smart cities

Article

The Intersection of the Green and the Smart City: A Data Platform for Health and Well-Being through Nature-Based Solutions

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Abstract: An increasingly important aspect of analyzing the challenges facing cities today is the integration of nature. Nature-based solutions have the potential to successfully cope with the adverse effects of extensive urbanization and climatic change. On the other hand, the incorporation of smartness in cities is a critical issue. This paper aims to analyze the steps towards integrating nature-based solutions and smart city aspects to develop a web-based data platform that focuses on tackling and investigating the role of nature-based solutions in city health and well-being and returns a digital twin of the natural and built environment, including health-related key performance indicators. Seven pilot cities are used as a basis for the analysis. The architecture of a smart green city data platform is described. The interaction with the citizens is ensured through apps and games. The paper lays the foundation for a future "phygital" NBS world.

Keywords: nature-based solutions; health; wellbeing; smart cities; platform

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1. Introduction and State of the Art

The overall increase in population in cities [1,2] creates a significant need for a deep understanding of the driving forces that influence the urban environment. Urbanization impacts the environment in several ways [3], affecting the urban climate and making cities vulnerable. Studies around extreme weather conditions connect the city structure and characteristics with these conditions. According to various studies [4–6], resilience and sustainability should be considered in cities' management to address the emerging challenges and the effects of climate on a large scale. Anthropogenic activity in urban areas changes water and energy use considerably. Surface cover alterations in the urban environment increase the sensible heat flux and surface runoff and reduce evaporation compared to the natural environment [6].

A significant aspect when analyzing the challenges that cities face is the incorporation of nature, i.e., renaturing cities [7–9]. Nature-based solutions have the potential to successfully cope with these adverse effects of extensive urbanization and climatic change. Nature-based solutions (NBS) can foster and simplify implementation actions in urban landscapes by considering the services provided by nature. They include the provision of urban green, such as parks and street trees that may ameliorate high temperatures in cities or regulate air and water flows, or the allocation of natural habitat space in floodplains that may buffer the impacts of flood events [10]. Architectural solutions for buildings, such as green roofs and wall installations, may reduce temperature and save energy [11–13]. This effort requires a better understanding and a transformative change in how planners, designers, managers, and citizens view nature as a solution for cities. Nature-based thinking and an inclusive approach are required where stakeholders' engagement is critical [14,15]. The current research work pinpoints the social, environmental, and economic benefits and co-benefits of nature-based solutions [8], showing the significant impact of the solutions on mitigating urban heat islands [16–18], improving health and well-being for citizens, etc. [16,19–21].

Conversely, cities experience challenges related to the emerging need to rapidly manage vast amounts of unstructured data [22]. As the world is increasingly populated by IoT devices and sensors that can sense their surroundings and communicate with each other, a digital environment needs to be created with vast volumes of volatile and diverse data. Various researchers have provided insights into the data management of cities. The City Data Hub [23] incorporated key elements for smart city platforms and standard application programming interfaces (APIs) that increased interoperability and guaranteed ecosystem extensibility. In addition, ref. [24] proposed correlating multiple city data flows in different shapes to support decision-makers in solving non-predefined problems. A system is proposed based on abstracting city events of social, urban, and natural backgrounds. Hence, hundreds of cities worldwide are living examples of what a smart city resembles regarding information technology advancement and everyday usage [2,25,26]. Each application or general system serves and exists for a specific purpose, using mobile applications and small sensors together to cooperate and deliver substantial economic and social benefits and a significant source of data. However, most of these applications are tied to specific domains and are solely designed to solve predefined problems. Data interoperability and "usable data" are still unsolved challenges in many cities, due to technical issues and the governance structure of public departments [27].

In recent decades, various names have been given to cities that enrich citizens' life quality by employing digital technology to improve sustainability and tackle the climate crisis, namely green cities, sustainable cities, smart cities, eco-city, etc. [24]. Regarding technical innovation, a smart city is a target for future cities. Although it is considered that a smart city is also a sustainable city, this is not always the case. The notion of the green smart city is also discussed to balance the technological and environmental aspects [28] and illustrate the synergies between a city's greenness and smartness.

Various data platforms are being proposed in the literature for deploying the combination of green and smart cities. By looking at nature-based solutions, online data knowledge-sharing platforms are proposed to support accelerating green and blue space adaptation in urban areas. Online citizen science platforms are presented to stimulate stakeholder engagement and promote nature-based solutions in the case of ClimateScan [29]. ClimateScan has adopted a bottom-up approach in which users have to create and update content. Other data platforms are dedicated to specific city aspects or problems, such as traffic data and road network monitoring [25,30], water management [31] green infrastructure and plants [32,33], and urban heat island data [34–36].

