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Smart, Sustainable, Resilient, and Inclusive Cities: Integrating Performance Assessment Indicators into an Ontology-Oriented Scheme in Support of the Urban Planning Practice

Maria Panagiotopoulou [1], Anastasia Stratigea [1,*] and Margarita Kokla [2]

[1] Department of Geography and Regional Planning, School of Rural, Surveying and Geoinformatics Engineering, National Technical University of Athens (NTUA), Heroon Polytechniou Str., 9, Zographou Campus, 15780 Athens, Greece; mapanagiot@yahoo.gr

[2] Department of Topography, School of Rural, Surveying and Geoinformatics Engineering, National Technical University of Athens (NTUA), Heroon Polytechniou Str., 9, Zographou Campus, 15780 Athens, Greece; mkokla@survey.ntua.gr

* Correspondence: stratige@central.ntua.gr

Abstract: The unprecedented pace of urbanization has been exerting significant strain on cities, raising critical concerns across environmental, economic, social, and technological aspects. In response, the ‘Smart City’ concept has emerged as a novel urban development paradigm, aiming at addressing contemporary urban issues, enhancing cities’ competitiveness and prosperity, and fostering active participation through the strategic utilization of state-of-the-art technologies. However, the smart city term suffers from considerable conceptual ambiguity, thereby provoking intense confusion and misunderstanding among interested parties and leading to the implementation of ineffective initiatives. Moreover, the priorities of sustainability, resilience, and inclusiveness have gained prominence in the urban planning discourse, necessitating a more integrated view that aligns urban targets with performance assessment across various domains. In light of these issues, this study endeavors to clarify the above-mentioned conceptual vagueness by developing a holistic, indicator-oriented smart city ontology. The proposed knowledge representation scheme is intended to serve as a Decision Support Tool that will facilitate policymakers to tackle urban challenges and formulate sound policies. Additionally, it is expected to contribute to the fields of spatial and developmental planning by establishing a standardized framework for assessing and monitoring cities’ performance, while elucidating the complex interrelationships and trade-offs among diverse urban dimensions.

Keywords: smart; sustainable; resilient and inclusive cities; urban planning; ontology; performance assessment indicators

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1. Introduction

Cities of today and large urban ecosystems have evolved into pivotal intersections of human societies, serving as poles of population influx and talent aggregation [1]. They are also deemed to be powerful engines of growth and prosperity that act as a real magnet for a highly qualified, young labour force and significant agents of innovation, creativity, and inclusion [2–4]. The unprecedented intensity of urbanization and the rapid expansion of urban environments, witnessed in recent decades, have uncovered new developmental opportunities, while simultaneously generating a host of critical challenges, thereby divulging the dual nature of these transformative forces. Therefore, even though modern cities operate as incubators of technology, innovation, investments, knowledge, entrepreneurship, creativity, culture, etc., they are also increasingly recognized as areas highly prone to acute problems and threats.

At present, approximately 56% of the global population—4.4 billion people—resides in urban areas, a figure projected to double by 2050, when nearly 70% of the world's inhabitants is predicted to be urban dwellers [5]. The frantically accelerating urbanization is primarily driven by the ongoing shift towards service-oriented economies in developed regions and the rapid industrialization observed in Southeast Asian countries. The constant concentration of population in urban areas has a catalytic effect on everyday life, economic activities, and social interactions. Established systems and services require significant restructuring in order to be consistent with the demands of this evolving landscape. However, the current architecture and operational mode of urban infrastructure, systems, and services are often ill-suited to adapt swiftly to such dynamic environments. Additionally, urbanization gives rise to several critical issues including overcrowding, housing crisis, proliferation of informal settlements, inadequate sanitation and water supply, public health risks, urban crime, heightened poverty levels, malnutrition, and obesity, among others.

Financial crises and fiscal imbalances—afflicting numerous cities around the globe—are frequently identified as some of the most pressing urban challenges, occupying a central position in nearly all current policies. This is largely attributed to the prevailing economic system's reliance on cities as engines of economic growth, with urban areas generating 80% of the global Gross Domestic Product (GDP) [2,5,6]. Yet, cities' magnitude in the economic status-quo is far from a novel phenomenon, since *"from their very inception, cities have arisen through the geographical and social concentration of a surplus product"* [7] (p. 5).

Urban unemployment remains a persistent and vexing issue, undermining both the livelihoods of residents and the overall functioning of urban communities, and drastically contributing to the emergence of social fragmentation phenomena. While unemployment is not exclusive to urban areas, the immense concentration of population within cities amplifies its severity, bringing about acute social tensions. Cities heavily dependent on specific industries or resources face additional challenges arising from market volatility, such as fluctuations in the price or demand for their goods and services.

Urban mobility and transportation represent another dire situation. Traffic congestion, in particular, has become an overwhelming burden for millions of urban inhabitants, as, apart from the lost time, it aggravates negative externalities like freight delay, inflationary pressure, and environmental damage. In 2023, the average American driver experienced 42 h of traffic delays, equating to a time loss valued at USD 733 and contributing to a total national cost of USD 70.4 billion. In the United Kingdom, drivers faced an average delay of 61 h, corresponding to approximately GBP 558 and a total loss of GBP 7.5 billion. Similarly, in Germany, the typical driver spent 40 h in traffic, amounting to an estimated individual loss of EUR 427 and a total national cost of EUR 3.3 billion in lost time [8].

The above issues are intricately interconnected, perpetuating a vicious cycle wherein financial instability undermines social cohesion, environmental crises exert economic and social pressures, and social disruption leads to further economic disarray. The underlying causes of these urban threats can be traced to four primary factors: urbanization, economic crises, climate change, and technological advancements. These factors directly trigger, are closely linked to, or function as catalysts for the challenges faced by cities at present.

The radical developments in Information and Communication Technologies (ICTs) have provided a multitude of diverse applications that support myriad urban operations, and deliver upgraded services to citizens, businesses, and both public and private agencies, thereby positively affecting promoted sustainable policies and cities' overall management [9–11]. These advancements offer remarkable potential to drive economic growth, improve organizational efficiency, boost governance, promote social equity, and elevate the overall quality of life in urban settings. As a consequence, policy makers and planners, in a bid to craft efficacious strategies for sustainable futures, increasingly rely on technological progress and its pertinent nascent opportunities. The technological evolution has also catalysed the emergence of innovative approaches, methodologies, tools, and techniques for achieving sustainability objectives, and has considerably broadened the scope for engaging citizens and stakeholders in these endeavors [12]. The latter is perceived by many researchers as quite critical for the successful treatment of contemporary urban predicaments [13–17].

In such a context, deeply marked by intractable urban challenges, but also by radical technological possibilities, the concept of smart cities comes to light as a novel tech-driven planning paradigm for effectively adapting to the evolving urban reality, a favourable strategy to many urban locales for steering economic competitiveness, innovation, environmental sustainability, and liveability [18–23], and mitigating the impacts of urbanization trends and the ensuing overpopulation pattern [24].

Despite its promising nature, a review of the literature unveils considerable heterogeneities concerning the meaning of the term smart city. A plethora of definitions, extending from purely technology-oriented views that perceive ICTs as the dominant developmental lever for urban environments, to broader and more integrated interpretations that incorporate aspects of society, economy, and governance, as well as participatory approaches for attaining sustainable urban development [10,25,26], have been introduced. Yet, the semantics of the term still remain a point of contention, reflecting the diverging perspectives across various academic and professional groups, and the consequent dearth of consensus on that matter. As a result, a notable gap in establishing and adopting a universally accepted understanding of the concept is detected. The absence of a holistic comprehension and documentation of the term, has, in many cases, failed to align the high expectations placed on the smart city notion—anticipated outcomes—with the outcomes ultimately achieved through the deployment of relevant technological applications [27].

Although the smart city paradigm has been gaining prominence globally as a new 'brand' and a transformative approach to urban planning [28], the way smart city performance can be assessed and monitored in terms of sustainability aspects remains unresolved. As highlighted in the Strategic Implementation Plan of the European Innovation Partnership on Smart Cities and Communities [29], despite several proposed well-established indicator frameworks, a widely accepted one that captures the 'smart city' dimension does not exist. This shortfall is primarily attributed to the lack of an unambiguous operational definition of the smart city term, whose conceptual exploration is still in progress [24,26,30,31].

Over recent decades, numerous organizations (e.g., International Standardization Organization—ISO, International Telecommunication Union—ITU, United Nations) have developed various indicator frameworks that are intended to assist urban planners and policy makers in shaping smart and sustainable urban futures and gauging urban sustainability progress [30,32–37]. The analysis of these frameworks unveils a wide range of differences among them, primarily originating from [30,34,38] their conceptual orientation and structure; the goal they aim to achieve; the methodological approach employed in assessing sustainability performance; their spatial scale; and the indicators they include. Nevertheless, the common foundation that they share regards their effort to foster sustainable urban development by synthesizing diverse data into relevant and applicable information and knowledge [39].

