RESEARCH ARTICLE

Smart city ontologies: Improving the effectiveness of smart city applications

Nicos Komninos*, **Charalampos Bratsas, Christina Kakderi and Panagiotis Tsarchopoulos**

URENIO Research, Department of Urban and Regional Development and Planning, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece

Abstract: This paper addresses the problem of low impact of smart city applications observed in the fields of energy and transport, which constitute high-priority domains for the development of smart cities. However, these are not the only fields where the impact of smart cities has been limited. The paper provides an explanation for the low impact of various individual applications of smart cities and discusses ways of improving their effectiveness. We argue that the impact of applications depends primarily on their ontology, and secondarily on smart technology and programming features. Consequently, we start by creating an overall ontology for the smart city, defining the building blocks of this ontology with respect to the most cited definitions of smart cities, and structuring this ontology with the Protégé 5.0 editor, defining entities, class hierarchy, object properties, and data type properties. We then analyze how the ontologies of a sample of smart city applications fit into the overall Smart City Ontology, the consistency between digital spaces, knowledge processes, city domains targeted by the applications, and the types of innovation that determine their impact. In conclusion, we underline the relationships between innovation and ontology, and discuss how we can improve the effectiveness of smart city applications, combining expert and user-driven ontology design with the integration and orchestration of applications over platforms and larger city entities such as neighborhoods, districts, clusters, and sectors of city activities.

Keywords: intelligent city, ontology, application, design, innovation, efficiency, impact

*Correspondence to: Nicos Komninos, URENIO Research, Department of Urban and Regional Development and Planning, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece; Email: komninos@urenio.org

Received: March 26, 2015; **Accepted:** May 26, 2015; **Published Online:** September 8, 2015

Citation: Komninos N, Bratsas C, Kakderi C, *et al*. 2015, Smart city ontologies: Improving the effectiveness of smart city applications. *Journal of Smart Cities*, vol.1(1): xxx–xxx. http://dx.doi.org/10.18063/JSC.2015.01.001.

1. Introduction: Smart City Applications and Search of Effectiveness

Intelligent and smart cities are created by a convergence of top-down and bottom-up processes, wherein market forces and strategic planning come together to build broadband networks, urban operational systems, embedded systems, and software, all of which change the functioning and life in cities. Nonetheless, bottom-up initiatives and the involvement of individuals and organizations are more than ever becoming dominant drivers of city making, mainly in building solutions and smart city applications without central planning and state control. The clustering of software applications that address urban needs marks a fundamental turning point in the making of cities, especially the making of intelligent cities, which rely on the creativity, digital skills, and learning processes that enhance the capabilities of their citizens.

Due to this open landscape, web and smartphone applications for smart cities are becoming increasingly important for smart city development. These applications are being created in increasing numbers by citizens, developers, city authorities, and companies. Smart city applications highlight the rise of a technologically adept popular culture and belief in the progressive role of technology. This social movement for creating and using applications is a great milestone in the making of intelligent and smart cities. It is sustained by software development toolkits, cloud platforms, content management systems, the compilation and re-use of existing software, open developers' communities, hackathons, and widespread digital skills, which together break down barriers to technology, reduce entry costs, and make smart city solutions available to any city, urban or rural community.

This culture in favor of smart city applications is clearly a movement of user-driven innovation and open business models within the wider landscape of open innovation[1,2], democratization of innovation[3], and digital disruption of innovation and entrepreneurship[4]. We have characterized this trend as "innovation for all", a condition which enables individuals and organizations to build their own innovation ecosystems within intelligent cities, smart environments, and virtual connectivity[5].

The plethora of smart city applications, created in an uncoordinated bottom-up manner, leads to the creation of smart cities by agglomeration. Somehow, the spontaneous urbanization process, which nurtured the growth of cities by the geographical concentration of people and activities, has begun to replicate. As in the case of spontaneous urbanization, smart cities created by the agglomeration of applications have no clear structure, and when the structure exists, it appears as a pattern emerging from chaotic behavior within complex systems.

The impact of each smart city application on the cities in question remains limited. Economic development and e-commerce, e-government and e-administration, and transportation and energy optimization are the domains most frequently targeted by smart city solutions. Detailed documentation on the impact of these solutions for cities is rare. However, many studies in the field of smart energy and intelligent transportation systems have recorded only a limited improvement of cities through individual applications and smart solutions. Given that cumulative effects are absent, due to low structuring and the complementarity of applications, the overall impact of applications remains limited, falling short of expectations of radical change for cities through digital technology.

For example, Amsterdam Smart City (ASC) is among the best showcases of smart city projects, applications, and solutions globally, and yet its measured impact is low. ASC was initiated in 2009 by a consortium of public and private organizations (including Amsterdam Innovation Motor, Liander, Amsterdam City, and TNO) with projects and social experiments enhancing sustainability in the fields of living, working, mobility, and public space. In the years that followed, ASC expanded into new fields and now covers eight domains of city life, with 43 current and 29 completed projects[6]. The overall Climate Programme of the City, in which ASC is a key component, aims to make all municipal organizations' climate impact neutral before 2015, and reduce CO_2 emissions by 40% with respect to the 1990 baseline by 2015. ASC aims to contribute to these targets by reducing energy use by at least 14% and reducing CO_2 emissions by an equal amount. Yet, the individual projects, applications, and solutions all fall short on these goals[7]. In the Geuzenveld neighborhood, 500 homes have been provided with smart meters, some of them with displays to enable users to be more aware of energy consumption, and energy-saving practices are discussed at brainstorming sessions. However, the energy savings per household was only 3.9%. In the West Orange project, 400 households have been provided with smart meters and displays that make it possible to see the energy usage per appliance, and a personal energy-saving goal was set for every household. Energy saving per household was only 7.8%. In the ITO Tower pilot, the goal was to obtain insights by testing energy saving in a large multi-tenant office building, using smart-building technologies, smart plugs, and data analytics. At the first baseline measurement in April 2010, "the energy usage seemed to rise instead of decrease". Later, in combination with switching off lighting and appliances outside office hours, energy consumption fell by 18%. In the Klimaatstraat project's holistic concept focusing on public space, logistics, and entrepreneurial spaces, energy conservation in individual businesses was 9% and within public spaces was 36.5%. Overall, the first round of ASC projects "alone generate a projected saving of 12.1 kton, which is only 0.5%. That is not very much, but bear in mind that these are just isolated small scale testing projects. The 'realistically' scaled up projects have a potential to reduce 171 kton, which is 7% of the Amsterdam ambition. The full, even if unrealistic, potential of all projects combined is 50.5% of the ambition".

In the field of Intelligent Transportation Systems (ITS), the report of the urban ITS expert group provides valuable information about the impact of such systems and applications on cities. The City of Ghent, for example, has implemented a multimodal traffic management system integrating Variable-Message Sign (VMS) for traffic information, traffic light management, and parking guidance system. By this way, it has increased the speed of public transport by 5%, and increased the park and ride facilities by 10%. In Aalborg, the implementation of an adaptive traffic signal control system has resulted in an 8.5% decrease in travel time during peak hours, while the smoother driving pattern has led to a 2.45% decrease in fuel consumption. In Bologna, the combination of ITS with traffic restriction regulations has led to an even greater reduction of absolute traffic by 23%–32% and of particle emissions by 47%. In this case, the impact was mainly due to traffic restriction rules rather than the urban ITS. In other cases presented, ITS have led to better and more reliable public transport, increasing use by 1%–3% per year[8].

These impact assessments of smart city applications and solutions record gains of less than 10% on the baseline situation in the domains of energy savings, CO_2 and particle reduction, and traffic improvement. However, low impact is not solely observed in these areas. Economic gains and the development of the knowledge economy within European smart cities vary considerably and in many cases are equal to or below the EU-27 average[9]. Such levels of improvement are somewhat disappointing compared with the ambitious targets and expectations surrounding smart city solutions, multi-billion estimates concerning the rising smart city global market, and real challenges emerging from actual rates of urbanization and climate change.