The challenge of integrating different aspects of green within the smart city concept remains. Especially in the area of applied research supported by European co-funding, the focus of smart city projects has traditionally been on the management and use of urban data, alongside technological innovation for energy efficiency in buildings and neighborhoods, and sustainable/electric mobility (see https://cordis.europa.eu/programme/id/H2020_LC-SC3-SCC-1-2018-2019-2020 (accessed on 6 July 2023)).

In contrast, projects in the NBS thread have focused on the innovation and co-design of green and blue infrastructure for buildings or public spaces, with little emphasis on real-time measurement of performance and its return to the public (see, for example, https://cordis.europa.eu/programme/id/H2020_SCC-02-2016-2017/en (accessed on 6 July 2023)), and far from the digital twin approach. Almost as if there were two philosophically distant approaches that are difficult to reconcile. Only recently have some projects begun to bridge this gap, creating a positive convergence between the two research lines. To this end, the present paper aims to analyze the steps towards integrating nature-based solutions and smart city aspects to develop a web-based data platform that focuses on tackling and investigating the role of nature-based solutions in city health and well-being and returns a digital twin of the natural and built environment, including health-related KPIs. Seven pilot cities and their nature-based and smart solutions to improve health and well-being, as well as other environmental challenges, are included in the specific study (Section 2). The architecture of the web-based data platform and its components are included in Section 3. The interaction with the users to create an attractive environment as well as the specifications of the various sensors, are included in Section 5, while the details of the different parts of the data platform's architecture are described in Section 6 to Section 7. The visualization of the platform, key performance indicators, and preliminary data are described in Section 8. Finally, the discussion and conclusions are integrated into Sections 9 and 10, respectively.

2. Materials and Methods

The research performed in the present paper has the following methodological steps:

I. **Selection of pilot cities** The selection criteria were:

a. Coverage of diverse climatic conditions and regions within Europe (see Figure 1).
b. Coverage of different urban scales ranging from street level to neighborhood and city or regional scale.
c. Tackling different challenges with nature-based solutions.

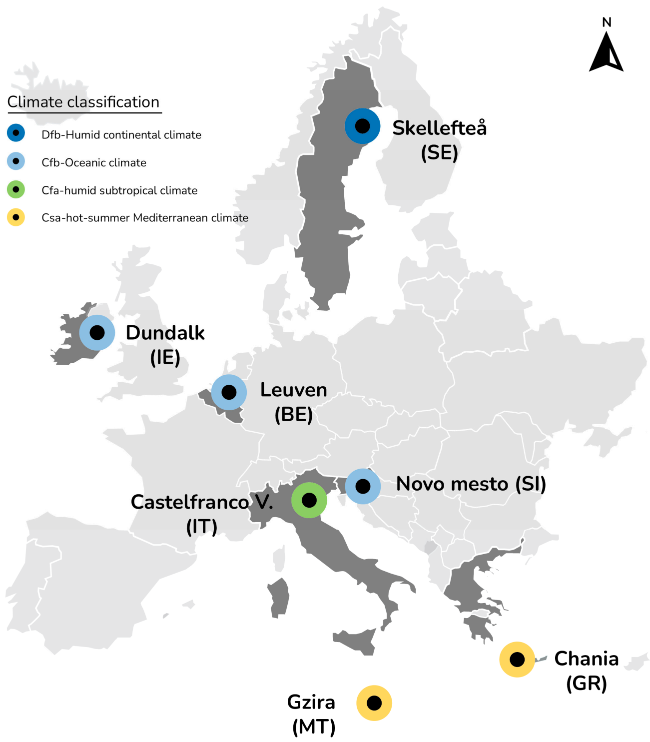


Figure 1. The map of the pilot cities.

II. **Analysis of the pilot cities' requirements and data collection needs** Focusing on the state of the art and available information at the urban scale, 14 sections corresponding to several relevant domains of knowledge for the intersection of the smart with the green city, have been defined:
   1. General information for each pilot;
   2. Climate and energy;
   3. Environmental issues;
   4. Urban green spaces and nature-based solutions;
   5. Social and economic aspects;
   6. Participatory planning and governance;
   7. Health and well-being of citizens;
   8. Innovation and smart city aspects;
   9. Vision and objectives;
   10. Stakeholders;
   11. Installed sensors;
   12. Local governance system;
   13. Major needs and challenges, barriers, and drivers;
   14. Potential multiple impacts.