Furthermore, several noteworthy works that build upon this existing knowledge have made substantial contributions to the critical examination of smart city indicators. For instance, Bosch et al. [33] developed a comprehensive and robust framework (CITYkeys framework), which incorporates over 100 standardized indicators tailored for assessing smart city projects and the overall performance of smart cities. The framework is closely aligned with the goals of sustainability, innovation, and citizen engagement, while also harmonizing with broader initiatives, such as the United Nations Sustainable Development Goals (SDGs) and EU urban sustainability priorities, thereby ensuring its global applicability. The development process involved input from a diverse range of stakeholders, including local governments, industry experts, and citizens, which boosted the relevance and practicality of the indicators. However, the framework's reliance on extensive data and its predominantly European focus suggest that additional customization may be necessary to improve its applicability across different global contexts. Sharifi [36] provides a critical and insightful typology of smart city assessment tools and indicator sets, offering an in-depth analysis of their goals, methodologies, and applications. The study systematically classifies existing smart city assessment tools to identify their strengths, limitations, and areas for improvement, with a particular emphasis on their role in evaluating urban sustainability and smart city initiatives. The author also underscores the need for integrated, inclusive, and context-sensitive tools to address the complex challenges of urban sustainability. The provided recommendations constitute a valuable foundation for future advancements in the field, although a greater focus on real-world applications could further enhance its practical relevance. Adiyarta et al. [35] conducted a systematic review of smart city indicators across various studies and reports. The primary objective of the study was to identify trends, gaps, and overlaps in smart city indicator frameworks, focusing on their applicability to assess urban sustainability and smart city initiatives. The authors offer a rigorous and methodical review of existing smart city indicators, highlighting key trends and areas for improvement. Their emphasis on standardization, technological integration, and inclusiveness provides useful guidance for the development of future frameworks. However, a deeper exploration of practical applications and case studies would enhance the study's relevance to urban planners and policymakers.

The aforementioned studies, along with other related works in the field, represent significant and well-established contributions to the classification and the thorough exploration of the extensive pool of available smart city indicators. These works unveil, inter alia, a notable lack of consensus regarding the adoption of an optimal conceptual framework and standardized approaches for measuring urban sustainability, as well as the selection of the most appropriate methodologies to be employed. Moreover, it is evident that limited progress has been made in assessing cities' performance with respect to their endeavors to promote the recently emerging goals of resilience and inclusiveness. Similarly, efforts to identify disaster-related risks and stresses and to develop effective preparedness strategies to address these challenges remain relatively underexplored [34,40].

In addition to the above, the selection procedure and deployment of the most appropriate framework has proven to be a complex and intriguing issue that requires expert knowledge [11]; it has also provoked intense confusion, thereby hindering planners and decision makers in their efforts to properly monitor urban projects. In many cases, the process ends up with insufficient performance metrics and/or equivocal definitions of these metrics that impede the replication of successful practices [41,42]. Moreover, concerns about transparency in the selection of indicators have fostered certain skepticism, raising questions about their reliability and soundness, and suggesting potential biases that favour pre-determined policy agendas.

Finally, the proliferation of emerging smart technologies and their largely uncharted impacts on urban sustainability further complicate the evaluation processes, since a solid foundation of empirical evidence is missing [43].

The profound definitional polyphony [26,31,40] surrounding the smart city term that has rendered it an exceptionally ambiguous, confusing, and contentious concept; the lack of a universally established and accepted definition and the consequent interoperability challenges; and the current experience and knowledge gained through various smart city initiatives underscore the overwhelming dominance of technology-driven strategies and the limited effectiveness of such approaches across multiple urban dimensions. This emphasizes the necessity of clearly delineating the various interpretations, uses, and applications of smart cities by examining the underlying concepts and their interrelationships. In other words, it requires a deeper understanding of a city's ontology, as a foundational step, followed by the integration of this ontology with that of technology or various smart applications [27].

Numerous studies [27,44–48] support that ontologies and semantic technologies are widely applicable in the field of smart cities, with communities, crisis management, e-learning, economics, energy, environment, health, home, public administration, risk management, security, social systems, sustainable development, and urban planning being the city sectors in which semantic approaches have been applied [47]. These technologies have progressively permeated this scientific domain, emerging as a novel and promising research area with substantial potential in terms of prospects and outcomes. An ontology, defined as *"a formal, explicit specification of a shared conceptualization"* [49] (p. 184)—that is, a formal description or representation of knowledge within a particular scientific domain—provides the essential concepts to be modelled along with their interrelations. Ontologies have been employed in various fields including medicine, biology, law, engineering, robotics, artificial intelligence, and geography, and they are especially valuable in applications that require a shared understanding among diverse actors (semantic Web, information extraction, retrieval, integration, etc.).

In light of these observations, the present paper aims at exploring, analyzing, and formalizing the semantics of the smart city terminology by developing a new conceptual model that aspires to [40]:

- Describe the essential building blocks/key drivers/fundamental concepts of the smart city (classes of the ontology), based on the findings, empirical evidence, and recommendations derived from the international literature.
- Delineate the direct relations between the ontology's fundamental classes in order to capture the dynamics of their interactions.
- Integrate a unified, multidimensional, global indicator framework into the ontology, thereby embedding the dimensions of smartness, sustainability, resilience, and inclusiveness into the new conceptual model, and, finally, providing a useful planning tool for performance assessment and benchmarking purposes.

2. Methodological Approach for Building the New Ontological Scheme

The construction of the new ontology for smart, sustainable, resilient, and inclusive cities (henceforth S2RICO), is the outcome of a painstaking work that includes multiple methodological steps illustrated in Figure 1 and described below [40].

- Step 1—'Demarcating the contextual background': serves as the backbone of the entire research and endeavors to detect and analyze the major challenges and threats—the actual instigators of the colossal smart city wave—that hammer contemporary urban environments.
- Step 2—'Setting the scene': delves into the emerging concept of smart cities, tracing its diachronic evolution and spatial expansion in order to provide a comprehensive

understanding of its significance and transformative potential. The key elements and defining characteristics of smart cities, such as advanced technologies, data-driven and knowledge-based decision-making processes, as well as sustainable urban practices, are critically examined. Particular focus is placed on the deep impact of technological advancements on fostering smart, sustainable, resilient, and inclusive urban development. This step also explores how technological innovations have revolutionized urban planning and management, thus enabling the shaping of more efficient, equitable, and environmentally friendly cities. Additionally, the most prevalent state-of-the-art technologies and tools, used to effectively implement (participatory) spatial planning exercises in the smart city context, are outlined. Moreover, this step offers a glimpse into real-world examples of smart, sustainable, resilient, and inclusive cities (S2RICs) and inspects noteworthy case studies that embody the principles and goals of S2RICs. The investigation of successful examples uncovers valuable insights into the practical implementation of smart city initiatives and the integration of sustainability, resilience, and inclusiveness goals.

- Step 3—'Embedding the notions of smartness, sustainability, resilience, and inclusiveness'*:* includes the process of structuring and deploying a multifaceted, integrated, and comprehensive indicator framework for assessing the performance of smart, sustainable, resilient, and inclusive cities (S2RICs). It digs into the complexities involved in evaluating the effectiveness and impact of urban development initiatives within the S2RIC paradigm, emphasizing the urgent need for a holistic and multidimensional approach to performance measurement. In particular, this step focuses on the formulation of a robust and comprehensive set of indicators that encompass various dimensions of urban performance, including social equity, environmental sustainability, economic vitality, and technological innovation. These indicators aim to capture the nuanced and interconnected aspects of urban development within the S2RIC framework, ensuring a balanced and thorough evaluation process. The proposed indicator framework may serve as a valuable tool for policy makers, urban planners, and researchers, to assess and monitor the progress of S2RIC initiatives effectively, thereby facilitating evidence-based decision-making and fostering continuous improvement. The unified indicator framework is constructed on the basis of a thorough exploration of seven global, widely recognized indicator frameworks, pertinent to the evaluation of urban sustainability performance (see Figure 1), and comprises 597 indicators in total, out of 1096 indicators that were initially inspected; its conceptual design is roughly sketched in Figure A1 of Appendix A.1.
- Step 4—'Delving into the ontological reality: provides a general overview of the scientific field of semantics and ontologies and explores various smart city ontological representations. It investigates how ontologies can be employed to capture the intricate interdependencies and relations that exist within the smart city systems, facilitating in this way comprehensive knowledge representation. Moreover, this step offers a structured framework for organizing and managing information through the utilization of ontological models, thus enabling the development of intelligent systems and decision support tools that are better equipped to address urban challenges effectively.
- Step 5—'Development of an OWL ontology for Smart, Sustainable, Resilient, and Inclusive (S2RIC) cities: is the core of the present paper and thoroughly describes the developmental procedure of the S2RIC Ontology (S2RICO), an ontological representation specifically designed to integrate the assessment of smart, sustainable, resilient, and inclusive cities' performance into the planning practice. It outlines the conceptual framework and methodology employed to construct the S2RICO and provides valuable insights into the processes and considerations involved in creating a

comprehensive knowledge model. The S2RICO may serve as a powerful tool for researchers, policymakers, and urban planners to grasp and overcome the complexities of S2RIC environments and assist them in incorporating data-driven, holistic approaches to urban development.

It is important to emphasize that the initial four methodological steps not only facilitate a deeper comprehension of the smart city paradigm and its associated components, but also offer valuable input to the development of the new ontological scheme, since numerous concepts, relations, and attributes are derived from them.

