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Spatial–Temporal Ontology of Indicators for Urban Landscapes

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Abstract: Urban development is increasingly scrutinized for its sustainability from an economic, social, and environmental viewpoint. This study emphasizes how important indicators are in capturing the complexity of urban settings when assessing urban landscapes and making sure that comprehensive development plans incorporate all these aspects. The work aim is to forward the investigation of the ontology of indicators related to urban sustainability, specifically, a framework for spatial and temporal analysis and an attempt to align terminology with the sustainability indicators of the ISO spectrum. The methodology encompasses three main phases: a systematic review of sustainability indicators from the scientific literature across various territorial scales; the mapping of individual indicators to their appropriate spatial–temporal measurement ranges; and the alignment of these spatially and temporally specific indicators with ISO standards. Focusing on the Italian context, this study establishes an ontological spatial–temporal framework. It analyzes ISO indicators that can be managed in Italian spatial settings. The main objective of this part of the research is to select through a critical analysis the most frequent indicators in order to be able to make an alignment and define those that aim more at the goals of the 2030 Agenda on sustainability. This innovative approach enhances urban issue awareness and supports informed decision-making by demonstrating how sustainability indicators can be effectively utilized in downscaling strategies to create a policy for the practical use of indicators.

Keywords: indicators; sustainability; ontology; framework; decision-making system

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1. Introduction

Sustainability in the urban environment is one of the burning questions and, at the same time, one of the greatest opportunities in modern societies. Considering the dynamics of urbanization around the world, the mobility of people at this age has also been raised. Outsourcing this task from the city to the urban context has become more imperative because it combines the commitment to sustainability within ever growing cities. This expansion requires the provision of economic development, social development and environment management/protection [1]. The further the urban areas expand, the more sophisticated the management of the different requirements becomes, hence the need for scalable and flexible sustainability initiatives. For this principle, understanding urban resilience and sustainability becomes a matter of the utmost urgency in addressing the risks of the rapidly urbanized world [2]. Viable solutions to this problem must be developed in such a way that, although specific to cities, they must enable them to combat issues within their region or at the global level.

Urban areas feature diverse economic zones characterized by a complex mix of industries, services, and commercial activities. The social fabric within metropolitan regions is equally sophisticated, comprising intricate networks of interactions among residents. These urban environments foster significant employment opportunities, contributing to their economic vitality [3]. However, these dynamics also influence living conditions and overall urban sustainability. Effective urban development requires comprehensive management frameworks capable of assessing multiple sustainability dimensions. Urban sustainability indicators (USIs) refer to established methods of measuring total contributions of the economic, social, and environmental components within urban areas [4]. Such approaches assist not only the decision makers, urban planners, and managers in the evaluation of the current situation, but also streamline the inclusion of sustainability development principles into a city's planning practices [5].

The last socio-technologic development of our population inside urban areas also brought changes in public-triggered urban sustainability indicators (USIs) [4,6] that have significantly evolved, incorporating innovative data collection and analysis methods. These advances also include a new type of USIs that incorporate and operate big data, including structural data, changing in real time. Enhancement with advanced analytics within the USI frameworks such as machine learning and geospatial analysis has made possible the accurate evaluation of sustainability criteria including time and space [4]. The absence of advanced analytical tools and real-time data collection methods can result in temporal and spatial inaccuracies when assessing sustainability. This is particularly evident when relying solely on brief sociological or ethical surveys, regardless of whether they are conducted independently or combined with more comprehensive interviews and investigations. This limitation can compromise the precision and reliability of sustainability evaluations. Using advanced technologies (real-time data, etc.) can allow one to evaluate indices in a faster way [7]. Within these systems, research is also ongoing as part of an effort to categorize the correlations which describe the core indicators and the influence (positive or negative) on other indicators.

The reversal of relation, however, leads to the emergence of the paradoxical situation as regards the perceived benefits of attributes present. It is very important to evidence out one fundamental requirement for the initial definition of the indicator and, more particularly, one that enables its interaction with various geometrical attributes which are suitable to the nature of the indicator and to the information in terms of geography and time. In that direction, each stakeholder must define time, space, and the indicator. After this first step, it is obligatory to define the correlation of the indicator with other systems. This does not involve thinking about the metropolitan range; such systems are created that will work at the micro district level as well as at the level of the hegemon city. Focusing on these spatial–temporal linkages might improve urban planning and policymaking in a way that decisions are made after weighing both the short- and long-term effects of development. The abundance of urban data, coupled with their analytical power, opens up new opportunities for innovation in sustainable cities [8].

This study is concerned with the USIs as tools both for assessing and for guiding the course of urbanization processes towards sustainability goals. It aims at looking into their relevance and effectiveness across different regions and time periods. A comprehensive spatial–temporal ontology of indicators has been designed and given a name that pertains to the International Organization for Standardization nomenclatures [4,9,10]. The scope of this research is to first analyze all indicators from ISO standards, after thoroughly identifying indicators that are based on the Italian territory (indicators that are defined and part of the literature); analyzing the spatial conditions of the latter indicators; and, lastly, evaluate the correlation of spatial conditions with those same indicators [8,11]. The

underlying concern is primarily one of resolving or supporting sustainable urbanization decision-making, enhancing the understanding of sustainability issues, and promoting the need for the adoption of multiple clearly defined sustainability metrics.

This work is organized in the following manner. Section 2 provides an overview of the development of the presented research, focusing on some of the key scientific literature from where several standards such as ISO and the policies in this domain are sourced. The methodological strategy adopted for the development of the USI ontological apparatus is given in Section 3. Section 4 presents the undertakings in the construction of the initial stages of the report by employing the case of an Italian spatial–temporal USI ontology. Section 5 synthesizes the main results of the work and presents the limitations of the research achievements.

2. Background

Sustainability indicators are of great importance for the evaluation of environmental, social, and economic activities in the context of different geographical levels from local communities to global policies. The formation of sustainability indicators is aimed at establishing a framework that would assist in promoting and assessing all-round sustainability practices. Most of these are crucial to policymakers, businesses, non-governmental organizations (NGOs), and communities and help them make better choices, investing in healthy long-term solutions rather than short-term profits. By measuring factors, such as carbon emissions, water quality, and poverty levels, the improvement of which grows the richness of the communities, it will be possible to have a clear picture of how far they are in achieving environmental sustainability goals.

The following sub-sections will touch upon the issue of urban sustainability indicators, focused on the evaluation, definition (and codification), and management of urban sustainability as found in international-level program-based documents (Section 2.1) and ISO standards (Section 2.2), as well as within the scientific literature (Section 2.3). These deepening windows also facilitate the need to research the ontology of urban sustainable development from a space and time point of view. It will be helpful to note that this will be under Section 3, which serves as the background of a tiered approach aimed at building a complete framework of indicators.

2.1. International Viewpoint

The above definition of sustainability has been able to serve the purpose for which USIs' operational usefulness for sustainable development is defined. The concept of sustainability was effectively created during the publication of the Brundtland Report authored in 1987, which gave the phrase "sustainable development" an entirely new meaning. The International Council for Local Environmental Initiatives (ICLEI)'s Cities for Climate Protection, which started in the mid-1990s, urged cities to implement policies and undertake actions towards both the mitigation and adaptation of climate change with the help of progress measurement tools and sustainability indicators. In addition, the European Union embarked on the Urban Audit Initiative (1990s), through which the measurement and evaluation of the quality of life in European cities relative to one another was undertaken in terms of the social, environmental, and economic aspects of life in the cities. The convergence of non-governmental organizations and the United Nations General Assembly set up the World Summit on Sustainable Development (WSSD) which initiated Agenda 21 (1992).