   These domains of knowledge are utilized for the development of the web-based data platform specifications.
III. **Creation of a baseline for the seven pilot cities by collecting data and creating a local database (see Section 7)**
IV. **Development of a smart nature-based solutions web-based data platform.**

Based on the domains of knowledge, the architecture and functionalities of the web-based data platform are extracted. The interaction with the citizens and their engagement, the utilization of sensors, as well as cities' biodiversity aspects are considered to enhance the aforementioned domains of knowledge.

V. **Extraction of key performance indicators**

The installed sensors and the developed applications for citizens' interactions and engagement are utilized for the development of key performance indicators that will allow the comparison of cities' performance.

VI. **Visualization of data and key performance indicators**

All the aforementioned steps are analyzed in the following sections.

3. Description of the Pilot Cities and Smart Nature-Based Solutions Architecture

Seven European cities were selected to implement smart nature-based solutions covering different climatic conditions in Europe. The research started in September 2020 with the collection of data, understanding the cities' needs, and defining smart nature-based solutions. The site descriptions as well as the different solutions are tabulated in Table 1.

The present section aims to describe the architecture and the interconnectivity of the various components that are integrated for the monitoring of the pilot cities' solutions (Table 1). This infrastructure collects, stores, analyses, and visualizes all pilot data, making them available to different stakeholders.

The main components are depicted in Figure 2 and consist of:

1. The physical layer includes the sensors and the sensor network. The sensor network is required for the data connectivity, i.e., the IP connectivity and the LoRaWAN communication protocol. The physical layer also includes the GoNature game ecosystem, which digests the sensors' data to dynamically adapt the game/app environment in real-time and achieve interaction with citizens.
2. The sensor management platform functionality ensures high-quality data by monitoring the sensors' battery level, signal-to-noise ratio, and signal strength indicator

of the channel. The specific platform ensures proper maintenance of the connected devices. The platform sends notifications about possible device failures and executes predictive maintenance, e.g., changing the device's battery before it fails.

3. The central REST-API is a critical component for the interaction of the various items and is described in detail in the next sections.
4. The local databases where all data from the seven pilot cities are stored. These local databases provide non-real-time access to the data through an open data platform. The open data platform provides a mechanism to share the collected data with citizens and enables the publication of collected data on the GEOSS portal and the regional and national open data platforms. Through the REST-API real-time data access is also anticipated.
5. The health and well-being platform enables the visualization of the collected data.

Table 1. Description of the smart nature-based solutions for each pilot city.

Skelleftea, SE. Transformation of an old landfill area into a residential and educational area using nature-based solutions.	
Pilot Site Description	The area was covered with industrial buildings, road works, a district heating facility, and a fueling station. A new residential area with family housing of different kinds is built on the landfill area, creating a green connection in the region.
Smart Nature-Based Solutions	SE1. Build natural infrastructure to create urban resilience with ditches and ponds—monitoring of water flow and quality. SE2. Creation of a wetland bed. Existing flora is complemented by planting to increase biodiversity (including pollinators), attractiveness, and functionality of the area. SE3. Installation of smart lighting to contribute to an inviting environment and encourage activities in the park. SE4. Educating and engaging citizens to increase their awareness of climate change and the importance of biodiversity. Information signs are installed in the park to help engage and educate visitors about nature-based solutions. SE5. Creation of a space in the park with bee hotels/insect habitats and permanent school material. Open-air classrooms are designed and built.
Dundalk, IE Creation of Dundalk Library and Museum Quarter.	
Pilot Site Description	Albeit the smallest in Ireland, County Louth is also one of the most densely populated. The regeneration of a neighborhood area and the removal of car parking spaces assist in the creation of an accessible and high-quality green space.
Smart Nature-Based Solutions	IE1. Creation of an outdoor learning pod between Dundalk Library and Museum Quarter to showcase the newest technologies and host shared functions. The sensors measure the number of visitors, monitoring improvements to the use of the space. IE2. Outdoor urban green learning and sensory garden. Increased sense of safety, recreation, relaxation, and stress reduction for the visitors by incorporating new seating areas and public lighting. A rainwater harvesting system encourages visitors to be more sustainable in water use. A new touch screen displays green learning. IE3. Sensors on bike stations. New bike stations equipped with sensors are installed at the site to improve cycling infrastructure for visitors and encourage active travel. The data collected on the number of cyclists provides a better understanding of space use.
Leuven, BE Regeneration of a former hospital site.	
Pilot Site Description	The pilot area is a former hospital site in the city's medieval center. This fully built area is transformed into a green district, where the rivers, the Dyle and the Aa, are re-opened, and the connection between the city center and the river landscape is re-established. The area becomes a multifunctional neighborhood with different housing typologies and economic and cultural functions.
Smart Nature-Based Solutions	BE1. Riverside urban living room linked to culture and heritage. An urban living room along the opened upriver area, directly connected with the history of the site, is integrated as part of the restored fortification wall. BE2. Sensors for health and water measurements. The microclimatic conditions are monitored and interrelated with the site characteristics. BE3. Health trail. A "health trail" is formed with elements that stimulate movement for different ages, helping people work on their physical condition. This health trail forms a "loop," like a closed circuit, connecting different points of attraction in the park (nature, education, playing, sports, moving, enjoying, meeting, etc.) BE4. IoT infrastructure for smart lighting and noise measurements. Smart lighting poles are installed next to the main walking trail in the new park. In those poles, noise sensors are integrated as a noise sensor ring. They can be used as a nudging tool to regulate the lighting intensity of the light poles in case night noise occurs.