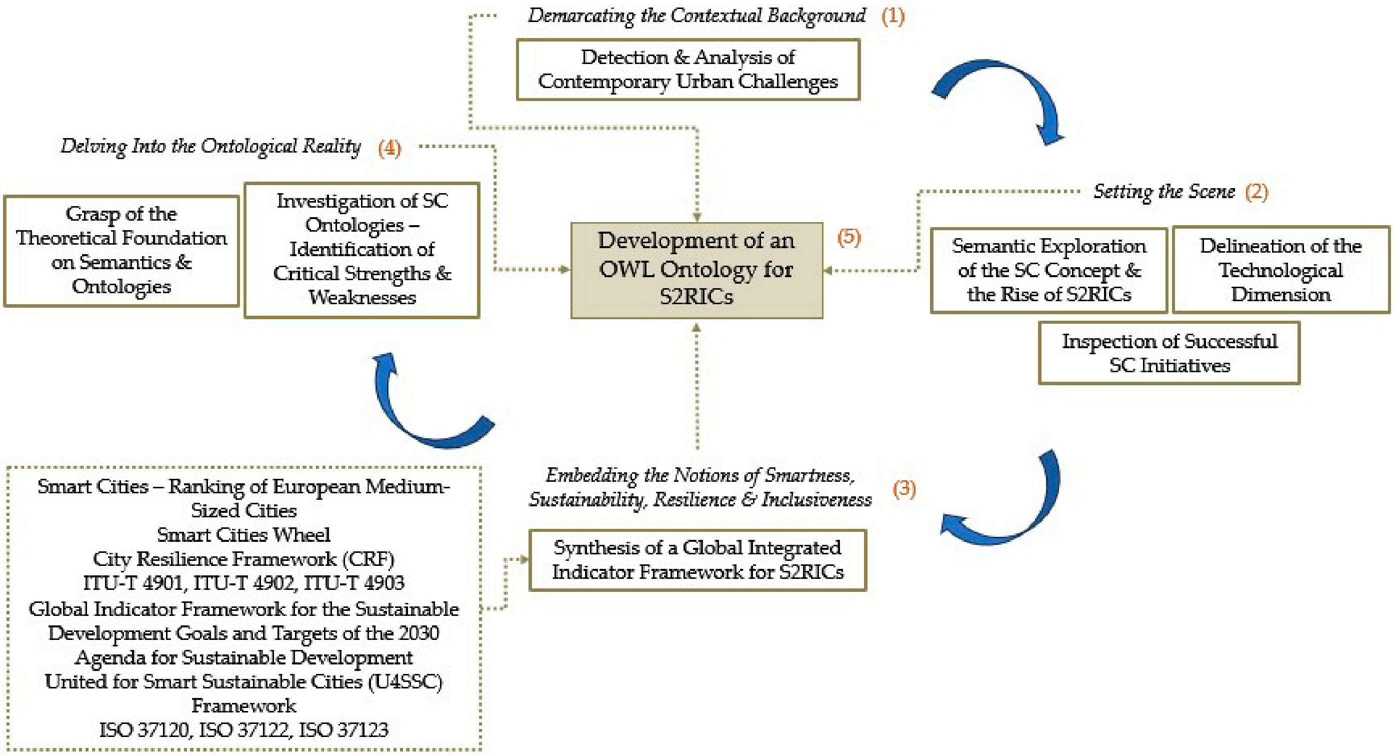


Figure 1. Methodological approach for building the proposed ontological scheme.

3. Materials and Methods

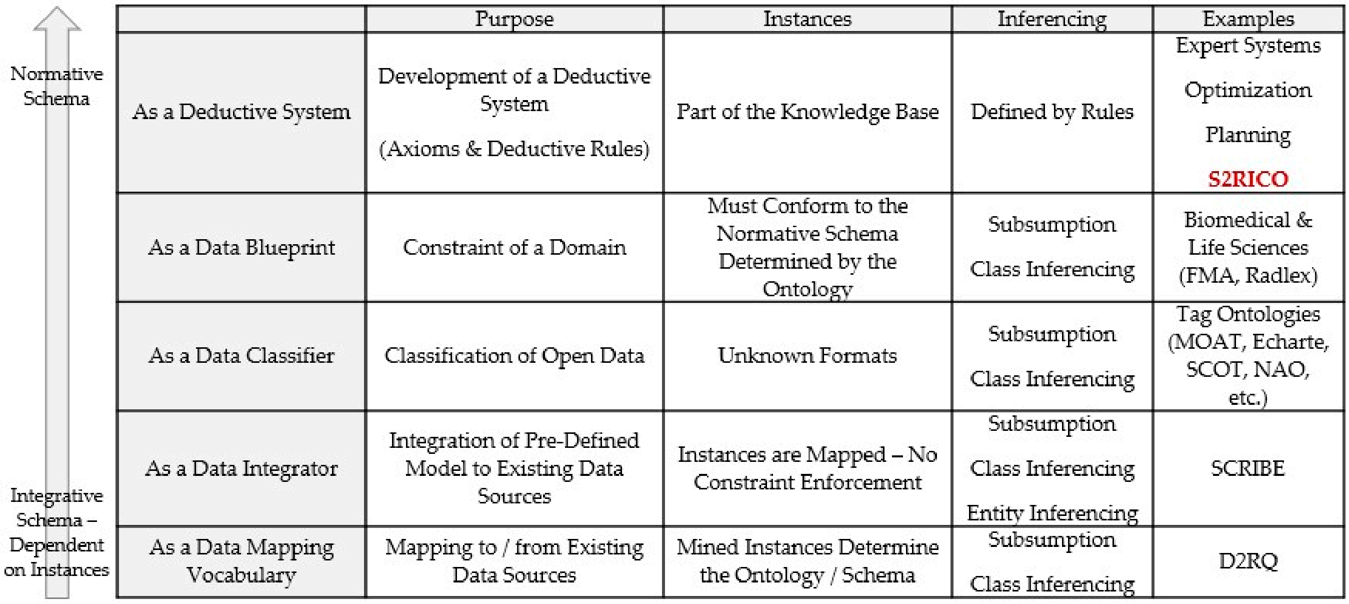
This section outlines the process of constructing the ontological scheme for smart, sustainable, resilient, and inclusive cities (S2RICs). The primary goals of this ontology focus on the [40]:

- Semantic exploration of the smart city concept by identifying its main key drivers/core components (classes);
- Delineation of their direct interrelationships (object properties);
- Provision of a common formal language and understanding among the different actors;
- Integration of a global, unified indicator framework into the ontological scheme.

The latter is intended to embed contemporary urban planning concerns/dimensions (sustainability, resilience, and inclusiveness) into the smart city discourse, provide planners and policy makers with structured guidance for navigating into this framework and selecting proper indicators for assessing urban sustainability achievements, and serve as a benchmarking tool for comparative analysis.

In general lines, the S2RICO is expected to support urban planning and more informed policy decisions (type of (spatial) interventions, focus sectors, smart applications that should be deployed, etc.) by feeding relative decision-making processes with the necessary organized knowledge, thus rendering the whole planning procedure more integrated, innovative, efficient, as well as citizen- and city-oriented.

Ontologies are built and utilized to encapsulate domain-specific knowledge by describing the essential elements (concepts) of the domain and mapping their interrelations. However, they can vary significantly in terms of their design, structure, scope, and application [50]. They are not intended to serve as one-size-fits-all tools; instead, their quality and effectiveness depend on the specific goals they aim to achieve and the context in which they are developed and used (Figure 2). Some ontologies may be simple, representing only basic relations between concepts, while others may be highly complex, incorporating advanced reasoning mechanisms, multiple layers of abstraction, and dynamic inference. This variability entails that an ontology's usefulness and success depend on how well it aligns with the requirements of the problem it is designed to treat.



	Purpose	Instances	Inferencing	Examples
As a Deductive System	Development of a Deductive System (Axioms & Deductive Rules)	Part of the Knowledge Base	Defined by Rules	Expert Systems Optimization Planning **S2RICO**
As a Data Blueprint	Constraint of a Domain	Must Conform to the Normative Schema Determined by the Ontology	Subsumption Class Inferencing	Biomedical & Life Sciences (FMA, Radlex)
As a Data Classifier	Classification of Open Data	Unknown Formats	Subsumption Class Inferencing	Tag Ontologies (MOAT, Echarte, SCOT, NAO, etc.)
As a Data Integrator	Integration of Pre-Defined Model to Existing Data Sources	Instances are Mapped – No Constraint Enforcement	Subsumption Class Inferencing Entity Inferencing	SCRIBE
As a Data Mapping Vocabulary	Mapping to / from Existing Data Sources	Mined Instances Determine the Ontology / Schema	Subsumption Class Inferencing	D2RQ

Figure 2. Categories of ontological schemata (adapted from [50]).

Pursuant to Figure 2, ontologies satisfy a variety of purposes, including data mapping vocabularies, data integrators, data classifiers, data blueprints, and deductive systems. S2RICO, specifically, falls within the latter category, operating as a deductive system that makes inferences based on defined constraints (axioms and rules), while offering an instantiated knowledge base. In essence, S2RICO organizes knowledge in a structured format, which is then processed using logical rules to derive conclusions from that available knowledge.

The latest advancement in standard ontology languages is the Ontology Web Language 2 (OWL2), developed by the World Wide Web Consortium (W3C). OWL 2 is a logic-based ontology language that incorporates classes, properties, individuals (instances), and data values, enabling the representation of intricate domain knowledge. It can be subjected to reasoning either to verify an ontology's consistency, or to render implicit knowledge explicit [51].

The S2RICO (OWL-based ontology) is structured using the Protégé 5.5.0 software, which is a free and open-source editor for developing, visualizing, and maintaining ontologies and supports numerous reasoners—tools used to validate ontological consistency and infer new information—and several additional knowledge management tools (plugins) [52].

Reasoners are automated computational tools designed to analyze and derive logical consequences and relations within a given ontology. They apply a set of logical rules and inference mechanisms to extract implicit knowledge from the explicit statements and relations encoded in the ontology [53–55]. By employing various reasoning techniques, such as deduction, classification, and inference, reasoners are able to [53,54] identify implicit facts that may not be directly defined in the ontology; investigate class satisfiability (check out whether it is possible for a class to have instances without provoking consistency errors); classify entities (determine the IS-A relations between classes, which is especially useful in cases of multiple inheritance); validate and verify ontologies by detecting logical inconsistencies and contradictions, thus ensuring the integrity and reliability of the knowledge representation scheme; conduct instance checking; and support advanced querying capabilities (complex queries that involve logical relations and constraints). Therefore, reasoners enhance the effectiveness of knowledge retrieval and boost more informed decision-making processes.