This paper focuses on this challenge: the limited effectiveness of smart city applications and the fact that most smart city applications fall short of tackling the big challenges and wicked problems that cities currently face. No application has yet fostered a truly radical change in city competitiveness, sustainability, or inclusion. On the other hand, complete systems or swarms of applications and solutions, which might produce a combined impact, are extremely rare. Yet, the creation and use of applications remain the dominant strategy for the development of smart cities.

Our assumption is that the causes of this limited effectiveness are to be found in the ontologies of the applications used; the way applications interact with the problems and needs of cities, rather than in the actual smart technology or programming features used. The problem is related to the applications' concepts and urban functions, rather than weaknesses in computer power, programming skills, data sources, data analytics, modeling, or any other aspects of the technology stack used in smart city solutions.

In the real life of cities, economic development and quality of life are determined by a series of routines that codify the daily practice of citizens, stakeholders, organizations, and governments. Smart city applications have to change these routines and introduce novel and more effective ways of doing things. However, it is the ontology of an application that defines its problem-solving potential. Communication technologies and programming are enablers that give flesh to applications' problem-solving heuristics. Linking smart city applications to changing city routines highlights two key variables concerning the effectiveness of applications: first, the domains of the city that are affected by the application, and second, the knowledge and innovation processes that are actualized by the application (for more on the fundamental relationship between organizational routines, innovation and changes introduced by the external environment that guide the transformation of knowledge into innovative products and services, see reference[10]).

This assumption led our research to study the overall ontology of the smart city as well as the ontologies of individual smart city applications. The methodology for assessing this assumption had two steps. First, we constructed an overall ontology for the smart city by defining building blocks, classes, and properties. Second, we studied the ontologies, digital spaces, knowledge processes, and the potential impact of a sample of applications for smart cities. We then analyzed key variables of the ontologies of this sample; how they fitted into the overall ontology of the smart city; and the consistency between their digital space, knowledge processes, and the type of innovation and impact.

Keeping this research methodology in mind, the remainder of the paper is structured as follows. In Section 2, we discuss the making of the Smart City Ontology (SCO). This is a new ontology built from scratch. We start with a review of existing ontologies for cities, and a review of the building blocks of smart or intelligent cities, which allows us to define the classes and properties of the SCO. Then, we build the

SCO using Protégé 5.0, an open-source editor, to construct and visualize ontologies. In Section 3, we turn to smart city applications. From the Intelligent/Smart Cities Open Source (ICOS) Community and the Code for America repositories we select a sample of well-known smart city applications, define their ontologies, and survey their key characteristics, including their entities, classes, properties, and individuals, as well as their digital space characteristics, knowledge processes, and innovation potential. We provide descriptive statistics, frequencies, and correlations among key variables of this sample. In Section 4, we attempt a comparative analysis by placing the ontologies of the selected smart city applications against the overall SCO. We focus on relationships among variables characterizing the ontology with variations of the digital space, knowledge processes, and innovation. The last section contains both conclusions and insights about the ways in which we might improve the effectiveness of smart city applications and their impact on the economic and social life of cities. We argue in favor of complex solutions rather than stand-alone applications, meticulous ontology design, use of smart city platforms, and development of systems of applications to address challenges at the level of city districts, clusters, and sectors.

2. Design of the Smart City Ontology

The concept of ontology originated in the field of philosophy, where it is used to describe the essence of existence, and later infiltrated the field of computer science. In simple terms, an ontology is composed of concepts and relationships describing some aspects of the world. In philosophy, "ontology is the science of what is, of the kinds and structures of the objects, properties and relations in every area of reality"[11]. In this field, the ontology deals with "what is" (sometimes called "metaphysics") and ontologists deal with the classification of entities and the parts of entities; with questions of identity and essence of entities coming into being and passing away.

In computer science, "an ontology is a formal explicit description of concepts in a domain of discourse (classes, sometimes called concepts), properties of each concept describing various features and attributes of the concept (slots, sometimes called roles or properties), and restrictions on slots (facets, sometimes called role restrictions). An ontology together with a set of individual instances of classes constitutes a knowledge base"[12]. Classes are the fundamental components of most ontologies; they describe the concepts in a domain of reality. Classes have subclasses, which include concepts more specific that the main class. Subclasses specialize their superclass. Classes and subclasses contain individuals or instances. Properties (or slots) describe binary relationships between individuals. Object properties link an individual to another through a relationship. Datatype properties link an individual to a value; therefore they describe relationships between individuals and data values.

Ontologies are the cornerstone for the development of the semantic web, where knowledge should be both explicit and transmittable across information networks. By representing knowledge in formal languages with clearly defined semantics, it is possible to infer new facts from existing data sets and knowledge bases[13], specify the semantics of webpages, and allow semantic verification[14], which enables extraction and ranking of entities in real time[15]. These three conditions — explicitness, networkability, and formal representation — give meaning to data and break down the information silos of symbolic representations of reality. Ontologies developed in OWL and RDF languages make up the core of the semantic web and can be shared, reused, and extended, creating linked data through common use of symbols and concepts.

The use of ontologies in the field of smart cities is a relatively new field of research. The need for ontology deployment and matching comes from the multi-dimensional character of the smart city, as a system of systems, in which information is obtained from various systems and registers, such as sensor data, administrative data, location data, social media data, and web and smartphone data. It is a common rule that each of these systems has its own hardware and software architecture, and ontologies are called in to provide communication and meaning across applications and systems.

There are a few developed smart city ontologies. The Smart Objects for Intelligent Applications (SOFIA) is an ontology developed in the framework of Smart Coruna in Spain. SOFIA is a middleware platform that allows interoperability among various urban systems and devices, offering a semantic layer to make real-world information available to smart applications. It works on the basis of information provided by different sources in the city, such as sensors, administration services, users, and institutions. Interoperability is achieved by limiting the ontologies used by different systems, as each ontology deployed must comply with one of the templates already defined in the platform[16,17].

Neighborhoods of Winnipeg (NOW) is one of the largest working instances of the Civic Dynamics Platform (CDP). The CDP is a proven open-source software framework for managing and publishing open community data[18]. NOW is a city ontology, which is used to describe and relate the various aspects of this community. NOW describes the 236 neighborhoods of Winnipeg, including all the facilities and services per neighborhood, zoning, economic development, living conditions, and the environment. NOW uses 12 domain ontologies; two are specific to NOW (the NOW ontology and the Canadian Census ontology) and ten others are external ontologies (such as FOAF, GeoNames, etc.). The NOW ontology contains nearly 3,000 concepts, and all are linked together and related to each other. Topics are clustered by color and by distance from the other. Labels denote the concepts.

SCRIBE is another modular semantic model for Smarter Cities, developed by IBM researchers[19]. It includes three components: a core model with classes such as events, messages, stakeholders, departments, services, city landmarks, key performance indicators (KPIs), etc.; extensions by domains, such as buildings, transportation, energy, water, etc.; and customizations by city. SCRIBE represents types of city services, but not the city organization itself, and describes messages, events, and services. City events generate messages, which are linked to city entities, organizations, and roles. Therefore, SCRIBE is a semantic model of events, city assets, location data, resources, city organizations, services, and KPIs. The aim is to support the working of the city's operation center and the coordination of city departments through events with messages generated during the events.