Table 1. *Cont.*

Novo mesto, SI Sports and recreational park Češča vas	
Pilot Site Description	The area of the sport and recreation park in Češča vas is a somewhat degraded forest area, where military facilities remained abandoned after 1991. An open velodrome was built in the southeastern part of the area in the 1990s, which was renovated in 2018 into a covered multifunctional facility for cycling and athletics. A comprehensive sports and recreation complex, which is used to cover the citizens' needs for active leisure, is under construction.
Smart Nature-Based Solutions	SI1. Brownfield remediation and greening. The military brownfield at the pilot site is regenerated with plant species indigenous to the nearby Natura 2000 areas. As part of this measure, sensors to monitor air quality and meteorological data are installed. SI2. Creating sustainable forest trails. To connect the facilities, sustainable trails in the surrounding mixed forest are created. SI3. Interconnectedness of facilities. Development of integrated business and environmental programs, information equipment for connecting facilities, enabling access for disabled people in and around facilities, social and educational events, strategic placement of Wi-Fi points, etc. SI4. Integrated management of SRC facilities. Sports and recreational facilities at ŠRC Češča vas are managed through a common ICT platform. Visitors' movement tracking and detection sensors are installed. Additionally, public screens are placed where the visitor flow data and statistics from the aggregated data collected from other IoT sensors are displayed. SI5. IoT solutions for health and well-being monitoring. Visitor tracking sensors are placed at the pilot site to track the movement of visitors more accurately.
Castelfranco Veneto, IT Blue and green areas for citizens' well-being and health	
Pilot Site Description	The pilot area is the famous historical garden of Villa Revedin Bolasco designed and created between 1852 and 1865. The garden of the Villa borders the oncology hospital and a dedicated house for elderly people, as well as an urban daycare center for people affected by Alzheimer's disease.
Smart Nature-Based Solutions	IT1. Garden access routes to ensure improved access according to the needs of the garden users. Renovation of the already existing access route to the garden, enhancing the accessibility of pedestrians and cyclists, and facilitating access for people with special mobility needs. IT2. Analysis and monitoring of the psychological and physiological well-being of the elderly and people with Alzheimer's visiting the historic garden. Collection of evidence about the behavior, physiological state, psychological well-being, and quality of life of the elderly and people with Alzheimer's visiting the historic garden. IT3. Monitoring the microclimatic and environmental conditions in the different areas of the garden (forest area, open area, lake area). Based on this, an assessment is carried out of the effect of green and blue areas on the health and well-being of visitors, elderly people, and people with Alzheimer's over the medium-term period. IT4. Best practices manual and local landscape observatory. Development of a best practices manual for the replicability of the design of green public spaces with a special focus on human health and well-being, and establishing a local observatory focused on the therapeutic effects of the landscape. IT5. Implementation of ICT tools. These tools support a rewarding experience for garden users and assist visitors with disabilities to increase safety during their visits to the garden. IT6. Adaptive and intelligent information systems (the so-called "virtual window" on the garden). Establishment of digital screens that show images and videos of the garden, and share sounds, to stimulate the curiosity of prospective visitors and engage citizens. Monitoring data are interactively visualized.
Chania, GR Green space revitalization by incorporating innovative infrastructure	
Pilot Site Description	The solutions are located in various green spaces, schoolyards, neighborhoods, and public squares in Chania, as the developed solutions are mobile.
Smart Nature-Based Solutions	GR1. Mobile urban living room (MULR). Development of a convertible construction that can create inviting points in various public spaces. Educational and social activities and pop-up cultural events are anticipated in and around the living room, addressing all ages, designed and implemented to be fully accessible. Sensors are installed in the MULR to monitor air pollution, noise exposure, microclimatic conditions, etc. Through hosting local events, the MULR encourages citizens to provide self-perceived health and well-being data. GR2. Sensors on bikes and bike stations. Public bikes and bike stations equipped with sensors collect environmental and health data. Combining these data with predictions from computational models and data from weather stations, urban health and well-being maps are created. Citizens can distinguish polluted from healthier, environmentally friendly urban areas. This strategy is expected to raise citizens' environmental awareness and encourage them to visit green spaces more often, improving their H&WB.