The role of local authorities was underlined in Agenda 21, further leading to the formulation of the Local Agenda 21. This encouraged municipalities the world over to integrate a planning dimension into sustainability activities, which included the creation and

employment of measures of performance. The Urban Development and Local Government Unit of the World Bank (1992) established principles for several questions including the development of sustainable urban indicators to be used in the project evaluation of urban management and infrastructure worldwide. These, therefore, are used by policymakers and investors to evaluate and enhance the sustainability of urban areas in developing countries. These aspects were comprehensively addressed from materials on sustainability indicators prepared by the Organization for Economic Co-operation and Development (OECD) from 2001 to 2005. Goal 11 (Sustainable Cities and Communities) of the Sustainable Development Goals (SDGs) in the UN's Agenda 2030 (2015) is a proposed solution to the arising problems that cities face, such as housing, basic amenities, or hazard issues. The Sustainable Development Goals (SDGs), adopted by the United Nations in 2015, represent a comprehensive global framework for achieving sustainable development by 2030. Goal 11, focusing on Sustainable Cities and Communities, is particularly crucial as cities continue to face unprecedented challenges with rapid urbanization. Beyond addressing basic housing and amenities, this goal encompasses several key targets including reducing the environmental impact of cities, ensuring universal access to safe and affordable transport systems, enhancing inclusive urbanization, and protecting cultural and natural heritage. Over 55% of the world's population lives in urban areas, making Goal 11's objectives increasingly vital [8]. The goal also emphasizes disaster risk reduction, air quality improvement, and universal access to green spaces, while promoting integrated policies between urban, peri-urban, and rural areas. This multi-dimensional approach recognizes that sustainable urban development requires balancing social equity, economic growth, and environmental protection. The hurdles to urban sustainability include the following:

Rapid Urbanization

Sustained urban migration has caused rapid urban extension in cities. Such rapid conversion of rural areas to urban centers puts an enormous strain on the existing infrastructure and service delivery systems, causing urban sprawl, skyrocketing energy usage, and inadequate waste management.

Environmental Degradation

The causes of degradation in a city environment include pollution, the heat island effect, and the loss of biodiversity. The managers of such cities seem to struggle to manage urban natural resources without deleterious implications for the efficiency of the urban economy.

Socio-economic Disparities

There are some cities that are polarized in that in some areas the well-off groups reside and in other areas, the below-the-poverty-line group lives. This situation calls for addressing these inequalities as a matter of urgency for social sustainability and demographic health.

Infrastructure and Housing

Several cities across the globe are affected by the problem of slum housing and poor-quality housing because of the need for good and low-cost housing. Environmental and social issues in cities call for collaboration to avoid the creation of slums and informal settlements.

Since then, the challenge has been how to measure and implement this ideal in a practical, ongoing way.

2.2. ISO Standards

The International Organization for Standardization (ISO) has an important function in this area in terms of formulating international norms on sustainable development evaluation processes and tools. The International Organization for Standardization is a

non-governmental organization that groups together 165 national standard bodies. This organization brings together such specialists to create, within a certain time frame, global voluntary standards which are based on consensus and are relevant to the market, and encourages innovation as well as solving global problems.

As the demand for sustainable construction projects grew, it was no longer relevant to generate ISO specifications solely pertaining to portable structures. The scope of providing and publishing organizational standards regarding sustainability and ISO standards as a concept has steadily expanded over the years and encompasses a wide range of standards, including those that define an energy management policy or social responsibility or even a building-construction process.

Finding one of the key areas in which ISO is making strides towards sustainability is the creation of the ISO 14000, which focuses on environmental management system standards. They help businesses to manage the environmental consequences of their operations, comply with applicable laws, codes and regulations, and other environmental concerns, and seek to improve in such aspects on a constant basis. Of these, ISO 14001 is the most relevant going forward in this particular direction as it provides a prescription which an entity or an organization may adopt in order to establish an efficient environmental management system [12].

At the same time, through the creation of standards and specifications, ISO has also contributed to the transformation of cities into smarter and more sustainable ones. For instance, ISO 37101 [4,6,10], which provides a management system for sustainable development in communities, enables such cities, and other localities, to enhance the quality of life of their residents and have a smaller environmental impact, all while maintaining an economically sustainable environment. These standards form part of a more comprehensive group related to various dimensions of human activity in cities, focusing on utilities and transport, waste treatment and management, and infrastructural construction.

In addition, ISO participates in the United Nations Sustainable Development Goals (SDGs), which is a way to promote global sustainability. The standards developed by ISO also help further the attainment of specific SDGs. This helps in achieving the specific goals of the organization. For example, ISO 26000 guides the responsibility of businesses on social development in accordance with political objectives such as human rights, labor, and environmental policies [13].

The significance of ISO's three-function model and the main editor of sustainable development principles room elements will be widely used as the problem of vertical enlargement becomes critical. These consist of assistance in the integration of sustainability into the organization's operations, facilitating the transition towards sustainable practices, and obtaining sustainability with the help of new strategic directions. In Table 1 below, the main ISO guidelines for urban sustainable development are displayed. The basic reference ISOs for the research of indicators of urban sustainability are formulated through dissecting headings of existing ISOs and testing their currency for the subject of interest by inserting the words "indicators" and/or "sustainable development" in the heading. Also, many researchers try to address the social aspects of sustainability as well as its environmental and financial issues, and this is common practice in many sustainability studies [14–17]. The same evidence and continuous research and guidelines are mounded from United Nations [18–21]. A brief explanation of the ISO list follows.

Table 1. ISO list pertaining to urban sustainability.

ISO on Urban Sustainability	
ISO/DIS 37123	Sustainable Development Indicators for Resilient Cities
ISO 37122:2019	Sustainable Development Indicators for Smart Cities
ISO 37120:2018	Sustainable Development Indicators for City Services and Quality of Life
ISO 37106:2021	Guidance on Establishing Smart City Operating Models for Sustainable Communities
ISO 14030:2022	Environmental Performance Evaluation (EPE) Guidelines
UNECE-ITU	Sustainable Indicators for Smart Cities
ETSI TS 103 463	Indicators for Smart Sustainable Cities
ITU-T Y.4903/L1603	Indicators for Smart Cities to Assess the Achievement of SDGs
ITU-T Y.4902/L1602:	ICT Sustainability Impact Indicators in Smart Cities
ITU-T Y.4901/L1601	ICT Indicators for Smart Cities

The following are the ISO standards and a summary description on their contents.

ISO/DIS 37123: Sustainable Development Indicators for Resilient Cities

The standard is intended to develop enough indicators, which cover all aspects of city resilience ranging from environmental to socio-economic ones [22].

ISO 37122:2019: Sustainable Development Indicators for Smart Cities

This standard attempts to develop indicators to evaluate the sustainability of smart city projects [6].

ISO 37120:2018: Sustainable Development Indicators for City Services and Quality of Life

In this respect, ISO 37120 attempts to provide international consensus on the evaluation of local government's performance in delivering various services to the public with a specific focus on the health, safety, recreation, and education sectors [4].