The first version of SCRIBE includes the ontology and the main sub-taxonomies: the *CityPhysicalBase*, which contains physical objects in the city, such as landmarks, roads, networks, etc.; the *EntityRoleBase*, describing organizations, people, items, and their roles; the *EventAndMessageBase*, including external events (like storms, road work), and messages; the *KPIBase*, including indicators related to cost, quality of service or response time; the *MeasurementBase*, for measurements (height, length) and measurement units; the *OrganisationBase*, which captures the abstract organization of a city plus the set of service areas; the *ProtocolBase*, describing the city protocols as a set of protocol steps, and the *SCGeo*, the geospatial core sub-ontology[20]. The main object properties that create horizontal relationships are "*hasAttribute*" for properties and attributes (name, identifier, etc.), "*hasAggregateMember*" for parts or members, and "*associatedTo*" for everything else.

We should take into account all the fundamental entities of cities and the relationships among them for building a comprehensive ontology of the smart city. What a "smart city" or an "intelligent city" entails can be found in the series of definitions for this concept. We use the concepts "smart city" and "intelligent city" as equivalent; their difference in connotation refers to technology-led versus (user-driven) innovation-led solutions for urban systems optimization and welfare. In *The Age of Intelligent Cities*[5] we gathered the most cited definitions for the terms "smart city" and "intelligent city" and plotted the cloud of terms contained in these definitions. The graphic produced with Wordle clearly outlines three building blocks or layers of intelligent or smart cities: (i) the city, citizen, and activities block; (ii) the knowledge, intelligence, and innovation block; and (iii) the smart systems and urban technologies block. These blocks reflect both the elements found in definitions of intelligent and smart cities and the fundamental dimensions of intelligence (human, collective, artificial) to be combined with intelligent cities. The "city block" includes the city's resources, such as communities, people, activities in manufacturing and services, and city infrastructure. The population of the city, knowledge workers, private and public organizations, clusters of companies, and city districts are the fundamental elements upon which intelligent cities are built. The "knowledge and innovation block" includes processes and settings for knowledge creation and cooperation in technology and innovation, such as information gathering and management, intelligence, communication, and networking. The "smart systems and technologies block" includes broadband networks, telecommunications, sustainable technologies, resources, digital applications, and e-services.

This is, however, a static perspective of the entities that form the smart city, and a more refined ontology should also contain the dynamic aspects of the smart city, which appear during the operation and functioning of urban systems. Starting from this perspective, we defined nine superclasses of the SCO: the three classes of spaces structuring any contemporary city (physical space, social space, and digital space); the classes of urban functions (civic, knowledge, innovation); and the classes of city type (challenges, type and planning) which define the character of a city (Figure 1).

We developed the SCO with the Protégé 5.0 editor, defining entities, class hierarchy, object properties, and datatype properties. The first version (v01) contains 10 superclasses, 708 entities, 422 classes, 62 object properties, 190 data properties, and 27 individuals from the software application class. Additionally, widely adopted extra ontologies are used, enriching the SCO, such as the Simple Knowledge Organization System (SKOS), a W3C recommendation designed for representation of thesauri, classification schemes, taxonomies, subject-heading systems, or any other type of structured controlled vocabulary[21]. The SKOS is used to describe production activities according to NACE codes, the statistical classification of economic activities in the EU[22].

The "Smart City Ontology" or "Intelligent City Ontology" describes cities and city districts that have adopted and implemented the intelligent city planning paradigm. Starting from the current version (v01), our goal is to release a new version every six months incorporating all the modifications suggested by the smart city community. This is an original enterprise, and among the first efforts made to improve this ontology collaboratively. The next version will reuse even more ontologies, such as the Good Relation ontology, the Organization (ORG) ontology, and the Friend of a Friend (FOAF) ontology. The Good Relations ontology will enable more accurate descriptions of city companies and their functions within the city (metadata about products and services, terms and conditions, offers, points of sale, prices, etc.) The ORG ontology will be used to describe organizations, institutions, and communities semantically. The FOAF ontology, which describes people, their activities, and their relations on the web semantically, will be added to the people class of the SCO.

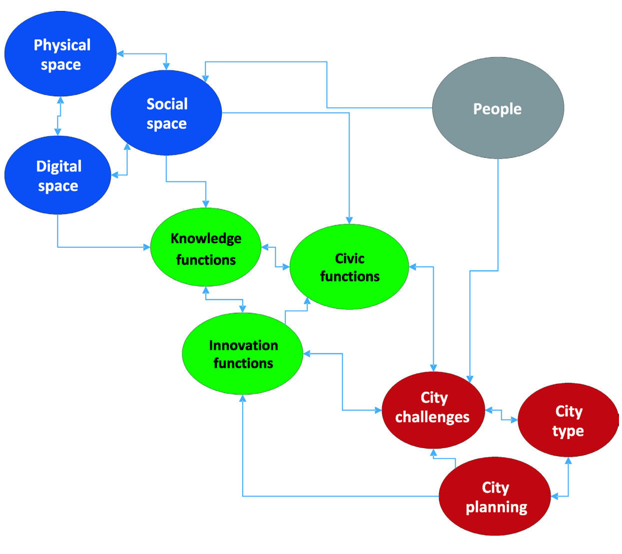

Figure 1. Smart city ontology superclasses.

This description of the SCO is coherent with and advances further the architecture of intelligent cities we have described[23], which is composed of three building blocks (physical, institutional, and digital space) and four core functions (information gathering, learning, collaborative innovation, and information dissemination). The SCO is built upon the central pattern of ten superclasses describing the main physical, social, digital, and functional elements of cities and city districts (Figure 1). As mentioned, these superclasses derive from the most cited definitions of smart/intelligent cities and their Wordle cloud[5] (Figure 2). With respect to traditional cities, new elements, which add intelligence to cities, are (i) the digital space, which contains broadband networks, the cloud, sensors, applications, and e-services, (ii) the knowledge functions activated by the digital space, which sustain the information and learning functionalities of intelligent cities, and (iii) the derived innovation functions, which offer higher effectiveness and problem-solving capabilities[24].

The main object properties of the SCO are "hasValue", "hasSubsystem", "hasElement", "hasInput", "hasOutput", and "hasMeasurementCapability", "isProducedBy", "isPropertyOf", "isFundedBy", "isMadeOf". Also, important relationships include "contains," which connects individuals in the subclasses with these 10 super modules; "facilitates" or "enables" which connect individuals in the subclasses of the digital space to those in the subclasses of knowledge and innovation functions; "addresses" or "resolves" which connect challenges and planning; "dematerialises" which connects digital space and physical space. Core knowledge properties are those of "collectInformation", "disseminateInformation", "processInformation", "prioritise", "benchmark", "hierarchise", "createKnowledge", "discover", "transferKnowledge", "absorbKnowledge", and other similar properties. Core innovation properties include "connect", "cooperate", "coCreate", "createNetwork", "resolve", "fund", "produce", "createMarket", and others that fall into the major innovation categories of researching, producing, funding, and market-making.

