpoint (Management, Integration, Operational) [51]
Smart City API [63], Utility-App Plane (Request Definition, Config & Monitor, Request Presentation) [62]
Stakeholder Engagement & Collaboration Capabilities [60]
City/Community Specific Capabilities [60]
User Interface [43], Presentation Layer [50]
Gateways (Protocol Adapters) for Vertical Domains [64]
Type B Dimensions
Service View [44], Middleware [48], Services Viewpoint [51], Common Data and Service Layer [47]
Open Integration Layer [42], Integration Layer [50], Integration, Choreography and Orchestration Capabilities [60], Generic City/Community Capabilities [60]
Integrated Databases Management [45], Management (ICT) [53], View Planning and Management [46]
Data [43] Data Management Layer [49], Data Services [59], View Data & Knowledge [46], Data View [44]
Data Management & Analytics Capabilities [60], Data Analysis and Modelling [45], Analytics View (Cyber) [44], Analytics and City Model Server [61]
Data Collection (IoT Broker and IoT-Agents) [61], Semantic Aggregation & Big Data Processing [63], Data Vitalization Layer [47], Data Context Broker [65]
Data Storage (Big Data Repository) [61], Big Data Management [48], Data Processing (Intensive Big Data Processing) [61]
Virtualized Plane Cloud and Big Data (Linked Stream Middleware, Scheduler, Service Deliver & Utility Manager) [62], Backend (Connectivity Management, Data Management, Authentication & Authorization) [64]
Type V Dimensions
Security [48], Privacy & Security Capabilities [60], Security Services [59], Security & Authentication [47]
Technology Services [59]
Supporting Services [43, 59], Common Services Capabilities [60]
Development Toolkit [48]
Type C Dimensions

(*continued*)

Table 2. (*continued*)

Interconnection Layer [42], Communications, Network & Transport Capabilities [60], Transmission layer [49], Cloud and Networking [48]
Device Asset Management & Operational Services Capabilities [60], IoT Backend [65]
Positioning Services [59]
Type D Dimensions
Sensing Layer [49], Field Equipment/Device Capabilities [60], Sensor/Actuator [43], Sensing Services [59], Physical plane IoT (Sensor Middleware) [62], Instrumentation Layer [42], IoT Edge (inc. IoT Gateways) [65]
Data Acquisition Layer [47, 50]
Infrastructure View (Physical) [44]
Place View (Physical) [44]
Participant View (Physical) [44]

After this thorough analysis of multiple existing models and architectures, we derived the unified reference architecture illustrated in Fig. 1, conjoint with a majority of proposed works. The figure illustrates the dimensions grouped in the categories human, institutional, city-component related and environmental, having a proportional dimension to their popularity in the literature studied, and supported by the ICT layers according to the classification justified above.

The non-technological dimensions appear on the top of the reference architecture as columns and in their role of consumers of the technological services provided below by the technological layers. This dimensions are grouped according to the viewpoints previously presented and which were derived and extended from Nam and Pardo [32] and Lea [66]. The chosen color gradation denotes this categorization. The number of times each non-technological dimension is referred to in the selected literature, as computed in Table 1 arises as the height of the respective column in the figure and denotes the relative importance and inescapability of each dimension.

At the bottom of the reference architecture appears the technological viewpoint. Each level or dimension provides services to the level immediately above. The exception and the reason for being a vertical and all-encompassing level in opposition to the others is the ICT Level V responsible for supporting and common services for all the remaining ICT levels.

Associated with each level is a list of the components derived from the dimensions aggregation illustrated in Table 2. Particularly, a component designation that could represent and identify the set of designations used in the literature for the similar dimensions that were arranged by row below each type. For instance, dimensions whose authors in the literature have designated as Applications, Application Layer, Applications (ICT), Services and Business (ICT), External Applications, and Application View (Cyber), are recognized as the component Applications inside ICT Level A.