ISO 37106: Guidance on Establishing Smart City Operating Models for Sustainable Communities

System designing principles, organization and accelerating transformation towards a new model. Municipalities adopting smart city operating frames that encourage growth without compromising quality of life are necessarily the targets of this paper [23].

ISO 14030: Environmental Performance Evaluation (EPE) Guidelines

This is another standard of the ISO 14000 series, designed for environmental management also under development, concerns senior management reviewing and improving environmental performance in organizations [24].

UNECE-ITU: Sustainable Indicators for Smart Cities

This is intended to identify the ICT impact factors in cities; this tool was jointly developed by the United Nations Economic Commission for Europe and the International Telecommunication Union [25].

ETSI TS 103 463: Indicators for Smart Sustainable Cities

This standard focuses on urban quality of life indicators determined by the European Telecommunications Standards Institute which deals with the greening of smart city technologies [26].

ITU-T Y.4903/L1603: Indicators for Smart Cities to Assess the Achievement of SDGs

This standard has been drawn by the International Telecommunication Union to facilitate the interdependence between the development of smart cities and the achievement of Sustainable Development Goals (SDGs) [27].

ITU-T Y.4902/L1602: ICT Sustainability Impact Indicators in Smart Cities

Such indicators target the impact of ICT use on environmental sustainability in cities [28].

ITU-T Y.4901/L1601: ICT Indicators for Smart Cities

With the focus on broad ICT issues in urban management, these indicators have assisted cities in achieving the efficiency of their electronic services, scaling up public participation in governance, and facilitating the functioning of city structures [29].

2.3. Relevant Scientific Literature

Various efforts can be found in the scientific literature concerning how an acceptance indicator on sustainable urban development may be translated into practice. A case in point are measures that are appropriate to the context of the study and that help accomplish the overall aim.

The work titled "Urban Sustainability Indicators from a Regional Perspective: Lessons from the Montreal Metropolitan Area" [30] by Tanguay et al. (2010) clearly and excellently reviews a large array of sustainability indicators when it comes to looking at urban areas from the perspective of sustainable development. The investigation captures all three facets of sustainability, economic, social, and environmental, which demonstrates all sides of the issue as they work hand in hand, particularly in cities. The study conducted by Tanguay et al. is not limited to a mere mention of these indicators; it undertakes an evaluation of the action or the absence of the action of such devices in various cities. Such an approach is useful in understanding the best practices and the difficulties which urban ministries and planners experience while aiming to implement those measures in sustainable development policies. The research concern stresses the criticality of these sustainability dimensions in a proportional manner for effective urban planning and design. Where economic, social, and environmental variables have been integrated, cities emerged with improvements in public policies and more effective and internalized urban solutions to socio-economic and environmental problems.

The study of the EEA (European Environment Agency) (2021) set out in the work "Urban Sustainability in Europe" [31] rather supports building the credibility of sustainability indicator systems focused on European countries. This research comprehensively determines and includes the basic economic, social, and environmental variables for the effective monitoring of urban sustainability in Europe. The economic indicators often include productivity, as well as the economic diversity index that measures different sectors of the economy. Social indicators include education, health, and equality, amongst others. Environmental indicators including measuring air and water pollution, as well as power usage and the availability of parkland. In such a manner, the research is intended to provide city managers with all necessary instruments for the monitoring of treatment effectiveness against sustainability targets with respect to domestic circumstances and policies in European countries. This research has made a significant contribution to the strengthening of the existing urban economic theory by helping urban planners and politicians come up with policies that foster economic growth, and, at the same time, factors in the regional specifics and norms.

The work "The application of urban sustainability indicators—A comparison between various practices" by Shen et al. [32] presents a comprehensive framework which the authors formulated for use in the assessment of sustainability within cities. This research comprehensibly integrates economic, social, and environmental indicators of sustainable development in urban areas, therefore emphasizing the need for a clear structure. While economic indicators are used to examine the condition of the city's economy along with the tendencies of its progress, social indicators follow issues such as the wellbeing, equality, and standard of living of the population, and environmental indicators concentrate on the

evaluation of the environmental degradation, natural resource management, and pollution of urbanized areas. The purpose of this framework is to support the efficient evaluation and planning of city development with a focus on sustainability, so that no independent or interrelated area of development is overlooked.

The work carried out by Mori and Christodoulou in (2012) "Review of Sustainability indices and indicators: Towards New City Sustainability Index" [33] commences an exercise in determining the shortcomings of existing sustainability indices, with a view to advocate a novel, holistic city sustainability index. Advances in research have critically assessed various economic, social, and environmental indicators that are practiced in different parts of the world and have raised issues concerning how different cities are able to account for sustainability, including gaps and redundancies. The researchers work on the development of a more comprehensive and flexible index, which would allow having a more accurate representation of sustainable urban environments and their functional goals, helping urban development and planning regimes. The proposed index takes into consideration most aspects of the economy, society, and environment, to ensure that there is equity in urban sustainability.

The research by Moreno Pires (2011), "Sustainability Indicators and Local Governance in Portugal" [16], presents the challenges and methods of using sustainability indicators in the process of developing the plans of municipalities. It mentions the need for an integrated approach to never compromise on cost efficiency, social justice, or environmental sustainability.

In the paper "Sustainability on the urban scale: Proposal of a structure of indicators for the Spanish context", Braulio-Gonzalo et al. (2015) [34] proffer a solution-based evaluation scheme which evaluates urban projects based on well-benchmarked criteria such as the economic, social, and environmental impacts of the proposed sustainability indicators. This system is also designed to support urban planners and developers in the sustainability impact assessment of different undertakings, to make sure that urban development activities are following the principles of sustainable development. The study goes further to explain the difficulties encountered in capturing and interpreting such indicators and the limits of contextualizing them, which require that the assessment protocols should be followed and consistently improved over time and practice.

A study by Dizdaroglu (2017) "The Role of Indicator-Based Sustainability Assessment in Policy and the Decision-Making Process: A Review and Outlook" [35] focuses on available policy questionnaires identifying which indicators are used in the understanding of policy decisions. Through a sophisticated analysis, the author explains how the economic, social, and environmental indicators are utilized to facilitate and manage cities and the activities taking place there. The report demonstrates the potential of using such indicators in evaluating policy outcomes and recommends ways in which such a relationship could further be strengthened to reduce the divide between sustainable urbanization and urban development. Against these backgrounds, the work highlights more theoretical, empirical, and contextual evidence while recommending the evidence-based usage of indicators for climate policies.

In "Urban Sustainability Indicators: Challenges and Opportunities" by Verma and Raghubanshi (2018) [17], the authors do a great deal more and consider the practicality and the effect of sustainability indicators on urban planning. Their analysis is complete: it covers the three-dimensional spheres of economy, society, and environment, which is what urban sustainability encompasses. According to the authors, there is a need to formulate more advanced indicators that will address not only the existing spearhead of the indicator set and bottom-to-top current policy tunes but also foresee future sustainability conditions.

This approach may allow cities to anticipate such challenges and take up such opportunities as they may arise.