Important datatype properties that give value to

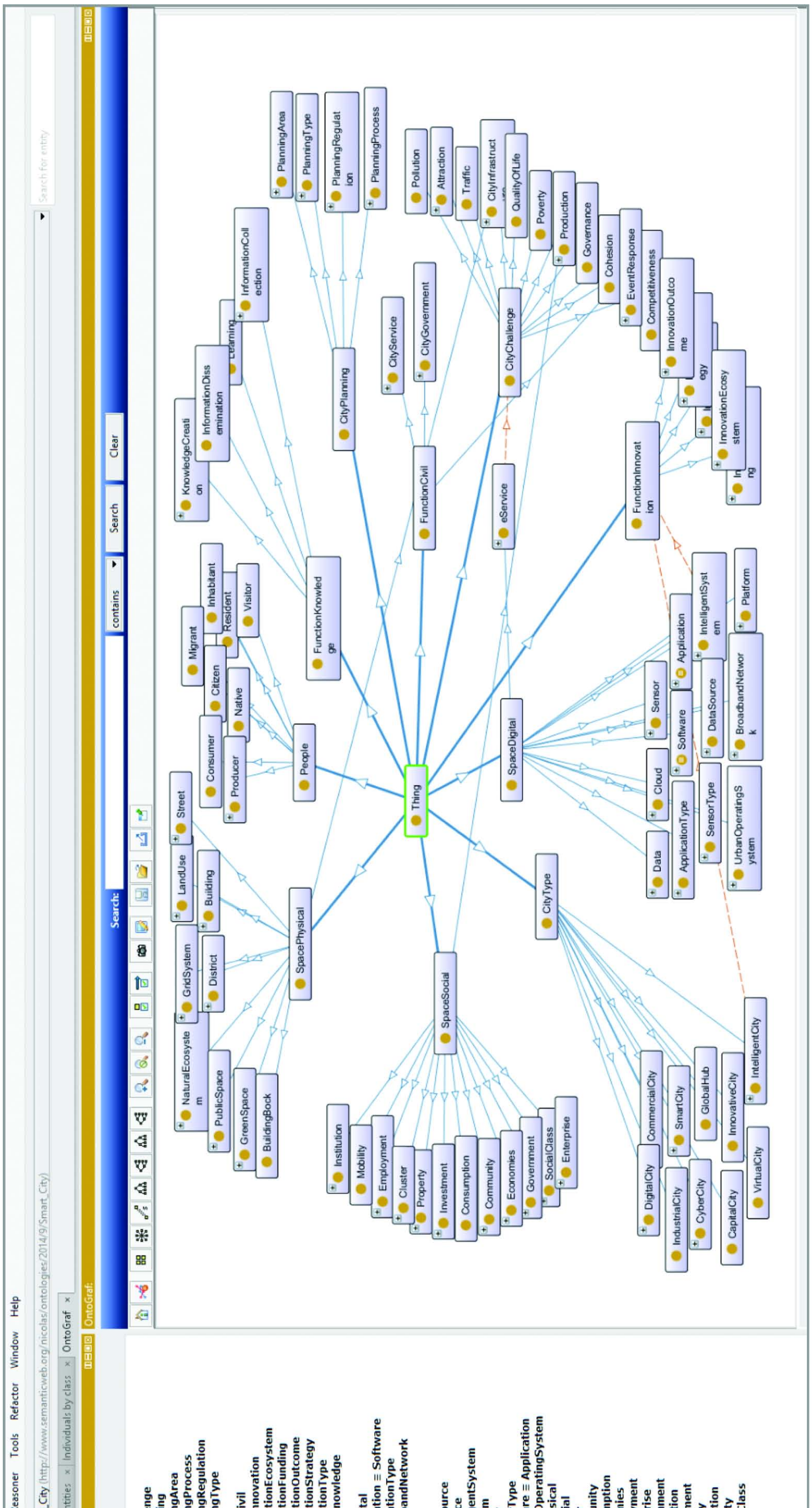

Figure 2. Graph of the smart city ontology developed with Protégé 5.0.

individuals include population and density; economic performance (growth, productivity, innovation); utility metrics (energy, water, speed, mobility); quality of life metrics (environment, pollution, health, social care, etc.); dimension metrics; and location in the physical space. We used established measurement indexes for innovation, productivity, growth, and urban development proposed by international organizations such as the OECD, the EU, and the ISO for the definition of datatype properties.

The Smart City Ontology can be found at the address below:

https://www.dropbox.com/s/q7tz39jjeeibhzl/2015-SMART%20CITY%20ONTOLOGY-V01.owl?dl=0.

The file is accessible with Protégé Editor, which can be downloaded from http://protege.stanford.edu/download/protege/4.3/installanywhere/Web_Installers/.

3. Survey: Ontologies of a Sample of Smart City Applications

Individual smart city applications cover some parts of the overall Smart City Ontology (SCO). They use a subset of classes, subclasses, and properties, and their digital space actualizes specific knowledge and innovation functions. The question that logically arises from this comparison concerns the way the ontologies of smart city applications fit into the overall SCO, which classes and properties they use, the knowledge creation processes they put in motion, and the innovation and optimization that can be achieved.

To address this question, we analyzed 20 smart city applications, which can be found in the Intelligent/Smart Cities Open Source (ICOS) Community and the Code for America repositories:

- ICOS is a meta-repository for intelligent/smart cities open source applications and solutions. ICOS is addressed to city authorities and applications developers with the aim of facilitating the uptake and implementation of smart city solutions. Each application is categorized by the domain it serves (economy, utilities, quality of life, governance), the type of software it uses, its technical characteristics, and license type. These four domains correspond to the classic structuring elements of cities, the production and consumption subsystems, the network system, and government system[25].
- Code for America supports the building of open source applications, and organizes a network of people dedicated to making government services simple, effective, and easy to use. Applications support local services or citizen engagement.

At both repositories, additional information is given, such as the application's official website, a link to Github to download the code, and documentation for installation and use.

Examining each application of the above sample, we attempt to identify the underlying ontology and knowledge and innovation functions. This is a reverse engineering approach, which describes the ontology of an application by observing the application itself. The method is accurate as far as the description of classes is concerned, but less accurate in the definition of object and data properties. An additional complication is that many of the applications examined were not designed with a semantic approach. However, this does not prohibit us from assuming their underlying ontology. Observing the working of the application also allows for describing its main knowledge and innovation functions with sufficient accuracy.

We have assessed 20 applications out of the 37 hosted on the ICOS and the 26 hosted on Code for America. These are listed in Table 1. The sample is stratified, and we selected an equal number of applications from each smart city domain, namely: innovation economy, quality of life, infrastructure and utilities, and governance.

The assessment of each application and its underlying ontology is based on metrics that describe the quality of the ontology and its cognitive value. The size of an ontology can be assessed with metrics such as the number of nodes, the maximal length from a root node to a leaf node, the number of leaves in the ontology graph, the number of nodes that have leaves among their children, and the number of arcs in the ontology graph. Critical errors can be assessed by considering the number of cycles in the ontology and the number of nodes that are members of any cycle with respect to all nodes. Tangledness can be assessed by counting the number of nodes with several parents, and the number of nodes that have only leaves as children[26].

Moreover, our aim is to understand how each smart city application fits into the entire smart city landscape, and what knowledge and innovation functions derive from it. Therefore, having completed the reverse engineering exercise, we tried to place the ontology of each application examined into the overall SCO and understand (i) how the ontologies examined are positioned