For the implementation of the S2RICO, the Pellet reasoner is employed. Pellet is a high-performance reasoning engine, designed to work with OWL ontologies, and presents several advantages such as scalability (capacity to handle ontologies with thousands or millions of concepts, properties, and individuals), expressive reasoning, rule-based reasoning (extension of reasoning capabilities by supporting rule-based reasoning using Sematic Web Rule Language (SWRL)), modularity and extensibility, compatibility and interoperability, active user community, and rich documentation [56].

3.1. Catalysts for the Development of the S2RICO Scheme

The most significant factors that have guided the development of the S2RICO are divided into two broad categories, on the basis of how imperatively they necessitate the structuring of this conceptual model (Figure 3).

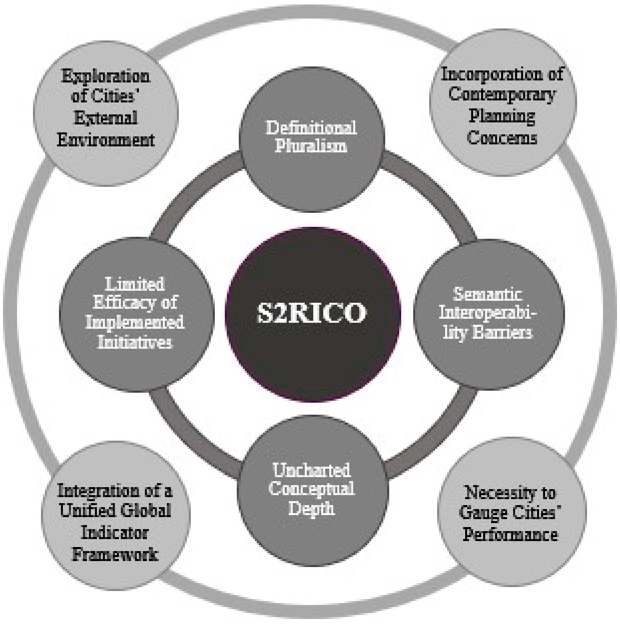


Figure 3. Decisive factors for the development of the S2RICO [40].

As illustrated in Figure 3, the most critical drivers (primary factors) underlying the development of the S2RICO are highlighted in darker grey color and form a smaller circle that surrounds the S2RICO concept. These factors are directly associated with the intense definitional pluralism and conceptual ambiguity inherent in the smart city term, which, in turn, have led to significant gaps in semantic interoperability. Moreover, the absence of a clear understanding regarding the fundamental components of smart cities and their interrelations, as well as the way smartness is operationalized in real urban environments, has induced substantial confusion among policy makers, planners, urban stakeholders, and municipal authorities, often resulting in ineffective or partially successful smart initiatives [40].

The less critical but still influential drivers (secondary factors) are shaded in lighter grey and form a larger circle encompassing both the S2RICO model and the primary factors. These emphasize the need to incorporate contemporary urban planning priorities (related to sustainability, resilience, and inclusiveness), as well as urban challenges and threats—often external in nature—that are either absent or insufficiently addressed in most existing smart city ontologies. Furthermore, the structuring of a unified indicator framework—founded on cities' exigent need to evaluate their performance in terms of smartness, sustainability, resilience, and inclusiveness—completes the set of secondary factors. This framework is intended to guide cities in selecting the most suitable metrics, while ensuring consistency among indicators developed and established by various standardization bodies, thereby reinforcing the rationale behind the construction of the S2RICO [40].

3.2. Steps of Ontological Development

Numerous methodologies for ontology development have been proposed [57–61], yet it is widely accepted that no single approach can be deemed definitely correct or incorrect. Conversely, there are always multiple, viable methods for structuring an ontological representation, with the final model largely influenced by the goals and expectations of its creator [62]. Ontology's domain and scope constitute two decisive factors that guide the adoption of the most appropriate methodology. Furthermore, ontology development is inherently iterative, requiring continual revision throughout its entire lifecycle. It is essential that the concepts included in an ontology correspond closely to relevant objects—whether physical or logical—and the relations applicable within a certain domain. In essence, the purpose for which the ontology is constructed, as well as the desired level of granularity (depth of the hierarchical structure), lead to various modelling decisions [62].

Given the absence of a standardized and rigid methodology for building ontologies, the steps of ontological development followed in the case of the present study are aligned with a set of general and empirical stages of ontological design and implementation, articulated by Noy and McGuinness [62]. These include:

- Demarcation of the domain and scope of the ontology.
- Reuse of existing ontologies.
- Enumeration of key domain-specific terms.
- Definition of classes and class hierarchy.
- Establishment of relations between classes.
- Assignment of properties and their respective values to classes.
- Addition of instances.

3.2.1. Demarcation of the Domain and Scope of the Ontology

The development of an ontological scheme should commence with a clear and explicit definition of its domain of interest and scope. This process necessitates careful consideration of several fundamental questions [62]:

- Which specific domain will the ontology cover?
- What are the underlying objectives for its creation?
- What types of questions is the ontology expected to resolve?
- Who constitutes the target audience, and who will be responsible for its ongoing maintenance?

In the context of this work, the field of smart cities—viewed through the lens of urban and developmental planning—has been identified as the domain of interest. The scope of the S2RICO encompasses several critical objectives, namely, gaining a deep insight into smart urban environments, as these are delineated by the available literature; addressing the pervasive issue of definitional impreciseness of the term smart city—which has induced significant semantic ambiguity and polysemy challenges and, therefore, a dearth of semantic interoperability—through the establishment of an integrated and cohesive conceptual basis; coping with the absence of a universally accepted indicator framework that adequately reflects current urban stresses and developmental goals (sustainability, resilience, inclusiveness) by integrating a relevant, unified, global indicator framework into the new scheme; delivering a conceptual tool for assisting planners and policy makers in grasping smart cities' foundational elements and their interrelations; developing a navigational guide for selecting the most appropriate indicators for assessing the performance—in terms of smartness, sustainability, resilience, and inclusiveness—across various urban sectors; and serving as a benchmarking instrument.

3.2.2. Reuse of Existing Ontologies

Use of existing ontologies or controlled vocabularies is a common, though not a mandatory practice of the ontological development process. Some of these resources may comprehensively cover the domain of interest, address it partially, or model related domains [62]. Therefore, it is prudent to examine whether these 'external resources' can be used as the grounds for developing a more target-oriented ontology. Ontology reuse entails the construction of a new ontology *"through maximizing the adoption of pre-used ontologies or ontology components"* [63] (p. 318), and offers several benefits, such as improving the quality of the developed ontology, facilitating mapping among input ontologies, and enabling ontology update [63].

At this preliminary stage of the S2RICO construction, no existing ontology has been incorporated into the new scheme. Nonetheless, the reuse of well-established ontological representations is anticipated to occur during the revisional phase of the initial model, ensuring that S2RICO remains robust, adaptable, and comprehensive in addressing the targeted domain.

3.2.3. Enumeration of Key Domain-Specific Terms

This stage involves the identification and compilation of all terms considered essential for describing the ontology's domain of interest; and may refer to concepts, relations, or properties, without taking into account any semantic equivalence or overlap at this phase.

Drawing from the thorough analysis of the profusion of smart and/or smart and sustainable cities' definitions (step 2 of the adopted methodological approach of Figure 1), all the fundamental components of these terms, their interrelations, and several of their attributes are collected and used as valuable input. In addition, the global indicator frameworks that are inspected (step 3 of the adopted methodological approach of Figure 1) provide an indispensable repository of concepts that further enrich the ontology.

It should be mentioned that several terms related to contemporary urban opportunities and threats emerged from a participatory procedure conducted during the 4th Euro-Mediterranean Conference, which was held in Athens in October 2020. Part of the conference was dedicated to a stimulating dialogue among scientific, entrepreneurial, and policy-making communities on the topics raised by the European "Green Deal" and particularly the "Mission for Climate-Neutral and Smart Cities". The discussion aimed at identifying opportunities and challenges associated with the downscaling of the Green Deal, as well as the Climate-Neutral and Smart Cities' priorities and targets to the regional and municipal levels [64]. In order to enrich the S2RICO, a well-structured questionnaire was distributed to 284 people in total, so as to detect and prioritize the key issues and obstacles with regard to the implementation of the above strategies. Respondents were given one month to fill in the questionnaire and, finally, 81 answers were received (28% of the initial sample). Despite the limited participation, it was decided to use the obtained preliminary results (derived concepts pertinent to contemporary urban challenges) and incorporate them in the S2RICO, since these originate from carefully selected city experts, policymakers, and researchers with massive experience in urban issues, thereby ensuring the quality and relevance of the insights gathered.

In the complementary part of the questionnaire, respondents were asked to describe their perceptions of modern cities using three keywords that encapsulate both positive and negative aspects, currently evolving or expected to affect future urban developmental trails in the medium to longer term. Based on the answers received, a word cloud (Figure 4) that highlights contemporary urban strengths and vulnerabilities was produced. Most of these terms are added in the S2RICO, specifically into the UrbanChallenge super-class, as detailed in the subsequent steps of the ontology development process.