Table 1. *Cont.*

Gzira, Mt Regeneration of a high-traffic road	
Pilot Site Description	The pilot site is a high-traffic road called Rue D'Argens. Flanked by residential and office buildings on both sides, the road sees constant traffic and has little to no greenery.
Smart Nature-Based Solutions	MT1. Micro-greening interventions. Supply of plant seeds to promote the greening of balconies, facades, and interiors of households to raise awareness about the benefits of green solutions to H&WB. Greening of a bus stop area to increase vegetation, improve the visual aesthetics of the streetscape, and attract biodiversity into our urban settings. Temporary "pop-up parks" with greening and educational activities as a placemaking exercise to promote inclusion and build community ties. MT2. Citizen science on air/noise quality to increase H&WB awareness. Sensors installed at various locations, mostly within Gzira, collect and compare data at different geographical points to identify the various pollutants and the amount of noise and air pollution in the area. MT3. Urban biodiversity education and engagement through a co-created community garden project. NBS interventions and citizen engagement activities are designed with local schools and Gzira Gardens with the intention of embedding a greener perspective into the educational institutions and cultural context.

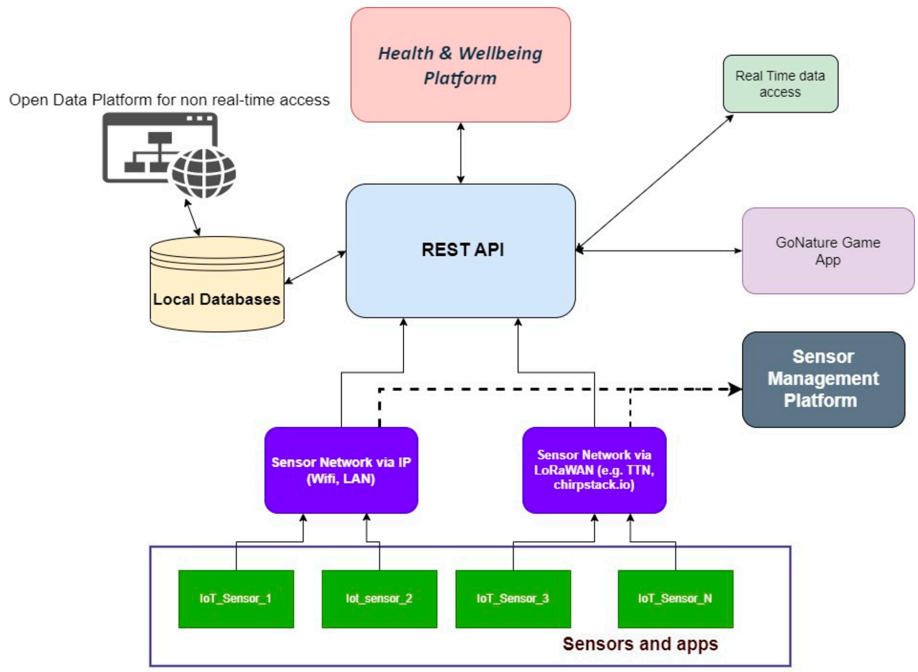


Figure 2. Smart nature-based solutions' architecture.

The specific components and their functionalities are described in detail in the next sections.

4. The Physical Layer—Sensors and Apps

4.1. The Sensors' Specifications

For each smart nature-based solution described in Table 1, a specific set of monitoring sensors is installed on-site. An overview of the monitoring parameters is tabulated in Table 2, while the full list of sensors is included in Appendix A. LoRaWAN communication technology is introduced to transmit the sensors' data in this configuration. LoRaWAN is a type of low-power wide-area wireless network. Measurements are encoded into bytes that are transmitted to the LoRaWAN network. The main benefit of LoRaWAN is that it operates on long ranges with low power consumption, making it suitable for outdoor sensors [37,38].