Table 1. Smart city applications assessed

SmartMarketplace http://icos.urenio.org/applications/virtual-city-market/ A virtual representation of a local marketplace, where local storekeepers manage e-shops. The application includes also a business directory that shows local businesses and professional services on the city map. E-shops offer promotional coupons and discounts, together with customer reviews.
OpenSpending http://icos.urenio.org/applications/openspending/ An open platform that presents financial information about local city budgets. OpenSpending helps users understand the budget and how governments spend money.
Gittip (renamed Gratipay) http://icos.urenio.org/applications/gittip/ A platform for crowdfunding. Donors can set up anonymous gifts to people they think do great work in different communities. Gifts are distributed weekly. The total amounts donated or received are displayed publicly.
Development FastPass http://lv-fastpass.herokuapp.com/#/ The application combines parcel data, land use, zoning, building occupancy, and business incentives to help business owners research the best locations for their businesses.
AuntBertha https://www.auntbertha.com/ The application collects information on federal, state, county, city, neighborhood, and non-profit programs in the fields of emergency response, food, housing, goods, transit, health, money, care, education, work, and legal.
BizFriend.ly http://bizfriend.ly/ A go-to resource where small to mid-sized businesses can find empowering, easy-to-use online/digital tools, as well as a learning and sharing community that helps entrepreneurs start, run, and grow their businesses.
CiviCRM https://civicrm.org/ Web-based Constituent Relationship Management (CRM) software geared toward meeting the needs of non-profit and other civic-sector organizations. CIVICRM supports their missions through contact management, fundraising, event management, member management, mass e-mail marketing, peer-to-peer campaigns, case management, and other applications.
Hoyrespiro http://hoyrespiro.people-project.eu/ A web application providing information about city air quality extracted from a city's pre-existing environmental monitoring networks. It provides a rapid and effective technological answer to the needs of people with special sensitivity to environmental allergies.
OpenTreeMap https://www.opentreemap.org/ A web and smartphone application, which provides an easy-to-use public inventorying platform enabling individuals, organizations, and governments to collaboratively create interactive and dynamic maps of a community's tree population.
Openair http://www.openair-project.org/ A web-based platform providing a collection of open-source tools for the analysis of air pollution data. OpenAir uses the statistical/data analysis software R as a platform, which offers a powerful, open-source programming language ideal for insightful data analysis.
CivicInsight http://civicinsight.com/index.html The application tracks properties and help residents make sense of complicated processes like code enforcement and building permits, as well as providing alerts about what's happening with properties in their neighborhood, and analyzing trends for strategic, data-driven decisions.
Prepared.ly https://www.codeforamerica.org/apps/prepared-ly/ Wildfires, hurricanes, tornadoes, and natural disasters are a regular and a real part of life. This application is easily redeployed for any type of disaster, offering near real-time information on home and business property risk and disaster preparedness tasks, as well as the ability to track progress and set reminders. It also connects to fire safety professionals.
OpenTripPlanner http://www.opentripplanner.org/ A multi-modal trip planner, which allows users to schedule transit, travel, and map information. OTP gives detailed step-by-step directions alongside interactive route maps, details of public transport services required, and transfer information.
Streetmix http://icos.urenio.org/applications/streetmix/ This application promotes two-way communication between planners and the public in designing and remixing a cross-section of a neighborhood street.
FixMyStreet https://www.fixmystreet.com/ The application enables user to report, view, or discuss local problems, such as graffiti, fly tipping, broken paving slabs, or street lighting issues.
Improve my city http://icos.urenio.org/applications/improve-my-city/ An application that enables citizens to report local non-emergency problems and suggest solutions for improving the environment of their neighborhood or city. Then local government agencies take action to address the issues reported. Feedback is provided to users.
Local Wiki http://icos.urenio.org/applications/localwiki/ A grassroot efforts to collect, share, and make available local knowledge. Anyone can contribute and learn about local government, neighborhoods, streets, social movements, social services, schools, and other facets of the community life.
OpenDataCatalog http://icos.urenio.org/applications/open-data-catalog/ Originally developed for Philadelphia, the application provides access to open data sets, applications, and APIs related to a city.
AllOurIdeas http://icos.urenio.org/applications/all-our-ideas/ A platform that enables groups to collect and prioritize ideas in a transparent, democratic, and bottom-up way.
Shareabouts http://openplans.org/ A web application for crowd-sourced mapping. It can be customized for different purposes and collecting public input. Users can suggest a location, add a comment, support other suggestions, and share locations with other users.

within the classes of the overall SCO; (ii) which object and data properties are most used; and (iii) which knowledge, optimization, and innovation processes are set in motion. For instance, how does the ontology of the *SmartMarketplace* application fit into the 10 superclasses, 422 classes, 62 object properties, and 190 data properties of the overall SCO? Which classes, objects, and datatype properties are shared between two ontologies? What type of knowledge processes and innovation derive from this application?

Consequently, for each application, we defined the following key variables: the size of the ontology of the application; the maximal length of nodes; the number of the object and data properties; the number of superclasses of the overall SCO used by the application; the position of the ontology within the overall SCO (upstream near the "thing" or downstream close to the end leaves). In addition, we defined the type of the digital space that makes the application operational, the different knowledge processes actualized by the application, and assessed its innovation and city improvement potential.

We used a scale of 1 to 5 to attribute values to these eight key variables characterizing each smart city application. These variables and the rationale for assigning values appear in Table 2.

The ordinal variables related to ontologies are transformations of continuous variables. "DSPACE," "KNOW," and "INNOV" are ordinal variables and the scale corresponds to low, middle, and high levels of complexity, knowledge width, and novelty. Some key statistics from this sample of smart city applications are given below in Tables 3 and 4.

4. Analysis and Discussion

Tables 2–4 allow us to analyze and discuss some key findings from our survey of the selected sample of smart city applications, in particular how the ontologies of these applications are positioned within the overall SCO, how the digital space of each application is constructed, which knowledge functions are set in motion, and finally, what potential the applications offer for changing the routines of the city's function. We will approach these questions with respect to the way smart cities operate, as represented in Figure 3, which depicts three innovation circuits actualized in smart cities[5,27].

Innovation Circuit 1 concerns the creation of the digital space of smart cities: the smart environment itself. This circuit leads to a multi-level construction composed of broadband networks, smart devices and smart meters, sensors and other embedded systems, data and data management technologies, cloud infrastructure, platforms, applications, and e-services. The digital edifice of cities emerges from the many uncoordinated initiatives of telecom companies, IT developers, producers, and users, each one adding some new digital component, as well as from the organized actions of institutions through planning and strategy for digital growth, action plans, project design, and implementation. Local solutions co-exist with

Table 2. Values attributions to key variables of smart city applications

Value	Ontology of the application			Position in the SCO		Application		
	ONTOSIZE	ONTOLEN	ONTOPRO	SUPCLASS	ONTOPOS	DSPACE	KNOW	INNOV
	Size: number of classes & subclasses	Max length of nodes	Number of object and datatype properties	Number of superclasses of the SCO used by the application	Position of the application ontology into the SCO graph	Digital space of the application: complexity and sophistication	Knowledge generation processes initiated by the application	Highest level of innovation to be achieved by the application
1	n = 1–20	n = 1–2	n = 1–15	n = 1–2	Downstream leaves	Simple portal, website, smartphone application	Information dissemination	Non-existent/undefined innovation
2	n = 21–40	n = 3–4	n = 16–30	n = 3–4	Downstream nodes	Web-based dataset creation, mashups, or CMS	Information collection and dissemination	Process or product new to the organization
3	n = 41–60	n = 5–6	n = 31–45	n = 5–6	Middle nodes	Application based on sensors, smart meters, and instrumentation	Big data collection, processing, and analytics	Social innovation within the community
4	n = 61–80	n = 7–8	n = 46–60	n = 7–8	Middle to upstream nodes	Platform aggregating many applications	Learning, skills creation, technology transfer	New to the sector or domain of innovation
5	$n \geqslant 81+$	$n \geqslant 9+$	$n \geqslant 61+$	n = 9–10	Upstream nodes close to "thing"	Complex system for workflow organization	New knowledge creation	Radical innovation globally

Table 3. Descriptive statistics from sample of smart city applications

	N	Minimum	Maximum	Mean	Std. Deviation
ONTOSIZE	20	1	5	2.70	1.302
ONTOLEN	20	1	3	2.05	0.605
ONTOPRO	20	1	4	1.55	0.759
SUPCLASS	20	1	4	2.20	1.005
ONTOPOS	20	1	4	2.20	1.056
DSPACE	20	1	4	2.05	0.510
KNOW	20	1	3	2.00	0.459
INNOV	20	1	5	2.25	1.118
Valid *N*	20				