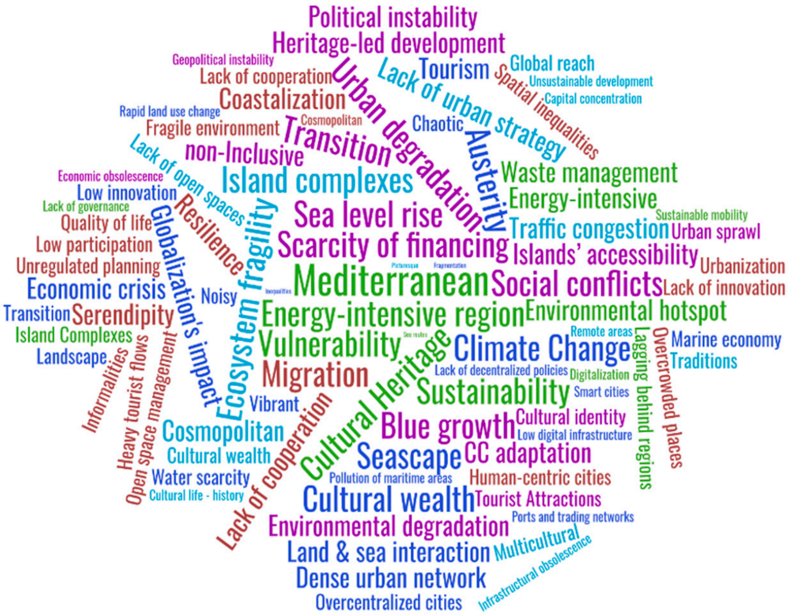


Figure 4. Cloud of terms regarding contemporary urban opportunities, challenges, and threats [64].

Finally, it is important to note that although the questionnaire's spatial focus was on the Mediterranean Region, most of the identified keywords were retained and incorporated into the ontology. This decision reflects the fact that these terms represent global challenges and threats, albeit with varying degrees of intensity compared to the Mediterranean context.

3.2.4. Definition of Classes and Class Hierarchy

This phase marks the initial organization of the terms gathered during the preceding step (enumeration of important terms in the ontology). Particular attention is devoted to ensuring their proper classification, thereby creating hierarchical structures that accurately represent the domain of discourse and fulfill the ontology's intended purpose. Terms representing entities characterized by independent existence are selected as classes, which serve to encapsulate all entities included in a concept and are associated with other classes through hierarchical (IS-A) relations.

Considering the very nature of the collected terms, but also the various proposed taxonomies and classifications emerging from the available international literature, nine super-classes that describe cities' main physical, digital/technological, social, institutional, and functional aspects are defined (Figure 5). Six of them (EconomyAspect, EnvironmentAspect, PeopleAspect, LivingAspect, TransportAspect, and GovernanceAspect) correspond to the six fundamental smart city characteristics as firstly articulated by Giffinger et al. [65]; i.e., smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. The seventh class, UrbanChallenge, includes concepts tied to contemporary urban issues, with the majority of them outlining the external decision environment. The eighth class, Indicator, includes all the indicators that comprise the integrated global indicator framework formed in the context of this work, while the ninth class, TechnologyAspect, reflects cities' digital skin, which permeates every urban facet, with particular focus on ICT infrastructure, online services, data, and applications.

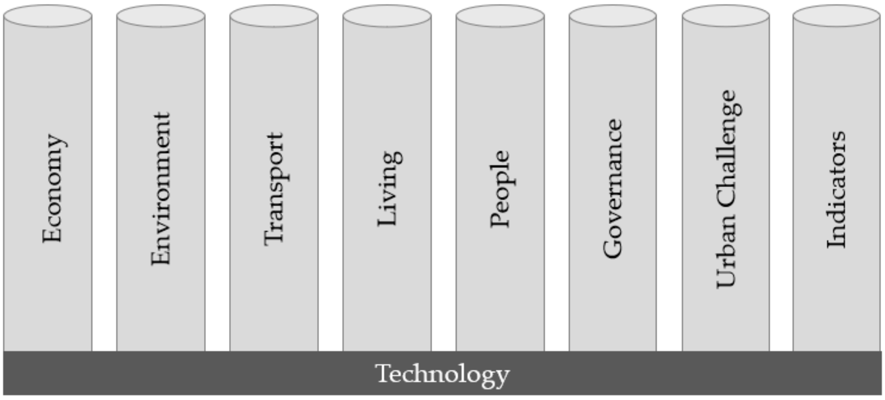


Figure 5. Super-classes of the S2RICO and the traversal nature of technology (adapted from [35]).

These nine super-classes of the S2RICO are in consistence with the three core dimensions of smart cities, as these are solidified by Nam and Pardo [66], namely, technological dimension, institutional dimension, and human dimension. The TechnologyAspect class describes the technological/hard dimension; the EconomyAspect, EnvironmentAspect, PeopleAspect, LivingAspect, and Transport&MobilityAspect classes demarcate the human (urban socio-economic) dimension; while the UrbanChallenge, Indicator, and GovernanceAspect classes represent the institutional dimension. Together, these super-classes consist of concepts that cover all the three different types of spaces—physical, social, and digital—that any modern city is composed of [67].

Additionally, it should be stressed that the nine super-classes incorporate both static and dynamic facets of contemporary urban environments [27]. Static facets refer to cities' entities that continue to exist through time (e.g., country, person, building, road, bridge), whereas dynamic facets focus on the operation and functions of urban systems and allude to processes of any kind (e.g., operation of city services, emergency response, innovation, learning and knowledge processes). These types of entities reflect the continuant and occurrent entities that are met in top-level ontologies. Continuants represent entities that exist in time while maintaining their identity, i.e., entities that are grasped as complete concepts at any point in time. On the contrary, occurrents describe entities which happen, unfold, or develop through time, i.e., entities that only a part of them can be perceived by someone at a given moment in time (e.g., an earthquake or a hurricane). Grenon and Smith [68] and Smith and Grenon [69] point out that occurrents are events in which continuants are involved. Moreover, it is noted that both continuants and occurrents extend to space and time, while their distinction allows for the classification of real-world entities, such as objects, processes, events, and states [70].

The final hierarchical structure (first and second level classes) of the S2RICO is presented in Figure A2 of Appendix B.1.

3.2.5. Establishment of Relations Between Classes

Apart from the hierarchical relations established in the former step, there are other types that connect the classes to each other, e.g., has part, contributes to, affects, provokes, increases, activates. It is essential to define and describe these relations in order to provide a comprehensive understanding of the interactions and interdependencies between the concepts. The importance of getting a deep insight into the relations developed between the elements of a smart city is aptly summarized in the words of Kanter and Litow [71] (p. 2), who state that *"A smarter city should be viewed as an organic whole—as a network, as a linked system. In a smarter city, attention is paid to the connections and not just to the parts. Civic improvement stems from improved interfaces and integration"*.

However, considering the innate complexity of cities and the impracticality of attempting to capture every possible relation between the S2RICO classes and sub-classes due to their sheer volume and the inevitable confusion this would cause—not to mention that such an endeavor would be completely futile, since all urban subsystems are interconnected, either directly or indirectly—it was decided that only the direct relations between the indicators (sub-classes of the Indicator super-class) and the core thematic categories/classes of the S2RICO will be mainly modelled.

The delineation of these relations is supported by a matrix that associates all the indicators of the global integrated indicator framework (Step 3 of Figure 1) with the fundamental concepts (core classes of the ontology) that refer to modern urban environments. To clearly demonstrate how the indicators address their thematic linkages (their interactions with the principal urban elements), in Table A1 of Appendix B.2, an overview of their potential to assess progress towards smartness, sustainability, resilience, and inclusiveness across the basic classes of the ontology is presented.

According to Table B1, the classes to which the indicators primarily apply are shaded in black and grey. Black indicates a very clear, strong, direct relation, while grey signifies a clear, direct, but less intense link, compared to the black color.

In OWL, relations between classes or individuals are represented by the so-called object properties. In the case of the S2RICO and the modelling of the relations between the indicators and other classes of the ontology, two inverse object properties are defined, isStronglyAssociatedWith and isRelatedTo. The first one reflects strong, direct relations of the constructed matrix, shaded in black color, while the second describes direct but weaker relations, shaded in grey.

It is worth mentioning that the use of isStronglyAssociatedWith and isRelatedTo relations is accompanied with the necessary quantifier existential restrictions, which entail that a property must have some or all values of a particular class. Existential restrictions represent classes of individuals that participate in at least one relation along a specified property. For example, the restriction isRelatedTo some UrbanPlanning is an existential restriction, which restricts the isRelatedTo object property to the UrbanPlanning realm. In other words, this restriction describes the class of all the individuals that have at least one isRelatedTo relation to an individual that is a member of the UrbanPlanning class. Apart from the isStronglyAssociatedWith and isRelatedTo relations, the S2RICO ontology includes many more object properties that connect the classes and the individuals to each other, such as hasPart, isPartOf, hasInput, hasOutput, hasValue, activates, creates, contains, increases, affects, causes, facilitates, funds, emergesFrom, etc.

3.2.6. Assignment of Properties and Their Respective Values to Classes

Aside from the object properties whose range and domain correspond to classes, there are also properties—henceforth data properties—whose range is defined as a simple datatype (e.g., string, integer, float, date). The distinction between object and datatype properties in OWL mirrors the differentiation between associations and attributes in the Unified Modelling Language (UML), or between relations and attributes in Entity-Relationship (E-R) modelling [55].

Within the S2RICO context, key data properties that assign values to classes and instances include population metrics, building, green, population densities, energy consumption metrics, environmental metrics, hospitality and culture metrics, etc. Most of them are derived from well-established frameworks, proposed by international organizations (e.g., International Organization for Standardization—ISO), or are included in the Innovation CitiesTM Index [72].