The study by Harsimran Kaur and Pushplata Garg (2019) titled "Urban Sustainability Assessment Tools: A Review" [36] focuses on assessment tools for evaluating the sustainability of urbanization processes and urban projects. The paper places several types of assessment before the audience and explains the nature of each one. Such comparison includes the following tools:

LEED (Leadership in Energy and Environmental Design);

BREEAM (Building Research Establishment Environmental Assessment Method);

CASBEE (Comprehensive Assessment System for Built Environment Efficiency);

Green Star.

Kaur and Garg's study provides interesting information on the strengths and weaknesses of the existing systems of urban sustainability assessment. The authors emphasize the necessity of ongoing development of such kinds of tools in pursuing newly found challenges and opportunities for the sake of better urbanism.

3. Methodology Behind the Spatial–Temporal USI Ontology Building

Considering the above background, the objective is to identify and define a set of USIs which are specific to time as well as geography, which can be useful in evaluating and monitoring the growth of sustaining development in all dimensions: economic, social, and physical. This process also meets the existing ISO requirements for urban sustainability.

The ontological apparatus on which the project hinges was constructed through a two-pronged approach. One method proceeded to the exploration of urban sustainability indicators from the existing body of knowledge (Section 3.1), while the other method focused on the examination of the existing urban sustainability ISO standards (Section 3.2). The outcome of certain research methods was utilized for comparative analysis (Section 3.3) aimed at the construction of a spatial–temporal USI ontology. In detail, the research methodology employs a comprehensive three-phase approach to develop a spatial–temporal USI ontology.

Phase 3.1—Scientific Literature Review

This phase involves a systematic examination of peer-reviewed academic publications, journal articles, and research papers focusing on urban sustainability indicators. It analyzes theoretical frameworks, empirical studies, and existing methodologies used in measuring urban sustainability. This academic review establishes the theoretical foundation and identifies current trends in USI research.

Phase 3.2—Grey Literature Review

This stage focuses on non-academic sources, particularly ISO standards and technical documentation. It examines industry practices, government reports, policy documents, and technical guidelines related to urban sustainability assessment. This review is crucial for understanding practical applications and standardized approaches currently used in urban planning and management.

Phase 3.3—Comparative Analysis

The final phase synthesizes findings from both reviews to develop a spatial–temporal USI ontology. This involves comparing theoretical concepts with practical standards, identifying commonalities and differences, and creating a unified framework that considers both spatial (geographic) and temporal (time-based) dimensions of urban sustainability. The resulting ontology serves as a structured knowledge representation system for understanding and measuring urban sustainability across different scales and timeframes.

The methodological workflow has been schematized in Figure 1. Each phase is reported in the description below.

3.1. Scientific Literature Review

Phase 1—Sector-Specific Literature Review

The sphere of sustainability indicators is not only broad-scoped but also multidimensional, spanning across various areas like ecological indicators, urban studies, and the economy, among other aspects. In recent times, there has been increasing evidence as well as research on this subject matter, which signifies that there is an increasing awareness and dedication to sustainable development in different industries. The emphasis on searching for and reviewing the relevant literature and studies regarding sustainability indicators for assessment systems highlights its importance in the assessment of sustainability [37–40]. Much of the literature has focused on the creation and improvement of measures of the effect of urban development activities on the environment. The literature scope also entails multiple case studies which have included, but are not limited to, the use of sustainability indicators in certain urban or regional settings. Such case studies prove to be very beneficial in understanding the practical application of the sustainability indicators and how such indicators can face various challenges or achieve optimal results [22,34,41–43]. There are such works that often discuss definitions and other generalizations of the construct "sustainability" and its evolution in the different centers of the world from the perspective of its measurement.

Phase 2—Data Collection

USI Suite Definition

The process of defining indicator sets is a detailed endeavor that also involves a literature review. Examples in the literature include published papers, articles, reports, and other documented materials. Indeed, in most publications, scholarly works focus on theoretical aspects as well as the definition of indicators and are devoid of the practical performance of said indicators or the values calculated. Always in such works, the authors elaborate to a large extent on the reasoning behind the use of some indicators, their definitions, the theory surrounding their usage, and how they are worded. However, they do not go on to conduct the next important phase, which is the detailed assessment of such indicators under various settings. This may be because of a lack of data, complicated methodologies, or because the research is still at a conceptual level and not yet aimed at answering practical questions. Their theoretical contribution has comprehensively advanced the understanding of indicators [15,16,30–32,44,45]. However, it has also languished in offering effective recommendations which can be useful for policy development or other practical usage. To tackle this problem, it is rather important to link the definition of the indicators with their actual measurement [14]. This is not only limited to searching relevant indicators from the literature but also making the effort of estimating their values using existing data [14,15,33,46–49]. Such a step is important to shift the nature of the indicators, which otherwise lie in theoretical realms, to actual working instruments that can facilitate and support decision-making.

USI Profiling Systems

The increasingly frequent tendencies to reduce indicators to three macro groups, namely, economic, social, and environmental, suggest the strategic direction and intent that serves to improve the lucidity, effectiveness, and orderliness of data analysis. In this method, the narrow divisions of numerous categories are replaced by these three wider divisions, thus eliminating the difficulty of the measurement of sustainability. The central reasoning behind this distribution is to ensure that there is a streamlined as well as an organized profiling system that captures the intricate details of sustainable development. This is achieved by integrating information from the three aspects and presenting an easy approach to organizing comprehensive databases without losing any key areas relating to sustainability. Such research basing the information on the three pillars of sustainability, economic, social, and environmental, is devoted to the factors governing the breakdown of

the pillars. This is important to appreciate and tackle the problem of sustainability which touches on different facets of both human beings and the ecological system.