Table 4. Spearman's rho test for correlation of the eight variables

Variable		ONTOSIZE	ONTOLEN	ONTOPRO	SUPCLASS	ONTOPOS	DSPACE	KNOW	INNOV
ONTOSIZE	Correlation Coefficient	1.000	0.753**	0.398	0.772**	0.746**	0.478*	0.617**	0.612**
	Sig. (2-tailed)	0.000	0.000	0.082	0.000	0.000	0.033	0.004	0.004
	N	20	20	20	20	20	20	20	20
ONTOLEN	Correlation Coefficient	0.753**	1.000	0.640**	0.532*	0.594**	0.535*	0.756**	0.458*
	Sig. (2-tailed)	0.000	0.000	0.002	0.016	0.006	0.015	0.000	0.042
	N	20	20	20	20	20	20	20	20
ONTOPRO	Correlation Coefficient	0.398	0.640**	1.000	0.091	0.314	0.297	0.519*	0.252
	Sig. (2-tailed)	0.082	0.002	0.000	0.703	0.178	0.204	0.019	0.283
	N	20	20	20	20	20	20	20	20
SUPCLASS	Correlation Coefficient	0.772**	0.532*	0.091	1.000	0.900**	0.171	0.364	0.610**
	Sig. (2-tailed)	0.000	0.016	0.703	0.000	0.000	0.470	0.115	0.004
	N	20	20	20	20	20	20	20	20
ONTOPOS	Correlation Coefficient	0.746**	0.594**	0.314	0.900**	1.000	0.186	0.444*	0.486*
	Sig. (2-tailed)	0.000	0.006	0.178	0.000	0.000	0.433	0.050	0.030
	N	20	20	20	20	20	20	20	20
DSPACE	Correlation Coefficient	0.478*	0.535*	0.297	0.171	0.186	1.000	0.707**	0.227
	Sig. (2-tailed)	0.033	0.015	0.204	0.470	0.433	0.000	0.000	0.337
	N	20	20	20	20	20	20	20	20
KNOW	Correlation Coefficient	0.617**	0.756**	0.519*	0.364	0.444*	0.707**	1.000	0.470*
	Sig. (2-tailed)	0.004	0.000	0.019	0.115	0.050	0.000	0.000	0.036
	N	20	20	20	20	20	20	20	20
INNOV	Correlation Coefficient	0.612**	0.458*	0.252	0.610**	0.486*	0.227	0.470*	1.000
	Sig. (2-tailed)	0.004	0.042	0.283	0.004	0.030	0.337	0.036	0.000
	N	20	20	20	20	20	20	20	20

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

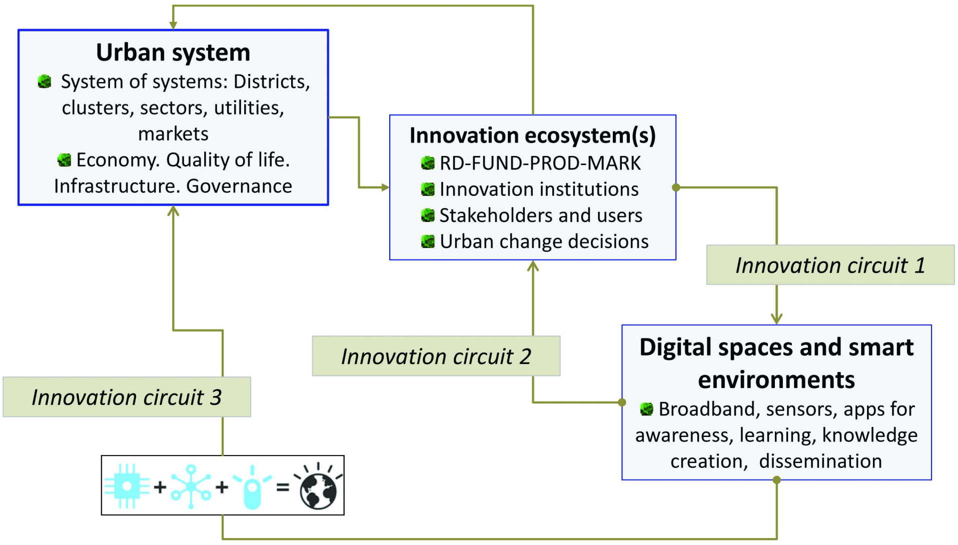

Figure 3. Innovation circuits in intelligent cities[5].

global platforms customized to local needs and demand. The digital spatiality of cities arises as a dynamic agglomeration of heterogeneous systems, solutions, and applications, in the same way that cities arise as heterogeneous agglomerations of production and consumption practices, buildings, and infrastructures.

Innovation Circuit 2 is about the improvement of the city's system of innovation. Many applications and web solutions can be used to change the governance of innovation, the way cities decide on changes, and the co-design of the urban environment with the involvement of users. Such applications bring radical changes to cities, related to (i) the creation of hybrid innovation ecosystems, in which R&D, funding, design, production and marketing elements of the innovation system obtain digital assistance, and (ii) the mobilization of people, locally and globally, offering creativity, ideas and insights through digital collaboration. A very interesting report published by Ericsson[4] highlights how these digital disruptors affect markets (pull economy, user centrism, open marketplaces, content-driven marketing), technology and innovation (user experience design, product-based organizations, on-demand production) and business models (platform-based models, distributed organizations).

Innovation Circuit 3 starts from other types of software applications and smart systems, which do not intend to change the city directly, but foster behavioral changes among citizens by promoting sustainability and optimizing the way citizens and organizations use the city daily. Intelligent transportation systems and GPS apps that guide urban mobility, sensor-based solutions or social media applications for finding parking places in the city and smart energy meters in housing districts are solutions that conserve resources and encourage more efficient use of the city's assets. In the same way, mash-up web applications gather and offer information about the city overall, along with cultural events, recreation, museums, historic sites, restaurants, hotels and marketplaces, facilitating daily access and usage. Most innovations in Circuit 3 are about resource conservation and dematerialization, transferring practices from the physical to the digital space of cities. But they also induce a behavioral change on behalf of the citizens, diffusing a culture concerned with resource sustainability, avoiding waste, care for the environment, and making more with less.

Our survey of smart city applications of all categories, enabling the improvement of the economy, quality of life, utilities, and governance, opens a field of research and an understanding of the dynamics that drive these three innovation circuits, and how the digital space and its ontology affects the knowledge processes, innovation, and impact of applications. However, this is not the only way of understanding the relationships between socio-technical urban systems and innovation. For an alternative solution to the innovation problem and search for this type of synergy, see Deakin's paper[28].

4.1 Innovation and Impact

We consider "INNOV" as a dependent variable, and all the others as independent ones. Innovation is a good proxy to assess the impact of smart city applications.

The more radical the innovation created by an application, the greater is the impact of the application. Low-level innovations, such as innovations that are only new to the organization or frugal innovations that have incremental impact, are usually related to some kind of cost reduction. Innovations new to the sector or globally radical innovations usually introduce major system changes to the city and their impact is much higher.

The survey data show a range for the INNOV variable (the highest level of innovation to be achieved by the application) of 1 to 5 and a mean value of 2.25 (Table 3). This is an indication that smart city apps can sustain any type of innovation, but most applications would support an incremental product or process innovations for organizations. Only a few applications could potentially sustain more radical innovations at sector or global levels.

4.2 Digital Space of Applications

In smart cities, the digital space mediates and orchestrates their entire function. Innovations circuits start from the digital space (the space of apps) with a decision-making circuit affecting the actions that change the city, optimizing the decisions that drive these changes; and an operation circuit affecting daily life in the city, optimizing the use of resources and infrastructure. These two circuits rely on continuity among the digital space—cognitive processes—and innovation practices.

In the applications examined, the digital space of smart city applications takes multiple forms: simple websites and web directories for information dissemination, mirror-spaces representing buildings and open spaces, content management systems, mash-up and aggregation portals, marketplaces and transaction spaces, and instrumental spaces based on sensors and analytics. Most of the applications, however, rely on simple forms of digital space, based on content management systems for data storage, retrieval, and dissemination.