At this point, it should be highlighted that in most of the existing smart city ontologies, incorporated indicators are defined as data properties and not as classes, contrary to the case of the S2RICO. It could be argued that since the indicators' range is a simple datatype and not a concept (class), these should be declared as data properties in an ontological schema. This is a quite interesting observation, considering that terms with exactly the same meaning can be defined as classes within a specific hierarchy or as properties within another.

Whether a term will be ultimately defined as class, property of a class, or value of a property of a class has been a topic of intense discussion between Noy and McGuiness [62], who point out that this largely depends on (i) the purpose an ontology is developed for; (ii) the significance of the term to the domain of interest; and (iii) if declaring this term as a property of a class (or value of a property) will cause any changes to the relations of this class with other classes. It is also stressed that if a certain distinction is quite important for the domain of interest and objects with different values of this distinction are considered to be of different types (as in case of embedded indicators), then a new class should be created for the given distinction.

Lastly, the decision to define indicators as classes has to do with the very nature of data properties. Data properties are less powerful than OWL objects, since they lack many of object properties' capabilities, such as having an inverse property or being transitive [55], thereby considerably limiting—inter alia—ontologies' inference mechanisms.

3.2.7. Addition of Instances

The S2RICO is populated with the smart initiatives, projects, and applications of successful smart city examples that are thoroughly explored during the second step of the methodological approach.

3.3. Creation of Defined Classes—Query and Reasoning

All the S2RICO classes analyzed so far are primitive classes, meaning they rely solely on necessary (but not sufficient) axioms that must be met by all their instances (if something is a member of class A then it is necessary to fulfill these conditions/axioms). However, in order to take further advantage of the reasoning capabilities offered by ontologies, it is possible to create defined classes, i.e., classes determined by both necessary and sufficient conditions, which render implicit knowledge explicit. Therefore, when the reasoner encounters an individual that satisfies all the conditions of a specific defined class, it will deduce that it is an instance of that class. Moreover, the reasoner uses the necessary and sufficient conditions of a defined class to change the class hierarchy (e.g., to infer that a class A is a sub-class of class B, as in the case of S2RICO) [55].

Focusing on the S2RICO, numerous defined classes (currently 33) are created using Description Logic (DL) axioms, so as to make inferences on the incorporated indicators, on the basis of the object properties that have been established in a former step (see "Establishment of relations between classes"). Specifically, the defined classes are used to automatically categorize all the indicators that are related to particular concepts. Such functionality allows users to pose complex questions to the ontology and obtain meaningful responses, thereby facilitating informed decisions and policymaking [48].

In closing, the S2RICO contains:

- 1032 classes (the multitude of classes is due to the large number of indicators included in the ontology);
- 46 object properties;
- 50 data properties;
- 68 individuals;
- 9 annotation properties.

The S2RICO file and the matrix that contains all the relations between the indicators and the classes of the ontology are accessible through the link: https://drive.google.com/drive/folders/1rSywDqdWN-PZQ0Tg9Z9x11ewqBp6LIdQT?usp=sharing (accessed on 11 September 2024).

4. Discussion

While the development and application of the S2RICO may exhibit significant potential in the planning realm, several critical considerations should be taken into account to ensure its continued efficacy and relevance. Chief among them is the degree of *subjectivity*, which appears in different ways during the various stages of the ontology construction process. The most complex manifestation of subjectivity lies in the selection of concepts and relations. These decisions may inadvertently reflect the personal biases or perspectives of the developers or domain experts involved, potentially leading to ontologies that lack representational diversity or are skewed towards specific viewpoints. A key strategy to mitigate such subjectivity concerns during the revisional phase of S2RICO is to involve multiple stakeholders. This collaborative approach helps to safeguard the ontology's multidimensional character, thereby reducing bias and minimizing inconsistencies.

In close connection to the former remark, conducting extensive participatory workshops is deemed to be absolutely essential throughout the update phase of the S2RICO. Engaging stakeholders ensures the ontology's alignment with its intended domain of interest and user requirements. More specifically, by involving various actors in the S2RICO update procedure, it is possible to [40]:

- Ensure the relevance of the represented domain. Stakeholders are an indispensable source of domain knowledge, experience, and expertise. Therefore, their engagement guarantees that the ontology reflects accurately key concepts, relations, and pertinent terminology.
- Enhance usability. Feedback provided from participants regarding the ontology's structure, terminology, and user interface helps refine the ontology, making it more accessible and functional.
- Foster broader adaptation. Engaged stakeholders are more likely to use and promote the ontology within their networks, organizations, or communities.
- Improve quality. Diverse and broad participation facilitates the identification of ontological errors, inconsistencies, or gaps, thereby boosting its completeness, accuracy, and applicability.

Future research into the S2RICO predicts expanding the ontological scheme by incorporating additional concepts, relations, properties, and instances derived from international literature and empirical findings. Furthermore, widely recognized and fully documented lightweight ontologies and vocabularies, such as the Dublin Core (DC) ontology, a Resource Description Framework Schema (RDF-S) vocabulary for describing generic metadata, and the Friend of a Friend (FOAF) ontology, a dictionary of properties and classes that describes persons, their activities, and their relations to other people and objects, are expected to enrich the S2RICO.

Apart from the refinement, update, and extension of the S2RICO, future research efforts will also focus on its application and validation through a real-world case study. This phase aims at evaluating the practical effectiveness, relevance, and adaptability of the ontology when applied to actual urban planning projects. The process will involve close collaboration with urban planners, policymakers, and relevant stakeholders to ensure a thorough, transparent, and participatory testing procedure. Additionally, it is expected that the case study will allow for the identification of potential gaps, limitations, or areas for improvement, enabling iterative refinement of the ontology and enhancing its robustness for broader applications in diverse urban contexts.

Ultimately, a pivotal area for future research revolves around linking the S2RICO to a top-level ontology (e.g., Basic Formal Ontology—BFO, General Formal Ontology—GFO, Descriptive Ontology for Linguistic and Cognitive Engineering—DOLCE, Suggested Upper Merged Ontology—SUMO). Such integration ensures that the ontology adheres to a shared top-level scheme, facilitating compatibility across multiple ontologies that follow a common architectural framework [73].

It is important to acknowledge that ontology development is an inherently dynamic and iterative process, necessitating continuous refinement and adaptation to remain effective. As urban environments evolve and encounter new challenges, the ontology must be responsive, integrating emerging trends, advancements in technology, and shifting priorities. To maintain its relevance and utility as a practical instrument for planning and evaluating smart cities, it is essential to conduct regular updates and revisions. These updates should be guided by the latest research, active involvement of stakeholders, and adherence to established best practices. This approach will ensure that the ontology evolves in tandem with the complexities of urban systems, securing its role as a vital resource for sustainable urban development.

At this point it should be mentioned that aside from the possible positive outcomes of the S2RICO's practical application that is expected to take place the following months, there are a series of considerations and limitations inherent in the implementation phase of such ontological schemata and refer to:

- Challenges in ontology maintenance: maintaining a smart city ontology represents a critical technical aspect that should be taken into account during its design and development process. As urban landscapes continue to evolve, introducing new data, entities, and relations, ontologies must undergo periodic updates and refinements to ensure they remain accurate and relevant [74]. This, in turn, demands considerable effort and resources, which may hinder the efficient utilization of the S2RICO in urban planning.
- Replicability concerns: despite certain commonalities, each city possesses a unique essence, defined by its distinct attributes, specificities, and priorities. Therefore, an ontology that proves to be effective in one urban context may not be directly applicable or entirely suitable in another.
- Limited stakeholder engagement: possible limited stakeholder participation during the update of the S2RICO may result in its failure to capture the diverse needs and perspectives of the broader local community, thereby diminishing its relevance and practicality.
- Privacy and security measures: data collection and sharing within a smart urban ecosystem may give rise to serious concerns regarding the usage of that data and the access to it [75]. Additionally, an ontology's limited 'waterproofness' may expose it

to heightened vulnerability, rendering it susceptible to cyber-attacks and potential breaches of sensitive information.

- Coverage issues: the practical application of the S2RICO may unveil concepts or areas that are not sufficiently covered, and thus the proposed model may fail to accurately represent the complexity and diversity inherent in urban systems [48].

5. Conclusions

The European Commission [76] envisions future cities as highly inclusive hubs, where environmental sustainability, social equity, affordable housing, and universal access to infrastructure and social services are ubiquitous. They are also grasped as catalysts for democracy, platforms of open dialogue, and dynamic drivers of economic prosperity.

Yet, the reality falls significantly short of this aspirational vision, which reflects an overarching goal within the broader context of sustainable urban development. Modern urban environments face enormous challenges that threaten to derail their progress towards achieving desirable future states. Although sustainable urban development has been a central planning priority for several decades, it remains both a critical planning goal and an elusive ‘moving target’, particularly in light of mounting challenges, with urbanization being the defining and prevailing trend of the 21st century [77].

In an attempt to adapt to this constantly evolving landscape, the concept of smart cities has appeared as a new, ambitious perspective for planning sustainable cities of tomorrow. These urban environments are designed to harness the power of state-of-the-art technologies so as to enhance quality of life, promote environmental sustainability, and stimulate economic prosperity. However, several critical obstructions, including the great ambiguity innate in the smart city concept, the consequent limited comprehension of the term’s meaning, and the huge interoperability gap provoked by the intense definitional impreciseness, have come to the surface. These challenges underscore the urgent need for the development of a conceptual framework that can deal with these intricacies.