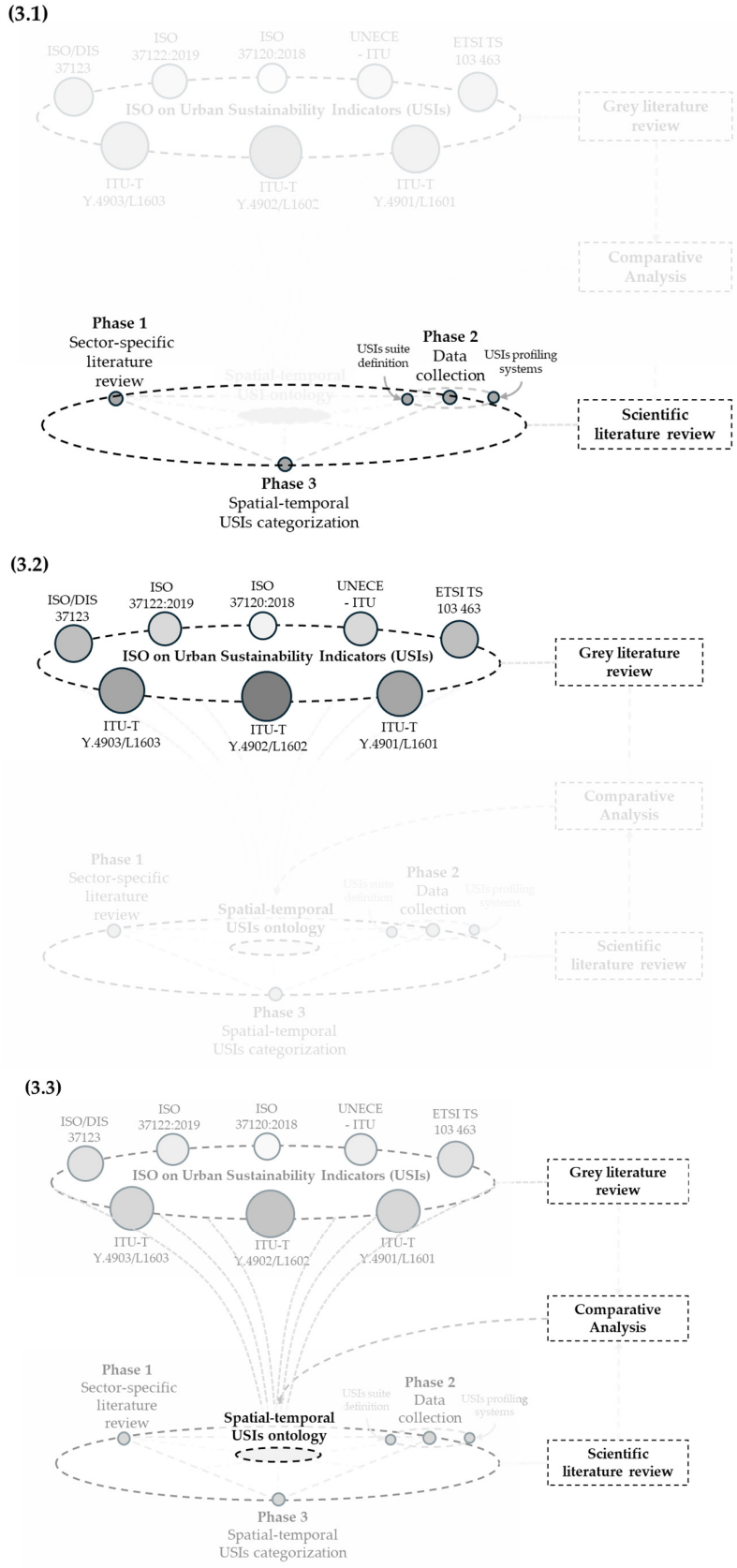


Figure 1. Work-flow to build a spatial–temporal USI ontology.

Phase 3—Spatial–Temporal USI Categorization

The information-gathering process should be finalized by specifying the year, source, unit measure, and geographic frame provided when collecting the data. This methodology of data organization is critical in terms of varying datasets in the relevant analytical context and contributes greatly to managing complex datasets across areas and periods [43,45,50–52]. Equally, the source of the data is of great consideration as it determines the reliability of the information. The data sources include the government, international organizations, research agencies, the EU, or associations of the sector. Each source is assessed and graded on the methodological fundamentals, level of obfuscation, and consistency. It is not uncommon that statistical information from official datasets is preferred, as its collection patterns are standardized as per the legal obligations in place, ensuring its source is accurate. Yet, in areas where formal data may not be available or are essentially obsolete, other combination sources like those of research or industry reports can be highly useful. The other basic factor is the unit of measurement, which ensures the compatibility of data over space and time. The adoption of common units of measurement facilitates data standardization by making it possible to use data at many levels of scale. For instance, economic statistics may be presented in euros, environmental statistics in metric tons of carbon dioxide equivalent, and health statistics in morbidity rates per one hundred thousand of the population. Such uniformity of measurement helps to avoid inconsistencies and increases the reliability of comparative analysis. This factor raises some important issues; for example, in various cases, the very same indicator analyzed by different authors was presented in different measurement units.

Territorial Nomenclature of Territorial Units for Statistics (NUTS) is a very important tool in the process of data collection. NUTS gives a system of classifying territorial units, which are arranged in hierarchies with levels of regions. This ensures that the information being collected is spatially accurate, thereby enhancing the spatial analysis on the data collected. NUTS regions are characterized by being as homogeneous as possible with respect to socio-economic features, which facilitates regional assessment and comparability as well as analysis improvement. Therefore, by geo-referencing the data to NUTS regions, analysts can analyze regional imbalances, improve regional policy implementation, and evaluate the effectiveness of regional policy objectives. This geographical limitation has always proved very useful in areas such as regional strategies, urban frameworks, and public management, where outcome parameters are dependent on local conditions. The adoption of NUTS was also aimed at correcting the problem of the statistical operationalization of regions in the European Union with data from several countries to enable or facilitate the comparison of areas of interest with the average statistics within the European Union. This harmonization is important in the policy framework at the European level, as it aims at regional cohesion and the balanced development of the territory. In this way, it has become possible to bring all regional strategies in line with the European spatial agenda and make the implementation of regional policies more efficient.

3.2. Gray Literature Review

USIs, developed by ISO, here, follow a series of consultations and emerging cooperations depending on regional input. These synthetic determinants have gone further to determine the standards acceptable internationally regarding issues concerning the practices and performance in the given region.

Many aspects can be considered in the history of the development of ISO standards. One such aspect are the changes in the priority of those components that make up sustainability. For example, as more emphasis was placed on climate change, there was more focus on carbon management and renewable energy indicators in the ISO system. Similarly, the

growing concerns over social justice and social rights also brought in social measures and their improvement. This continuous adjustment is important to confirm that ISO assures a centralized soundness of quality in connection to the appropriate issues of the time.

The potential of ISO-USIs lies in their universal ability to be effective yet still be local in their usage. They also provide an integrated vocabulary within which various stakeholders, policymakers, businesses, and civil society can operate their relationships and have a gauge of their actions. Such coordination is becoming more important because globalization forces us to address the problems of sustainable development, climate change, loss of biodiversity, and inequality by working across aims and geographies.

This study maps out the indicators of all ISOs connected with sustainability concerns. For the ISOs for which there was an analysis, categories with a related list of indicators were created. One of the principal reasons for the thorough elimination of certain ISO sustainability indicators is to make certain that the indicators that are retained fit the strategic focal points and operational environments of the company. Not all sustainability indicators are 'equal', in the sense that some would be more important than others regarding certain factors or regions. For instance, wastewater discharges would be significantly unacceptable for a manufacturing industry that is situated in a water-scarce geographical region but do not matter for a technology firm which is based in a region with ample water resources. In this way, organizations can maximize the attainment of their sustainability goals by identifying and utilizing only those indicators that are relevant to their area of work.

This approach to the screening of ISO sustainability indicators means that it becomes easy to provide feedback on improving the corporate focus on successful sustainability outcomes. An effective reporting approach on relevant indicators defines that this study tries to link together data without competency loss through the numbers of indicators that have been quantified and are theoretically known.

3.3. Comparative Analysis

Spatial–Temporal USI Ontology

Getting a sense of the full range of sustainability criteria is the critical first phase in creating the matching matrix. Usually, these indicators can be divided into three major categories: environmental, social, and economic. The creation of a matching matrix for the indicators of sustainability is, in fact, a management technique which makes it possible to integrate the database built into the ISO system under examination. As a matter of fact, the formation of a matching matrix is one of the visual and analytical aspects of the automatic tracking system, which allows us to see how an indicator's set list and its ISO internal tracker correlate. In this regard, the subsequent stage is represented by the task of providing a description of internal indicators in every minor detail and core-assessing qualitatively every aspect of the internal matching matrix. This entails looking at how each indicator is defined and how each one is assessed. For example, the company may conclude that its own internal indicators are defined in a different way and/or assessed using different criteria than the ISO standards. The goal is to ensure that all indicators are standardized, which facilitates a unified and coherent ontology of sustainability metrics.