The digital space of the applications examined has a significant relationship with the size and length of ontologies characterizing the applications. The relationship between digital space and knowledge processes is even stronger. However, no direct relationship to innovation is observed. This indicates that the continuity among ontology-digital space-knowledge processes-innovation breaks down, and the ontology of applications becomes disconnected from its innovation potential and impact. This weakness should be addressed at the design stage of each application, considering those entities of the ontology that would secure and increase the innovation potential of the application.

4.3 Classes

In principle, the classes of a smart city application are critical elements of its effectiveness. The number of classes (size of the ontology) that the application contains is related to the range of urban problems that can be addressed. Narrow applications having some classes tend to be very focused on specific problems and operations (find a location, meter a flow, show environmental conditions, etc.) On the other hand, wide applications possessing many classes can address more complex urban problems (competitiveness, sustainability, government), which depend on many variables. The same holds true for the position that the classes of an application occupy within the overall SCO. An upstream position close to the "thing" indicates that the application can affect all classes in lower position, while a downstream position close to end-leaves indicates that the application can affect very specific aspects of the urban system. Therefore, the size of the ontology, in terms of classes, and its positioning in the overall SCO are good proxies of its effectiveness, problem-solving potential, and innovation.

In the sample of applications we examined, the number of classes varies considerably; the range of the "ONTOSIZE" variable is from 1 to 5, and the mean value is 2.70 (Table 3). Applications in the field of government and dataset creation are larger, as the government is expected to address all urban problems. On the other hand, applications in the field of transport, energy, and utilities tend to focus on their particular domain. Applications dealing with data generation have no predefined ontology, but adapt to the concepts and classes created by the users. This is, for instance, the case for "AllOurIdeas," which collects and prioritizes ideas, and "OpenSpending," which enables users to explore public finance data with visualization and benchmarking (Table 1).

The position of the application ontologies examined falls mostly within the superclass of "social space" and deals with socio-economic activities and communities of users, indicating that the applications affect primarily the social condition of cities and the activities located in the cities. The physical space (buildings, roads, infrastructure, etc.) comes together with the maps and is usually not functional within the applications.

The matrix of correlation coefficients (Table 2) shows that the size, length, and position of the application ontologies into the superclasses of the SCO, are variables with significant correlations to innovation and potential impact. Such relationships were expected and the data support our initial assumption. However, the relationships observed are valid for incremental product and process innovations within the organization or social innovations within the community. More radical innovations with the potential to change entire city clusters and industries or globally radical innovations are not observed.

4.4 Properties

Another group of ontology variables allows for understanding the internal structuring of smart city applications, such as the number of nodes with several parents; the number of nodes that have only leaves as children; the maximal length of the path from a root node to a leaf node; and both the number of object properties and data properties. The complexity of the internal structuring is a proxy of the information processes that occur during the operation of the application; it is an indication of the capacity of the application to transform information inputs into knowledge outputs, and data into insights for innovation.

To assess the internal structure of smart city applications we used two metrics: (i) the maximal length of the path from the top root node to the lowest leaf node (ONTOLEN) and (ii) the number of object and data properties (ONTOPRO). For both variables, low values are most frequent (Table 5), indicating a low level of internal information structuring; low processing capacity to transform information, reveal hidden information, and sustain information intelligence; and weak association between classes and concepts.

In terms of impact and correlation of the above variables to innovation potential, only the length of the ontology shows a weak linear relationship to innovation. Moreover, the low values of the datatype properties observed indicate that most smart city applications do not support a fundamental transformation related to the setting up of cities measurable systems, producing quantitative data throughout their operation.

4.5 Knowledge Processes

The literature on learning and cognition categorizes knowledge in multiple types, such as generic and domain specific, concrete and abstract, formal and informal, declarative and tacit, conceptual and procedural, elaborated and compiled, structured and unstructured, strategic, acquired, situated, and many others. To reduce the complexity of these endless classifications, De Jong and Ferguson-Hessler[29] suggest a matrix approach based on types and qualities (or properties) that can be relevant to different types of knowledge. Types of knowledge include situational (typical problem-situations in a domain), conceptual (knowing facts, understanding concepts and principles), procedural (set of actions to solve a problem), and strategic knowledge (planning, decision-making, what and when to do). Qualities of knowledge include modality (way of expression), generality (general or domain-specific), automation (explicit or tacit), structure (coherently organized), and level (superficial to deep). This approach has much in common with ontology structuring, where individuals (type of knowledge) belong to different classes and properties define additional characteristics for individuals.

In the SCO, the definition of knowledge classes followed a similar approach, but it was conducted from a knowledge generation perspective rather than static knowledge characteristics. We defined four classes of knowledge generation, namely, information collection and processing, information and knowledge dissemination, learning and skill creation, and new knowledge creation. These classes are universal and each of them includes its own sub-classes. Then a series of object properties defines additional restrictions. Though object property restrictions form anonymous

Table 5. Frequencies of variables ONTOLEN and ONTOPRO

ONTOLEN					ONTOPRO				
	Frequency	Percent	Valid Percent	Cumulative Percent		Frequency	Percent	Valid Percent	Cumulative Percent
1	3	15.0	15.0	15.0	1	11	55.0	55.0	55.0
2	13	65.0	65.0	80.0	2	8	40.0	40.0	95.0
3	4	20.0	20.0	100.0	4	1	5.0	5.0	100.0
Total	20	100.0	100.0		Total	20	100.0	100.0	

classes, object properties should not be seen as creating classes, but as acts of reasoning.

Knowledge processes generated from each smart city application were assessed with respect to the above classes of the SCO. Excluding data (fact and figures about a specific field, but not organized or providing information about patterns and context), knowledge processes range from information collection (contextualized and categorized data), to knowledge creation (contextualized information, justified true belief, skill creation, know-how). These knowledge functions are intermediate outputs, which mediate between the digital space and the innovation potential or impact of the application.

The correlation matrix (Table 4) shows significant relationships between (i) knowledge processes and the digital space and ontology variables and (ii) knowledge processes and the innovation variable, while no significant relationships exist between the digital space and innovation variables. This highlights the go-between role of knowledge processes in relation to the city ontology, the digital space, and innovation. As expected from the understanding of innovation as the application of knowledge to produce new value, knowledge processes rather than the digital space itself are what transform the city features to innovation.

A second and equally important finding concerns the type of knowledge generated by smart city applications. The dominant form is related to information collection and dissemination (80%), followed by information dissemination and big data collection and analytics. None of the examined smart city applications concerned skills creation or new knowledge creation, which are more advanced types of knowledge. If this is not merely a circumstantial result arising from the particular sample of smart city applications examined, it would explain the low-to-medium innovation potential of smart city applications that was also observed.

5. Conclusion: Improving the Effectiveness of Smart City Applications

In this paper, we assessed the potential impact of smart city applications with variables pertaining to the urban system (ONTO-X variables), the digital space of application (DSPACE), and the knowledge processes derived (KNOW). We have seen that the innovation potential of most smart city applications is incremental, close to product or process innovation to the organization, which means that they can introduce small-scale novelties without wider system-level changes. The classes of most smart city applications focus on narrowly-defined urban problems, which prevent them from having a significant impact, and the ontologies of most smart city applications have a very narrow horizon of events compared to the complexity, extent, and the externalities of urban systems and challenges. We have also seen that the innovations introduced by the applications relate strongly to variables of the city ontology, to a second degree to knowledge processes sustained by the applications, and have no relationship to the digital space created by the application. This is a significant conclusion, in line with perspectives on smart cities, arguing that city intelligence is a product of citizen engagement rather than of smart city technology[30,31].