Table 2. Overview of the monitoring parameters for each pilot city.

Pilot/Monitoring	Skelleftea	Dundalk	Leuven	Novo Mesto	Castelfranco	Chania	Gzira
Microclimatic conditions	X	X	X	X	X	X	X
Air quality	-	X	X	X	X	X	X
Wind	-	-	X	-	X	-	X
Noise	-	-	X	-	X	X	X
Water/Snow level and quality	X	X (rainwater harvesting)	-	-	-	-	-
Visitor numbers	X	X	X	X	X	X	X
Wearables for citizens	-	-	-	X	-	X	-
Energy meters	-	X	-	-	-	X	-

The Things Network (TTN) (https://www.thethingsnetwork.org/ (accessed on 1 December 2023)) is used as the LoRaWAN network for transmitting the sensor measurements from the pilot sites to the sensor management platform. All sensors are first registered on The Things Network, which acts as the central LoRaWAN network server (LNS).

4.2. Apps and Interaction with Citizens

The interaction with the pilots' citizens is performed via augmented and virtual reality (AR&VR) apps and the so-called "GoNature" game. The interaction aims to enrich the experience of each pilot site with engaging and innovative digital technologies as part of the nature-based solutions described in Section 2. The "GoNature" game provides an immersive experience across the whole cross-reality (XR) spectrum ranging from entirely virtual worlds to real-world augmentation. Research has shown that digital games can be an effective educational tool for young people [39], providing a fun and interactive way to learn. Games have been used to teach a variety of subjects, including science, math, and history, and can be effective at increasing motivation, engagement, and learning outcomes.

Additionally, digital games are effective at teaching complex concepts and skills, such as critical thinking, problem-solving, and collaboration. For instance, a National Institute for Play study found that digital games can help children develop important cognitive skills such as attention [40], memory, and decision-making. Furthermore, games can be effective at reaching and engaging a younger audience. For example, a study by the Joan Ganz Cooney Center [41] found that children who played educational games were likelier to learn about the subject matter and retain the information they had learned.

Figure 3 illustrates the overall architecture of the apps and the "GoNature" ecosystem. A brief description of the main components of GoNature:

- Central REST API connectivity, as depicted in Figure 2. The REST API is described in Section 6. The GoNature ecosystem retrieves data from the sensors' network through REST API.
- SoHi platform (Figure 4), which is a content services platform specially designed for specific research that provides a set of tools that allow users to create and publish multimedia content, such as text, images, video, and 3D models as well as mixed reality (MR/VR/AR) experiences. Additionally, this platform also includes tools for content management, allowing users to organize and manage their content easily. The platform also allows for easy publishing, making it simple for users to share their content with a wide audience. The platform is also highly customizable, allowing users to personalize their content and make it truly their own. SoHi offers a unique and dynamic way for users to express themselves and share their ideas with the world.
- The GoNature game: The mobile version of the game runs on Android and iOS. Each pilot site has several identified key points of interest (POIs) strategically selected to promote the benefits of public green spaces and their positive effects on health and well-being. These POIs encourage citizens to explore each pilot site physically and virtually through the game. At each POI, citizens interact with non-playable characters (NPCs) using a dialogue system that provides citizens with essential information about

environmental phenomena and the advantages of green spaces. The dialogues are both in English and the local language (see Figure 5). Treasure hunts via geocaching are also included. Geocaches are placed in various locations on the pilot sites as points of interest. Apart from being shown informational and educational facts, the players can interact with a virtual representation of the geocache. The idea is to earn reward points for each geocache visited. To gamify the interaction further, interacting with the geocaches grants an item to the player, with each geocache having a unique in-game virtual item. The player's aim would be to collect all virtual items and take them to a specific location to promote physical activity and pilot site exploration. In doing so, the player would gain bonus points to qualify for a physical gift.

- GoNature VR: The virtual reality version of the game running on a mobile device using Cardboard. To further increase the dissemination power of the application, a VR version is also being worked on, and to lower the entry barrier as much as possible, an affordable platform is chosen, namely Google Cardboard. Google Cardboard is a simple and economical way for users to dive in and explore the immersive experience of virtual reality using their smartphone [42].