4. Results

4.1. Scientific Literature Review

4.1.1. Sector-Specific Literature Review and Data Collection

The first phase of the research involved a comprehensive review of the existing literature on sustainability indicators, focusing on how these indicators have been utilized to assess and monitor sustainable development across different contexts [53,54]. For a

better definition of intersections at the content level, searches were defined for several sustainability-related terms: «Sustainability»; «Methods and tools of evaluation»; and «Urban policies».

Through this methodical approach, an extensive database of more than 500 indicators was created, each with its unique definition and intended application. The following findings were deduced from the review activity.

Economic indicators provide insights into the financial viability and economic health of a society, focusing on metrics such as GDP, employment rates, income distribution, and levels of investment in sustainable technologies. These indicators are vital for assessing the efficiency and resilience of economic systems, ensuring that growth is both inclusive and sustainable. They help in identifying economic disparities, promoting equitable resource distribution, and fostering innovation in green technologies. For instance, the transition to a low-carbon economy can be monitored through indicators like renewable energy investments and green job creation, which are pivotal for reducing carbon footprints while maintaining economic growth.

Social indicators, on the other hand, measure the wellbeing and quality of life of individuals within a society. These include metrics related to education, health, equity, and community vitality. Social sustainability indicators are essential for evaluating how societal progress impacts human development and social equity. They provide critical data on issues such as access to education and healthcare, gender equality, and the inclusiveness of social services. By monitoring these indicators, policymakers can address social inequities and ensure that all community members benefit from sustainable development initiatives. For example, indicators like literacy rates, life expectancy, and social mobility are instrumental in assessing the effectiveness of social policies and interventions. They help in identifying gaps in social services, promoting social cohesion, and enhancing the overall quality of life.

Environmental indicators are equally crucial, as they reflect the state of natural ecosystems and the impact of human activities on the environment. These indicators include data on air and water quality, biodiversity, carbon emissions, and natural resource management. Environmental sustainability indicators are vital for tracking the health of ecosystems, assessing the sustainability of resource use, and measuring progress towards environmental conservation goals. They help in identifying environmental degradation, promoting sustainable resource management practices, and mitigating the adverse effects of climate change. For instance, indicators such as deforestation rates, levels of pollutants, and biodiversity indices provide valuable insights into the sustainability of environmental practices. They are essential for developing policies that protect natural habitats, conserve biodiversity, and reduce ecological footprints.

4.1.2. Spatial–Temporal USI Categorization

The collection of data and the research was defined for the past 5 years. For each NUTS considered, a gradient of color was used. A darker color demonstrates the higher access and affordability of the indicator analyzed. Orange color defines social indicators, green color defines environmental indicators, and blue color defines economic indicators. To show the approach, NUTS related to the setting of Italy were explored. How the dataset was organized, assuming, for example, the Italian NUTS, is shown in Figure 2 below.

Sustainability category	Variables	Measurement unit	Indicator reference source	Area ref. indicator	Source	Value	Reference year data	Territorial scale						
								Nuts 0 (Italy)	Nuts 1 (macro-regions)	Nuts 2 (regions)	Nuts 3 (province)	Nuts 4 (city)	Nuts 5 (municipality)	Nuts 6 (district)
	Per capita GDP	GDP per capita is the indicator generally used to express the level of wealth per inhabitant produced by an area in a given period, allowing comparisons to be made between areas of different demographic size. Unit of measurement dollar/person. Human Development Index (HDI) - Index of Sustainable Economic Welfare - Genuine Progress Indicator (GPI) - Subjective Well Being (SWB)	Determinants of energy consumption in the tertiary sector: Evidence at European level	Worldwide	https://european-union.europa.eu/principles-countries-history/key-facts-and-figures/economy_it		2023	2024	2023	2022	2023	2023		
Economic	Ratio of commercial final energy to tertiary sector employees	%		Worldwide	https://www.sciencedirect.com/science/article/pii/S2352484723003591									
	Ratio of environmental protection spending to GDP	%		Worldwide	https://www.sciencedirect.com/science/article/pii/S2352484723003591			2023						
	Tertiary industry/GDP ratio	%		Worldwide	https://www.sciencedirect.com/science/article/pii/S2352484723003591			2022		2022		2023		
	Carbon productivity	CO2 emission		Worldwide	https://www.emerald.com/insight/content/doi/10.1108/IJCCSM-11-2019-0065/full/pdf			2022	2022	2022		2022		

Figure 2. Dataset structure.

4.2. Gray Literature Review

Sector-Specific Literature Review and Data Collection

In recognizing them, these practices, coupled with the performance evaluation indicators, enable inter-country compatibility. ISO standards may be cited as additional tools to increase the credibility and reliability of analysis performances. The choice of five years' worth of time data has been especially pertinent in this study since there was a need for the respondents to be contemporaneous. Data of this period can often be related to the latest trends, events, programs, and publications. For systematic graphical visualization throughout time, all information is coded with the corresponding year of the data collection. Each of these frameworks and standards provides an opportunity for benchmarking how urban spaces are performing and evolving, all of which points to the need for a systemic and integrated approach to the design of sustainable, resilient, and livable cities. They fill the gaps in forensic tools for urban planning and, once applied, signing off the transformation of spaces, making way to sustainable urbanization.

In Table 2, which contains the number of sustainable indicators as well as the number of indicator types for each of the three interrelated aspects of sustainability (economic, social, and environmental), the ISO sustainability list included in Table 1 from Section 2.2 is reproduced. The ISO 37106 and 14030 standards are, however, excluded from the list because information on sustainability metrics is lacking.

Table 2. ISO characterization under the three sustainability dimensions.

ISO on Urban Sustainability Indicators	N° of Indicators	Economic	Social	Environmental
ISO/DIS 37123—Sustainable Development Indicators for Resilient Cities	73	18	37	18
ISO 37122:2019—Sustainable Development Indicators for Smart Cities	80	26	31	23
ISO 37120:2018—Sustainable Development Indicators for City Services and Quality of Life	104	31	32	41
UNECE-ITU—Sustainable Indicators for Smart Cities	72	26	27	19
ETSI TS 103 463—Indicators for Smart Sustainable Cities	76	29	23	24
ITU-T Y.4903/L1603—Indicators for Smart Cities to Assess the Achievement of SDGs	52	13	20	19
ITU-T Y.4902/L1602—ICT Sustainability Impact Indicators in Smart Cities	30	7	7	16
ITU-T Y.4901/L1601—ICT Indicators for Smart Cities	48	21	13	14

4.3. Comparative Analysis

Spatial–Temporal USI Ontology

The general design of the framework should satisfy the following requirements: (i) identify ranks among the various policy domains; (ii) make an evaluation of the trade-offs required between the various dimensions of sustainable development; (iii) organize information and structure the indicators; and (iv) provide integrated or abridged indicators.

A framework is defined as a consistent plan or outline employed by a researcher to help in organizing, interpreting, and deriving conceptual categories out of textual information of any form. Whenever there is a large scope of research analysis in qualitative methods, it is effortlessly a very helpful guide. There have been many Sustainable Development Goals (SDGs) promoted by the United Nations (UN) for the purpose of creating many of the frameworks that are internally used in some countries and referenced the world over.