These findings have significant implications for the design and development of smart city applications. If we wish to improve their effectiveness and impact, then among the parameters of their design (city of reference, user interface, aesthetics, data, and programming) priority should be given to the design of their ontology, the relationship to the overall ontology of the smart city, and the classes and properties contained in the application. The innovation potential at the highest level should be defined as the strategic objective of the design, and the knowledge processes capable of sustaining this high level of innovation should be meticulously designed and organized through the digital space of the application.

A series of strategies can contribute to more successful, high impact applications[32], such as the design of groups of applications instead of stand-alone solutions; working with large-scale urban entities such as city districts, clusters, communities of users; targeting solutions that sustain up-skilling of human capital; and prioritizing applications that affect the city's innovation system rather than the daily working of the city (*Innovation Circuit 2* rather than *Circuit 3*). In all cases, smart city application designers should seek the input and advice of urban and innovation experts, user involvement, experience design, and crowdsourcing, to increase the probability of discovering ideas and insights for innovation.

Conflict of Interest

No conflict of interest was reported by the authors.

References

1. Chesbrough H W, 2003, The new imperative for creating and profiting from technology, in *Open Innovation*, Harvard Business School Press, Boston MA.

2. Chesbrough H W, 2006, *How to Thrive in the New Innovation Landscape: Open Business Models*, Harvard Business School Press, Boston, Harvard Business School.
3. Von Hippel E, 2005, *Democratizing Innovation*, Cambridge (in MIT Press).
4. *Digital disruptors: Models of digital operations* n.d., viewed March 21, 2015, <http://www.ericsson.com/res/docs/2014/digital-distuptors.pdf>
5. Komninos N, 2014, Smart environments and innovation-for-all strategies, in *The Age of Intelligent Cities*, Routledge, London and New York.
6. *Amsterdam Smart City*, 2015, viewed March 15, 2015, <http://amsterdamsmartcity.com/projects>
7. Amsterdam Smart City, 2011, in *Smart stories*, Maaike Osieck, Amsterdam, Netherlands, viewed Apr 19, 2011, <http://issuu.com/amsterdamsmartcity/docs/smart_stories>
8. Egeler C and Dell G, 2013, Best practices in urban ITS: collection of projects, in *Urban ITS Expert Group*. <http://ec.europa.eu/transport/themes/its/road/action_plan/doc/2013-urban-its-expert_group-best-practice-collection.pdf>
9. Caragliu A, Del Bo C S, Kourtit K, *et al*. Performance of smart cities in the North Sea Basin, in *Smart Cities*. <http://www.smartcities.info/files/13%20-%20Peter%20Nijkamp%20-%20Performance%20of%20Smart%20Cities.pdf>
10. Nelson R and Winters S, 1982, in *An Evolutionary Theory of Economic Change*, Harvard University Press, Cambridge.
11. Cohnitz D and Smith B, 2003, Assessing ontologies: the question of human origins and its ethical significance. Reprint version of a paper published in Runggaldier E and Kanzian C (eds), *Persons–An Interdisciplinary Approach*, Vienna, 243–59. <http://ontology.buffalo.edu/smith/articles/humanorigins.pdf>
12. Noy N F and McGuinness D L, 2001, *Ontology Development 101: A Guide to Creating Your First Ontology*, Stanford University, viewed March 2001. <http://www.ksl.stanford.edu/people/dlm/papers/ontology-tutorial-noy-mcguinness-abstract.html>
13. Magee L, 2010, A framework for assessing commensurability of semantic web ontologies. *Electronic Journal of Knowledge Management*, vol.8(1): 91–102.
14. Despeyroux T and Trousse B, 2000, Semantic verification of web sites using natural semantics: proceedings of the sixth conference on content-based multimedia.
15. Komninos A and Arampatzis A, 2013, Entity ranking as a search engine front-end. *International Journal on Advances in Internet Technology*, vol.6(1)&(2): 68–78.
16. Otero-Cerdeira L, Rordiguez-Martinez F R and Gómez-Rodríguez A, 2014, Definition of an ontology matching algorithm for context integration in smart cities. *Sensors*, vol.14: 23581–23619.
17. *SOFIA2* concepts, 2014, viewed March 3, 2015, <http://sofia2.com/docs/(EN)%20SOFIA2-SOFIA2%20Concepts.pdf>
18. *Civic dynamics platform* n.d., viewed March 15, 2015, <http://civic-dynamics.com/features/gallery>
19. Uceda-Sosa R, Srivastava B and Schloss R J, 2012, *Using ontologies to make smart cities smarter*, IBM Research, viewed June 30, 2012, <http://docslide.us/documents/using-ontologies-to-make-smart-cities-smarter-rosario-uceda-sosa-biplav-srivastava-and-bob-schloss-ibm-research-rosariouus-rschlossus-sbiplavin.html>
20. Uceda-Sosa R, Srivastava B and Schloss R J, 2011, Building a highly consumable semantic model for smarter cities: p*roceedings of the AI for an intelligent planet*, 3:1–3:8. http://dx.doi.org/10.1145/2018316.2018319.
21. Miles A and Bechhofer S, 2009, *SKOS Simple Knowledge Organization System Reference*, W3C Recommendation, viewed August 18, 2009, <www.w3.org/TR/skos-reference/>
22. Bratsas C and Filipidis P, *SKOS Representation of NACE statistical classification of economic activities in the European Community*, n.d., viewed August 3, 2015, <http://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF>
23. Komninos N, 2006, The architecture of intelligent cities: integrating human, collective and artificial intelligence to enhance knowledge and innovation: proceedings of the second IET international conference on intelligent environments, IE 06, vol.1: 13–20, viewed March 23, 2015, Academic OneFile database.
24. Anthopoulos L G and Vakali A, 2012, Urban planning and smart cities: interrelations and reciprocities. *The Future Internet*, vol.7281: 178–189. http://dx.doi.org/10.1007/978-3-642-30241-1_16.
25. Castells M, 1975, *La Question Urbaine*, Paris, edn, F. Maspero, Pergamon Press, Paris.
26. Gavrilova T, Gorovoy V and Bolotnikova E, 2012, New ergonomic metrics for educational ontology design and evaluation. *New Trends in Software Methodologies, Tools and Techniques*, eds, IOS Press, Amsterdam, vol.246: 361–378. http://dx.doi.org/10.3233/978-1-61499-125-0-361.
27. Komninos N, Kakderi C and Tsarchopoulos P, 2014, New services design for smart cities: a planning roadmap for user-driven innovation: proceedings of the 2014 ACM international workshop on Wireless and mobile technologies for smart cities (WiMobCity '14): 29–39, viewed March 23, 2015, Academic OneFile database. http://dx.doi.org/10.1145/2633661.2633664.
28. Deakin M, 2014, Smart cities: the state-of-the-art and governance challenge. *Triple Helix*, vol.1(1): 1–16. http://dx.doi.org/10.1186/s40604-014-0007-9.
29. De Jong, T and Ferguson-Hessler M G, 1996, Types and qualities of knowledge. *Educational Psychologist*, vol.31(2): 105–113. http://dx.doi.org/10.1207/s15326985ep3102_2.
30. Deakin M, 2013, *Smart Cities: Governing, Modelling and Analysing the Transition*. New York, Routledge.
31. Belissent J, 2010, *Getting clever about smart cities: new opportunities require new business models*, Forrester for Ventor Strategy Professionals, viewed November 2, 2010. <https://www.forrester.com/Getting+Clever+About+Smart+Cities+New+Opportunities+Require+New+Business+Models/fulltext/-/E-RES56701>
32. Angelidou M, 2015, *Strategic Planning for the Development of Smart Cities*, thesis, University of Thessaloniki, IKEE / Aristotle University of Thessaloniki – Library, viewed March 11, 2015.