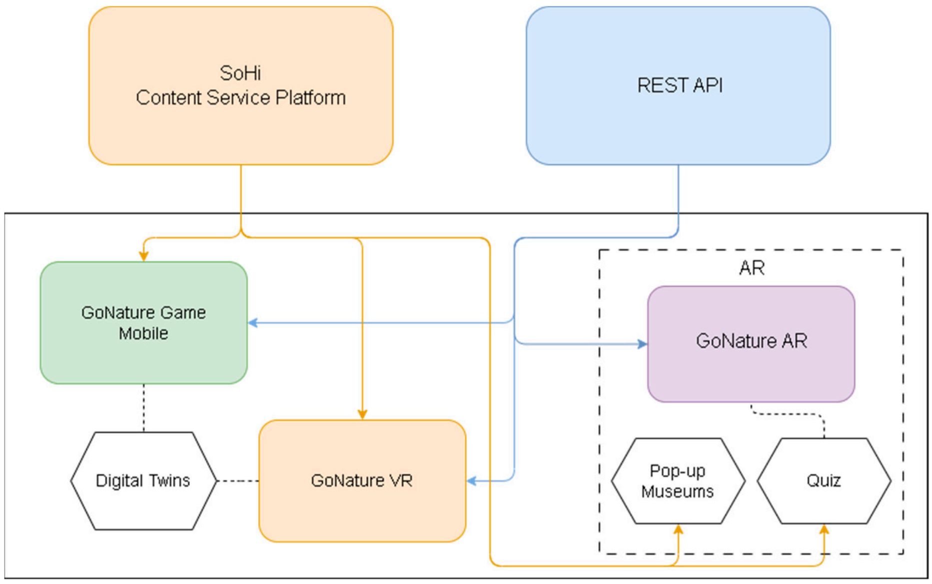


Figure 3. The apps' architecture.

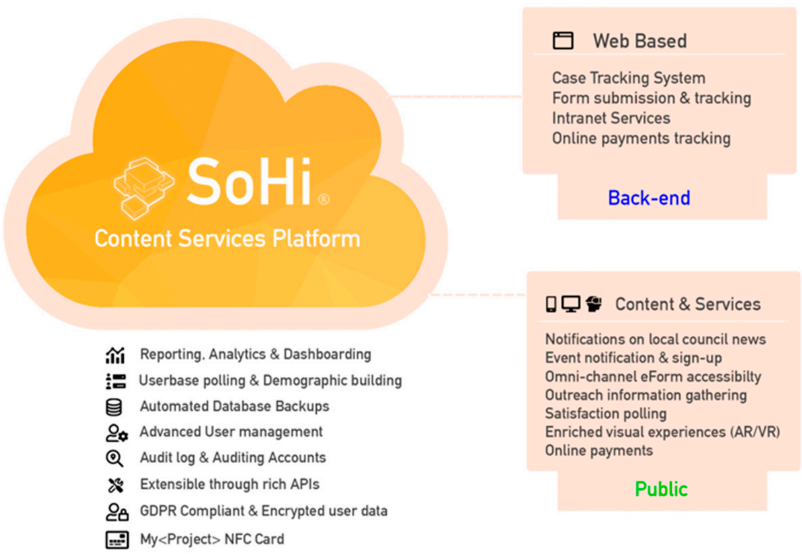


Figure 4. SoHi platform and a brief set of features.

Figure 5. The dialogue system.

- Digital twins: Digitalization of the pilot sites in a 3D environment that is exploited for both the mobile and VR versions of the game. Digital twins of the pilot sites are created to fulfill the interaction with citizens. Various methods are used to gather reference material, such as online mapping tools and satellite imagery. GIS and LiDAR data were also exploited and used to further enhance models by providing a high degree of accuracy and realism. Digital twins, apart from the 3D digitization of the pilot areas, provide a layer on top of the 3D geometry, which is the real-time status of the area, and their respective metrics regarding air, noise, and temperature conditions. These data received through REST API affect both the Mobile and VR experience. Indicative images from the sites and their digital twins are depicted in Table 3. The daytime and nighttime cycle of the VR game is illustrated in Figure 6.
- GoNature AR: An augmented reality gamified experience running on Hololens2 headsets (57). The AR version allows the game to interface with the physical world and provides an immersive, emotion-provoking experience. HoloLens 2 is selected to deliver the augmented reality experience. HoloLens 2 provides a hands-free experience, including multimodal interactions such as eye-gaze, voice, and hands or gestures, enhancing immersion and allowing for further research on interactions in a mixed reality environment [43]. GoNature AR is a multimodal augmented reality narration story that guides the user through an immersive audio-visual experience in which the user becomes aware of environmental phenomena and their consequences for human health and well-being. In this narration, the user follows a virtual companion through three different visualization scenarios (air pollution, noise exposure, and thermal comfort). The visualization scenarios are dynamically affected by the sensor metrics the app receives through REST API for the specific location.