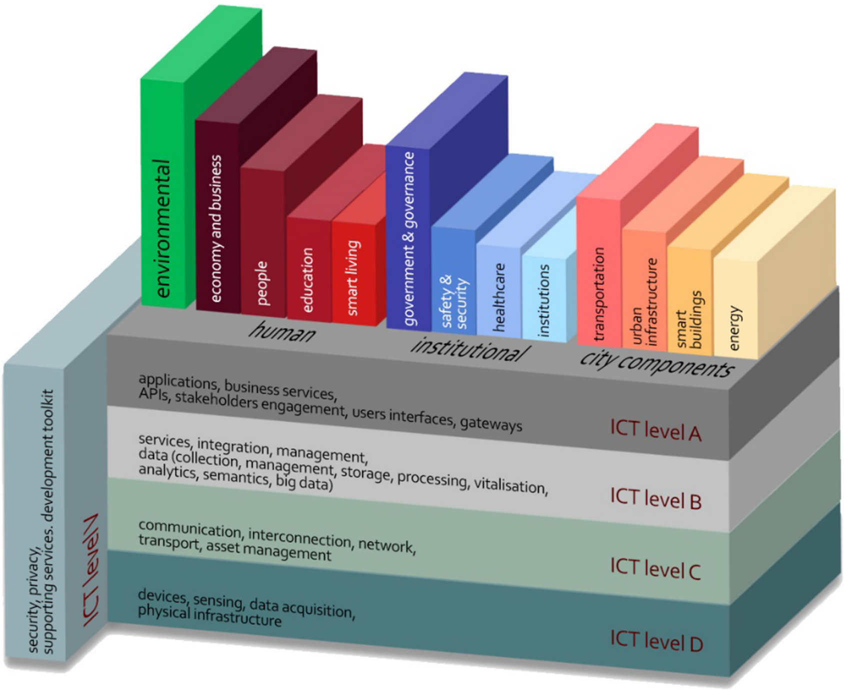

Fig. 1. Unified reference architecture for smart cities

6 Conclusion

This paper attempts to clarify the meaning of the smart cities concept, trying to reveal all its mostly accepted aspects. Researchers have been working on models and reference architectures for smart cities, in order to ease real-world deployment. However, also because of the variability of concepts and the various arrangements of key components for cities, a universal smart city reference architecture for real world deployment is far from reality, yet theoretically possible. Lack of consensus on a common language/taxonomy that begin with a multiplicity of names chosen for the dimensions involved, continues with the variety of the arrangements proposed for them, and ends in heterogeneous supporting ICT building blocks, lead to divergence on architectural standardization efforts.

This paper reviewed existing smart city modelling proposals, ranging from the more conceptual to the more technological, and synthesized them into a unified smart city reference architecture, contributing to the definition of the components that must be part of such models. The result is a set of dimensions organized by human, institutional, city-component related and environmental viewpoints, supported by a services provider five layers ICT framework.

The study shows that the overall vision of a smart city recognizes the growing importance of ICT as a core element and driver to foster smartness and the resulting sustainability and liveability of cities. ICT is inescapable in the smart cities ecosystem as services provider for the other dimensions. Although the variety of building blocks proposed to architect the overall ICT infrastructure of a city, the proper model to present these components is multi-layered, where each layer uses services from the lower level and provides services to the upper level. As an exception, some ICT supporting functions must be arranged vertically as they cut across various other layers within the architecture. The upper ICT layer must interface with the various domains of smart city stakeholders who consume these ICT services. The work presents these domains grouped in the categories human, institutional, city component-related and environmental and testifies their relative popularity and recognition, also denoting the importance that satisfying the requirements of each domain may have to achieve the ultimate goal of an increasing smart and sustainable city.

A critical remark and a perplexity when studying the contributions to this subject: a domain that, despite its importance, appears much neglected and outside the cast of the most mentioned - industry.

Although this work came to a reference architecture, the next suitable step could be to attain a truly reference model for smart cities, a yet easier to understand representation of the smart cities entire ecosystem that could be used or usable for reference, almost constituting a standard for. The reference model could extend this reference architecture providing the common semantics that can be used unambiguously across and between different implementations for the various smart cities domains.

Also as future research, we recommend studies that evaluate the incorporation of smart industry in smart cities, establishing similarities and realizing eventual common paths between smart cities and the current smart manufacturing initiatives that inhabit the same physical space and seem to have so many common purposes, resources and constraints. Moreover, an all-encompassing reference architecture is also currently pursued for digital factories.

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