The purpose of the central content analysis was to find out and group the indicators which were collected about each of the ontological components present in the outputs of the scientific as well as the gray literature for this study. A deductive approach was applied. Consequently, Table S1 of Supplementary Materials lists a set of indicators that are calibrated within space and time for Italy. In the case of Table S1, only the indicators which carry names as per the ISO standards are presented, and the latest available data of this reservation are available from a temporal source which has a hyperlink. The indicators are in fact joined with sub-sections, and such sub-sections are pronounced as in ISO but rendered in different colors: green for the environmental aspect, yellow for the social aspect, and blue for the economic aspect. A mean reference average value for reference points has been defined within the framework of each indicator in the Italian dimension.

5. Conclusions

This comprehensive research makes several significant contributions to the field of urban sustainability assessment, particularly within the Italian context. For the Italian context, the most important process was about data matching from ISO indicators, the literature, and the research of available data for a future evaluation of indicators for the Italian territory. Through the development of a sophisticated ontological framework that integrates both spatial and temporal perspectives, this study addresses crucial gaps in existing sustainability evaluation methodologies.

The primary achievement of this research lies in establishing a robust and standardized approach to urban sustainability indicators, which harmonizes various data sources and assessment methods that have historically been fragmented and inconsistent. By analyzing

contemporary practices and the academic literature from the past five years, the study captures the rapid evolution of sustainability metrics while ensuring that its findings remain relevant to current challenges facing urban environments.

The ontological framework developed here serves multiple critical functions. First, it provides a standardized terminological foundation that aligns with international ISO standards while maintaining flexibility for the local context. Second, it successfully bridges the gap between different territorial scales, allowing for coherent assessment from neighborhood to metropolitan levels. Third, it introduces an innovative spatial–temporal context modifier that enables a more nuanced understanding of sustainability indicators across different time frames and geographical contexts.

A particularly valuable aspect of this work is its practical applicability. The framework has been specifically designed to enhance the operational capacity of city planners and policymakers, providing them with concrete tools for evidence-based decision-making. This practical orientation is especially crucial given the growing complexity of urban sustainability challenges and the need for more sophisticated assessment methods.

This research also makes a substantial contribution to the standardization of sustainability assessments, addressing the persistent challenge of data source disparities. This standardization is essential for enabling meaningful comparisons between different urban areas and tracking progress over time. The framework's ability to accommodate both quantitative and qualitative indicators while maintaining methodological rigor represents a significant advancement in the field.

Furthermore, while the framework has been developed with specific attention to the Italian context, its underlying principles and methodological approach have broader applicability. This makes it a valuable contribution to the international discourse on urban sustainability assessment and management.

This research highlights the intricate relationship between data analysis and urban development. In detail, the strength of this work lies in its comprehensive methodology considering all the "dimensions" connected with sustainability; to recapitulate, we can summarize the list in a sequence of points:

Urban policies and governance

The spatial–temporal structure of urban landscape indicators is crucial for urban policies and governance. This research can provide policymakers with robust evidence-based tools for making informed decisions about urban development, particularly in addressing social equity, environmental sustainability, and economic growth. The findings suggest that policies should adopt a more integrated approach to urban planning, considering the complex interplay between spatial configurations and social outcomes. These indicators help to assess the potential effects of urban interventions and prevent unwanted impacts such as gentrification and particular social dislodgement. By integrating tools of data visualization and data analysis, local stakeholders can appreciate the impact of the planning decisions which they make. The framework constructed through this research can be helpful in designing better urban policies regarding equity and sustainability along with enabling economic growth, social equity, and the environment.

Environmental sustainability

Environmental sustainability emerges as a cornerstone of this research framework, demonstrating how urban development trajectories significantly influence environmental outcomes across multiple scales. This study's comprehensive mapping of ISO indicators allows the identification of the interactions between environmental sustainability and other indicators. However, as global environmental challenges intensify, future research must evolve to incorporate more sophisticated climate change modeling techniques, including dynamic downscaling methods and coupled human–natural system models.

Enhanced adaptation strategies should focus on nature-based solutions, green infrastructure implementation, and innovative approaches to urban resilience. The integration of real-time environmental monitoring systems, advanced remote sensing technologies, and artificial intelligence-driven predictive models would strengthen our understanding of urban–environmental interactions and support more effective climate adaptation planning. Additionally, the research framework should expand to address emerging environmental challenges such as urban heat island effects, extreme weather events, and biodiversity loss, while considering the interconnected nature of urban–environmental systems and their capacity to support sustainable development goals.

Social factors for sustainability development

The social factor of sustainability plays a fundamental role in building resilient cities, encompassing various aspects of community wellbeing and social cohesion. Resilient cities must prioritize social equity, inclusive governance, and community participation to ensure long-term sustainability. The social dimension includes access to essential services, affordable housing, quality education, healthcare, and cultural amenities that contribute to the residents' quality of life. Furthermore, social sustainability requires attention to diversity, social inclusion, and the needs of vulnerable populations, ensuring that urban development benefits all community members equitably. About this point, this analysis is fundamental in defining the complexity of connecting this kind of indicator with others. This research paves the way for more advanced indicators that can be scaled for small cities or quarters. This can be important for a better awareness of the population, assisting policymakers in data collection and better mapping the indicators. Cultural heritage preservation, intergenerational connections, and social integration initiatives strengthen community resilience and adaptive capacity. Additionally, addressing social issues such as poverty, inequality, and discrimination is crucial for building truly sustainable and resilient urban environments. These social factors are interconnected with economic and environmental aspects of sustainability, creating a comprehensive framework for urban resilience that recognizes the fundamental role of human relationships and social structures in creating lasting, adaptive urban communities.

This study's emphasis on creating a scientifically valid yet practically implementable system is particularly relevant for developing cities, where resources and technical capacity may be limited. By providing a clear, structured approach to sustainability assessment, this research helps bridge the gap between theoretical frameworks and practical implementation.

These research results can also be elaborated for use in other applications through the spatial–temporal ontology framework:

Industrial Zone Planning

The framework can optimize industrial zone placement by analyzing environmental impact, transportation networks, and workforce accessibility, which is particularly useful in developing metropolitan areas.

Tourism Management

The methodology helps analyze visitor flows, cultural asset distribution, and tourism infrastructure capacity, enabling better tourism development strategies in urban centers.

Education Resource Distribution

It can map educational needs across urban areas, helping optimize school locations and resource allocation based on demographic patterns.

Urban Agriculture

The framework can support planning urban farming initiatives by identifying suitable locations considering sunlight, pollution levels, and population density.

Healthcare Infrastructure

Beyond public health, it can guide the placement of specialized medical facilities and emergency response units based on population demographics and access patterns.

These applications are particularly relevant for the following:

- Metropolitan regions undergoing rapid development;
- Historic cities balancing preservation with modernization;
- Coastal urban areas adapting to climate change.

The framework's ability to integrate multiple data layers makes it valuable for complex urban planning challenges requiring holistic solutions.