In this respect, ontologies—as formalized representations of domain-specific knowledge—offer a powerful tool for modelling the multifaceted nature of smart cities. By establishing a shared vocabulary, they facilitate a common understanding of the smart city term, thereby enabling more effective communication and collaboration among urban stakeholders, and ultimately contributing to the launch of successful smart city initiatives.

To address this need, S2RICO has been meticulously developed to establish a shared conceptualization of the smart city, viewed as an interconnected system of systems [78], thereby deepening the understanding of the concept, resolving semantic vagueness, and bridging semantic gaps. Moreover, the integration of a unified, global indicator framework into the ontological scheme is anticipated to offer a common, cohesive platform for fostering collaboration among urban stakeholders and standardization organizations; enable cities to evaluate their progress towards becoming smarter, more sustainable, resilient, and inclusive [30,34,40]; assist municipal authorities in grasping the various perplexed and interrelating dimensions, factors, and domains of smart cities and guide them in formulating appropriate standards and requirements to ensure the success of their projects; and align indicators developed by different standardization bodies [79].

The creation of S2RICO may offer substantial benefits for all urban actors. First and foremost, a conceptual representation of the smart city domain facilitates semantic interoperability among heterogeneous systems. Contemporary cities are inundated with plentiful diverse systems, services, and applications that utilize (produce and/or provide) data in varied formats and structures. By establishing a shared conceptual basis, it is possible to secure effective and seamless communication among systems, thus eliminating data ‘silos’ and ensuring that stakeholders have unhampered and equitable access to the information required for reasoned decisions.

S2RICO holds the potential to significantly enhance the comprehensive understanding of the intricate dynamics within smart cities by providing a systematically organized framework encompassing concepts, relations, and attributes, thereby empowering urban planners to develop strategies and policies that embrace a more holistic and integrative approach. Additionally, the adoption of S2RICO may pave the way for innovative advancements and foster collaboration. A shared understanding of cities' diverse components can probably uncover critical areas, where groundbreaking technologies or transformative methodologies could be applied to boost efficiency, productivity, sustainability, or quality of life. This, in turn, encourages the establishment of partnerships and coalitions among various stakeholders, including governmental agencies, private sector organizations, and academic institutions.

The deployment of S2RICO may, also, contribute to enhanced transparency and accountability in urban operations. By employing a standardized vocabulary to describe urban constituents and their interrelations, stakeholders can gain a deeper insight into city functionalities. This clarity facilitates citizens and other interested parties to better understand decision-making processes and resource allocation, thereby fostering mutual trust and increasing public support of urban initiatives.

Ultimately, S2RICO can play a pivotal role in ensuring the fair distribution of urban resources. A detailed comprehension of urban sub-systems and their interactions allows urban planners and municipal authorities to identify critical inequalities or disparities in access to services and resources. Such insight encourages collaborative efforts to address these issues, ensuring that all citizens reap the benefits of smart city initiatives. Furthermore, by leveraging incorporated indicators, planners and policymakers can prioritize investments, allocate budgets strategically, and focus interventions on areas where they will yield the greatest impact.

Incorporating an extended indicator framework into the S2RICO, along with defining the relations between these indicators and core smart city components, offers a robust tool for data integration, analysis, and decision-making, which may enable organizations, both public and private, to fully harness the potential of their data. Specifically, embedding indicators into the S2RICO framework unveils several key advantages, such as:

- Improvement of data analysis: ontological structures facilitate complex analyses, such as executing intricate queries, deducing hierarchies, and understanding relations, thereby revealing insights unattainable through conventional data analysis techniques.
- Facilitation of data discovery and exploration: indicator-oriented ontologies allow users to uncover and explore data based on concepts and indicators pertinent to the domain of interest, therefore making it easier to identify patterns, trends, and valuable insights.
- Enhancement of data quality and reliability: integrating indicators ensures standardized and precise data collection, minimizing errors, ambiguities, and inconsistencies in data handling, by providing clear definitions, semantic relations, and contextual information.
- Boosting of data-driven decision-making: indicator-based ontological representations constitute a holistic and integrative framework for analyzing and interpreting data, supported by standardized metrics and a shared understanding of their significance. Such an approach strengthens evidence-based decision-making, enabling policy makers to evaluate options effectively, identify trends, monitor progress, and make informed choices that support sustainable, resilient, and inclusive urban development.
- Increasing of transparency and accountability: clearly defining indicators and the methodologies for their calculation ensures that data are valid and verifiable, thereby

building trust in decision-making processes by reinforcing their transparency and accountability, since these are grounded in credible evidence.

- Facilitation of data integration and interoperability: ontologies provide a shared vocabulary and a common understanding of domain concepts and relations, which allow seamless data exchange and integration across diverse systems and organizations. Populated with a well-established, commonly accepted, standardized set of indicators, S2RICO enables the efficient combination and comparison of heterogeneous data sources, fostering interoperability.
- Support for long-term urban goals: the continuous monitoring and evaluation of key metrics related to smartness, sustainability, resilience, and inclusiveness allow for informed long-term planning. By aligning urban development strategies with environmental, economic, and social objectives, S2RICO helps to identify areas for improvement and ensures the sustained advancement of cities towards sustainability.

The development of a smart city ontology from the ground up brings to light several critical points that should be addressed by developers and relate to the effectiveness, relevance, and longevity of the ontology. The key points are summarized below:

- Emphasizing standardization: the creation of a smart city ontology lies in the standardization of involved terms and concepts. Establishing a common language and framework is essential for securing interoperability and seamless communication among diverse smart city systems and stakeholders.
- Prioritizing collaborative efforts: the construction of a smart city ontology is an inherently complex undertaking that necessitates the involvement of various stakeholders, including governmental bodies, urban planners, technology providers, and citizens. Their collective expertise and perspectives are vital for capturing the multifaceted nature of smart cities and crafting a comprehensive ontological representation.
- Ensuring flexibility and scalability: ontologies should be designed to accommodate future developments and changes. With the rapid evolution of technologies and the emergence of new applications, it is imperative that the framework remains adaptable, capable of integrating new concepts and relations without disrupting its existing structure.
- Committing to continuous refinement and updates: a smart city ontology is not a one-time task, but rather an ongoing process that requires constant updates to reflect technological advancements, shifts in urban infrastructure, evolving citizen needs, and changing city dynamics. Regular feedback and active participation from stakeholders play a critical role in maintaining the ontology's relevance and accuracy.

Despite the complexities involved, S2RICO has the potential to become an indispensable tool in urban planners' arsenal for effectively implementing integrated, interoperable, participatory planning exercises that take into account cities' multidimensional nature and complex interactions. Moreover, S2RICO serves as a crucial link between the conceptual domain of smart cities and the performance assessment of various urban sectors, by providing a global, unified indicator framework and delineating the relations between indicators and fundamental city concepts. With this tool at their disposal, planners are empowered to envision and create smarter, more sustainable, and liveable cities that cater to the needs of both their current residents and future generations.

Author Contributions: M.P. has contributed to all aspects of this research, including conceptualization, methodology, software, validation, formal analysis, data curation, visualization, investigation, resources, writing, reviewing, and editing. A.S. has supervised the whole research and has critically contributed to the introductory and concluding parts of this paper. M.K. has participated in the

development of the methodological approach for the construction of the ontology and has provided vital technical support. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All data related to the development of the S2RICO (defined relations and the .owl file) are available via the link https://drive.google.com/drive/folders/1rSywDqdWN-PZQ0Tg9Z9x11ewqBp6LIdQT?usp=sharing

Conflicts of Interest: The authors declare no conflicts of interest.