This research reveals several significant findings regarding urban sustainability and its measurement through urban sustainability indicators (USIs) [4,6,10]. Particularly noteworthy is the emergence of spatial–temporal frameworks that consider both geographical and temporal dimensions of sustainability indicators, as emphasized by Zeng et al. (2022) in their work on urban resilience [2]. The standardization of these indicators through ISO frameworks (37120, 37122, and 37123) has provided cities with comprehensive tools for measuring and comparing their sustainability performance across different domains. This research also identifies some challenges, particularly in the integration of diverse data sources and the need for more sophisticated analytical tools to handle complex urban systems. Vodak et al. (2021) emphasize how advanced technologies can help address these challenges by enabling a faster and more accurate evaluation of sustainability indices [7]. The World Cities Report (2022) further supports these findings by highlighting the critical role of sustainable urban development in addressing global challenges, while emphasizing the need for a continued evolution of measurement tools and methodologies to keep pace with rapidly changing urban environments.

In conclusion, this work represents a step forward in the operationalization of urban sustainability assessment. Its comprehensive approach, combining theoretical rigor with practical applicability, positions it as a valuable tool for advancing sustainable urban development, particularly in the Italian context but with potential applications beyond. The framework's ability to adapt to different spatial and temporal contexts while maintaining methodological consistency makes it a robust foundation for future developments in urban sustainability assessment and management.

5.1. Limitations of the Study

Despite the concerted efforts of this study, there are unavoidably areas within this research where gaps may remain, particularly regarding the merging of geospatial data with ISO 9000 standards. Even though there are hundreds of different US catalogs and USIFs currently present and operating worldwide, each with a variety of theme categories and indicator languages, it is not possible to assert that our sample reflects the whole picture. It should be added that our attention to the major sustainability dimensions, categories, and indicators, increasing the clarity of understanding, does not eliminate the need for the remaining aspects of the system, which are necessary for achieving sustainable development goals. Such is even more the case within the broader ISO scope itself, since different cities may have different degrees of usefulness and relevance depending on the ISO data. That being so, it is therefore important to stress that our results are mostly intended as an early stage of the decision-making process rather than an answer to addressing policy challenges. They point towards the importance of engaging and adapting strategies to specific contexts and goals in ways that include meeting ISO standards wherever feasible to maximize relevance and efficiency.

Recognition must be made here that this only represents a small percentage of all these frameworks that come into play in the entire world. These frameworks are not only different in language but also in thematic content and are rich in quantitative, qualitative,

nutritional, and several other indicators of sustainability, many more than those depicted in our sample. The tendency to focus mainly on the most common dimensions of sustainability and on ordinary indicators reveals the complexity that lies in the pursuit of sustainable developments.

5.2. Future Development

The focus on this section should be continued for the indicators of sustainability and the evaluation of its efficiency to be more effective. One of the most important development objectives is the convergence of these tools with ISO data so that they can be used uniformly in different urban environments.

Looking forward, this study lays the groundwork for several important developments. It provides a foundation for the following:

- Enhanced integration of sustainability metrics across different urban governance levels;
- More effective policy formulation addressing specific urban environmental challenges;
- Improved coordination between local sustainability initiatives and broader national and international sustainability agendas;
- Better monitoring and evaluation of sustainability interventions in Italian cities (evaluation for hundreds of indicators for the seven NUTS data availability);
- More informed decision-making processes in urban planning and development (this process will be possible after defining the indicators in a spatial–temporal condition).

The methodological approach of the study can be improved with the integration of data and by performing spatial analysis using GIS as well as visually depicting over time the transformation of cities using maps. The integration of GIS technologies and remote sensing data adds to the knowledge of the patterns of urban transformation. It would also be critical for this study if additional social measures of a robust character are applied that enable further the analysis of community dynamics and the preservation of cultural practices. The economic assessment of the market aspects was quite thorough, though with an increased focus on combining parameters, and not detailed enough on the informal economies and how they fit in urban sustainability, and more on that front would be expected. Through sophisticated GIS analysis and environmental monitoring data, this research effectively illustrates how different urban forms and development decisions directly affect ecosystem services, from local microclimate regulation to regional carbon sequestration capacity. The findings highlight critical thresholds in resource consumption patterns and identify potential tipping points in urban ecosystem health.

More systemic research should be conducted that would seek to formulate standards for the implementation of USIs in situations where local peculiarities are considered, without breaching uniform international standards such as those of ISO. This pertains to designing a comprehensive yet flexible set of indicators, which can be generalized as well as localized to suit a specific context. Thus, indicators regarding the quality of the atmosphere, bodily fluids, and power intensity should comply with the International Organization for Standardization (ISO) requirements to enhance uniformity in the collection and analysis of data for comparative purposes across cities.

It can also be very valuable to investigate the possibilities for enhancing the level of attention which is paid to each of the dimensions of sustainability—environmental, social, and economic—and to institutional coherence within the USIs. However, our existing frameworks, while making progress, are largely under pressure on how to structure these sustainability dimensions to enhance sustainable development. Therefore, future frameworks should pursue the development of integrated indices that reflect the intricacies of these interrelationships.

The temporal analysis in urban research and sustainability development, while providing crucial insights into city evolution patterns, currently faces limitations that could be addressed through expanded methodological approaches. By extending the time horizons beyond conventional study periods and implementing advanced forecasting techniques such as machine learning algorithms, artificial intelligence, and complex system modeling, researchers could develop a more comprehensive understanding of urban transformation trajectories. Vodak's study on advanced technologies in smart city management defined that the use of emerging technological solutions in an integrated frameworks for smart city systems can help future smart city development [7].

These enhanced methods would enable a better prediction of long-term development patterns, incorporating factors such as climate change impacts, demographic shifts, technological advancements, and socio-economic dynamics. Advanced temporal analysis could also facilitate more accurate assessments of urban resilience by examining how cities have historically responded to various stressors and challenges. Future developments of the method explained here can use the integration of sophisticated forecasting tools, including scenario planning and system dynamics modeling, which would allow planners and policymakers to better anticipate future challenges and develop more effective strategies for sustainable urban development. This expanded temporal framework would be particularly valuable in understanding cyclical patterns in urban development, identifying critical intervention points, and developing more robust strategies for building resilient, sustainable cities that can adapt to future challenges while maintaining their social, economic, and environmental integrity.

The expansion of urban research technology through digital twin implementation aligns directly with the UN's 2030 Agenda for Sustainable Development and the Resilient Cities Network program objectives. These virtual replicas of urban environments enable sophisticated simulation and the testing of various interventions, supporting the key resilience targets of the 2030 framework, particularly in climate adaptation and risk reduction. The integration of IoT devices and sensor networks aligns with the Smart Cities initiatives under the 2030 agenda, enhancing urban monitoring capabilities for climate action, sustainable infrastructure, and inclusive communities. Digital twins and AI analytics support the Resilient Cities Network's goals by enabling cities to better prepare for, and respond to, physical, social, and economic challenges. This technological framework particularly advances the 2030 targets for sustainable cities (SDG 11) by providing tools for comprehensive urban planning, risk management, and adaptive governance. The real-time data collection and analysis capabilities help cities track their progress toward resilience objectives while supporting evidence-based strategies for climate action and sustainable development.

There is a need to extend the goals of documentation to enable greater inclusion of stakeholders, where necessary, during the creation and revision of sustainability indicators. This participatory approach would ensure that the indicators are not only scientifically sound but are also sensitive to and appropriate within the context of the local communities, thereby enhancing sustainability assessments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14010072/s1, Table S1. Italy's standardized indicator ontology.

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