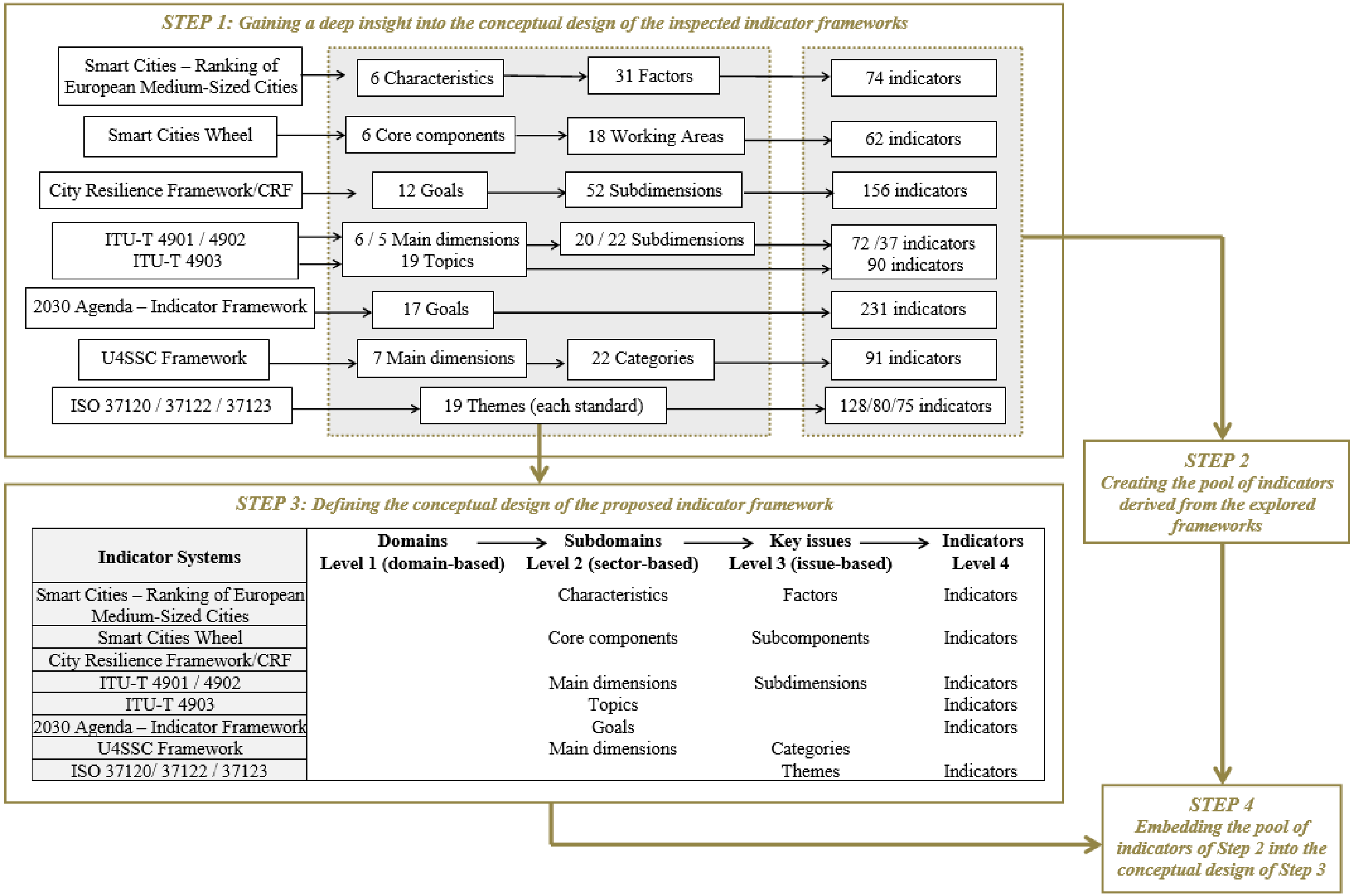
Abbreviations

The following abbreviations are used in this manuscript:

GDP	Gross Domestic Product
ICTs	Information and Communication Technologies
S2RICO	Ontology for Smart, Sustainable, Resilient, and Inclusive Cities
S2RICs	Smart, Sustainable, Resilient, and Inclusive Cities
OWL2	Ontology Web Language 2
W3C	World Wide Web Consortium
SWRL	Sematic Web Rule Language
UML	Unified Modelling Language
E-R	Entity-Relationship
DL	Description Logic
ISO	International Organization for Standardization
DC	Dublin Core
RDF-S	Resource Description Framework Schema
FOAF	Friend of a Friend
BFO	Basic Formal Ontology
GFO	General Formal Ontology
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering
SUMO	Suggested Upper Merged Ontology

Appendix A

Appendix A.1



Indicator Systems	Domains → Level 1 (domain-based)	Subdomains → Level 2 (sector-based)	Key issues → Level 3 (issue-based)	Indicators Level 4
Smart Cities – Ranking of European Medium-Sized Cities		Characteristics	Factors	Indicators
Smart Cities Wheel		Core components	Subcomponents	Indicators
City Resilience Framework/CRF				
ITU-T 4901 / 4902		Main dimensions	Subdimensions	Indicators
ITU-T 4903		Topics		Indicators
2030 Agenda – Indicator Framework		Goals		Indicators
U4SSC Framework		Main dimensions	Categories	
ISO 37120/ 37122 / 37123			Themes	Indicators

Figure A1. Fundamental steps for structuring the proposed integrated indicator framework (adapted from [30,34,40]).

Appendix B

Appendix B.1

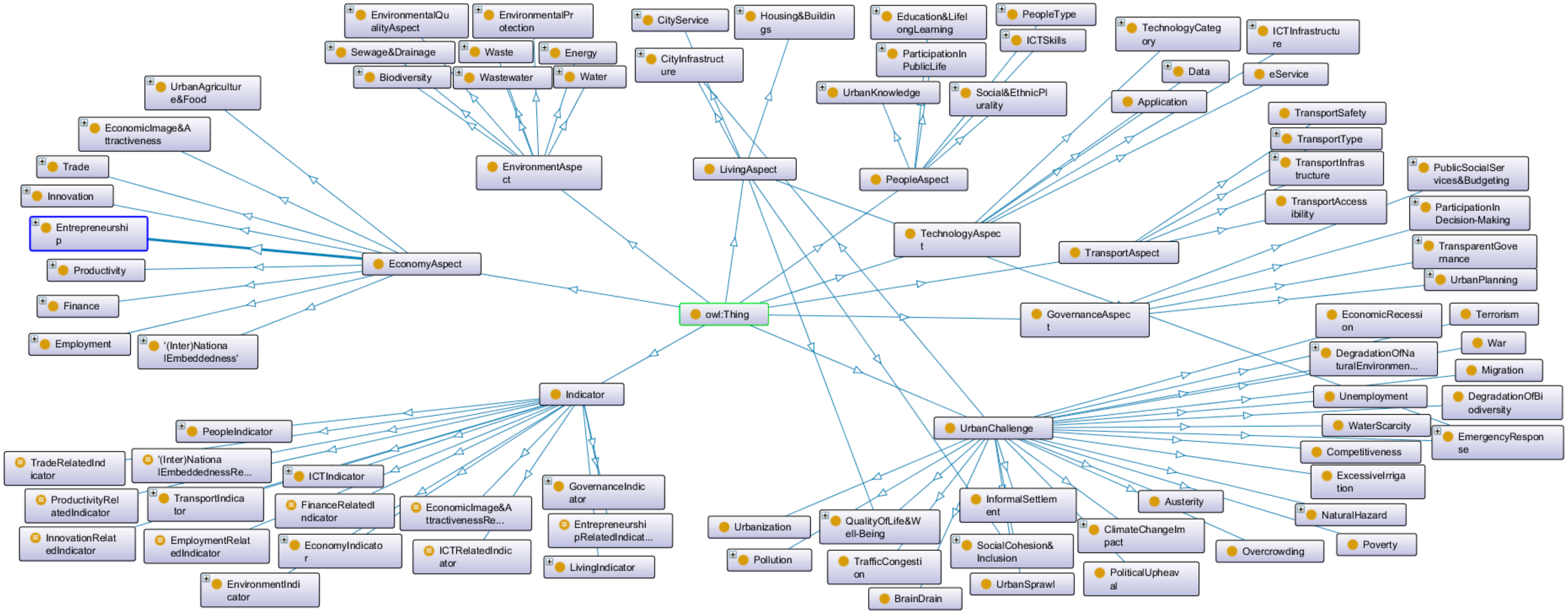


Figure A2. Basic hierarchical structure (first and second level) of the S2RICO [40].

Appendix B.2

Table A1. Indicative set of indicators for 'water' and their relations with S2RICO's classes [40].

Indicators	Innovation	Entrepreneurship	Finance	Employment	Economic Image and Attractiveness	Productivity	Trade	(Inter)national Embeddedness	Urban Agriculture and Food	Transport and Mobility	Technology	Environmental Quality	Environmental Protection and Awareness	Waste	Wastewater	Biodiversity	Water	Sewage/Drainage	Energy	Lifelong Learning, Training and Level of Qualification	Social and Ethnic Plurality	Participation in Public Life	ICT Skills	Culture and Sports	Health and Care	Safety and Security	Housing and Buildings	Education	Social Cohesion and Inclusion	Quality of Life and Well-Being	Participation in Decision Making/Active Citizens	Public Social Services and Budgeting	Urban Planning	Transparent Governance
17.1 Total water consumption per capita									▨				▨				■			▨									▨	■			▨	
17.2 Freshwater consumption													▨				■			▨									▨	■			▨	
17.3 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources													▨				■			▨									▨	■			▨	
17.4 Total domestic water consumption per capita													▨				■			▨									▨	■			▨	
17.5 Compliance rate of drinking water quality												▨	▨				■								■					■			▨	
17.6 Proportion of households with water saving installations												▨	▨		▨		■	▨		▨							▨			▨				
17.7 Efficient use of water (use per GDP)—Water productivity			▨										▨				■			▨										▨				
17.8 Change in water-use efficiency over time			▨										▨				■			▨										▨				
17.9 Percentage of water loss in the water distribution system											▨	▨	▨				■									▨							▨	
17.10 Average annual hours of water service interruptions per household													▨				■								▨	▨				■		■	■	
17.11 Availability of smart water meters	▨										■		▨				■			▨		▨					▨			▨		▨	▨	
17.12 Percentage of the city's water distribution network monitored by a smart water system	▨										■		▨				■								▨	▨				▨		▨	▨	
17.13 Percentage of drinking water tracked by real-time, water quality monitoring station	▨										■		▨				■								■					▨		▨	▨	
17.14 Environmental water quality monitored by ICT	▨										■	■	■			■	■								■					■		▨	▨	
17.15 City freshwater sources monitored using ICT	▨										■	▨	▨				■								■					■		▨	▨	
17.16 Availability of visualised real-time information regarding water use	▨										■		▨				■			▨		▨					▨			▨				
17.17 Number of different sources providing at least 5% of total water supply capacity												▨					■								■	■				■		■	■	
17.18 How many years ahead does the city's water plan look (e.g., does it analyze the city's 10 year + needs?)												▨	▨			▨	■									■			▨	■		▨	■	
17.19 Percentage of city population that can be supplied with potable water by alternative methods for 72 h during disruption																	■								■	■			■	■		▨	■	

Blue color represents the category of economy, yellow signifies aspects related to transport, mobility and technology, green denotes environment, pink corresponds to people , purple pertains to living and orange symbolizes governance.

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