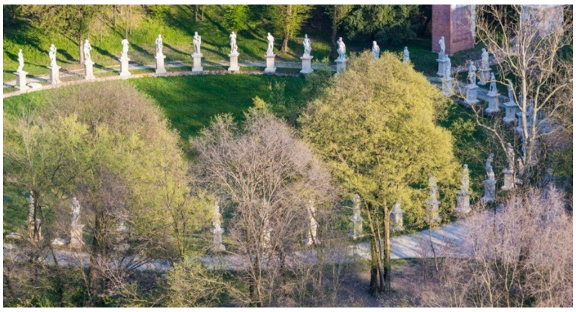
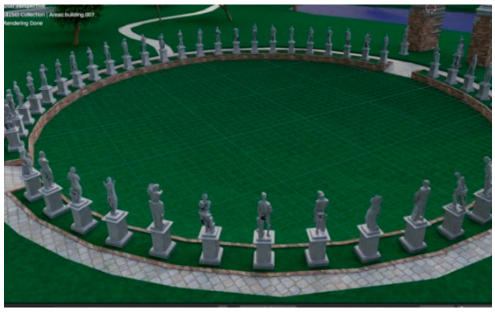
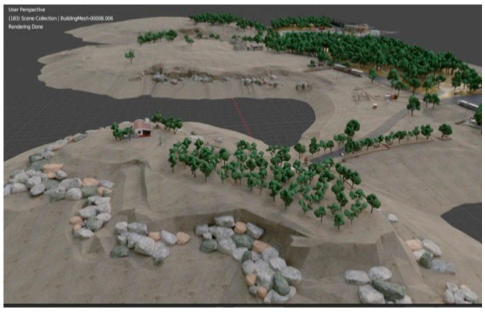
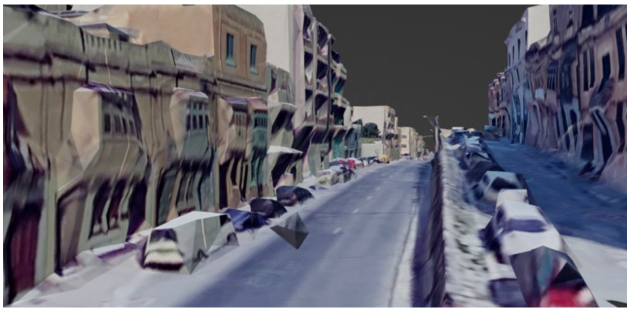
Figure 6. The daytime and nighttime cycles in the game.

- AR Quiz: A quiz system for fast implementation of AR-enabled quizzes.
- Pop-up museums: An AR system for fast virtual museum/gallery implementation using 3D virtual objects and video or text annotations. The specific functionality is connected with the SoHi platform and is designed to bring virtual objects of various categories into the real world and provide immersive visualization. It can be used both for cultural promotion and education for all pilots.

Table 3. The sites and their digital twins.

Site	Aerial Images	Digital Twins
Skelleftea		
Dundalk		
Leuven		
Novo mesto		

Table 3. *Cont.*

Site	Aerial Images	Digital Twins
Castelfranco		
Chania, GR		
Gzira, MT		

5. The Sensor Management Platform

The sensor management platform keeps track of the sensor quality data. The architecture and the components of the platform are depicted in Figure 7.

The core part of the platform is responsible for receiving and processing the sensor data and is separated into three different modules, as depicted in Figure 7, i.e., the backend where data are stored, and the GO inbound and outbound REST API. This is a local REST API for short-term data gathering to support the data quality features. The configuration and data are stored in a combination of CockroachDB and TimescaleDB. CockroachDB is designed to be a robust cloud-based solution and TimescaleDB is suitable for storing short-term time-series data from the sensors. The inbound local REST API receives the sensor data, and the outbound local REST API provides access to the sensor data. The programming language Go (https://go.dev/ (access on 1 December 2023)) is used for the development of the specific REST APIs. The main advantages are that it is memory-safe and structurally typed.

The platform's apps support the frontend to perform different functionalities. The Senzemo Dash app is responsible for the graphical user interface that the user experiences by visiting the platform's webpage. The second app, Senzemo Analytics, is responsible for processing the received data from the backend. The creation of the sensor management platform allows the connection with The Things Network using a webhook.

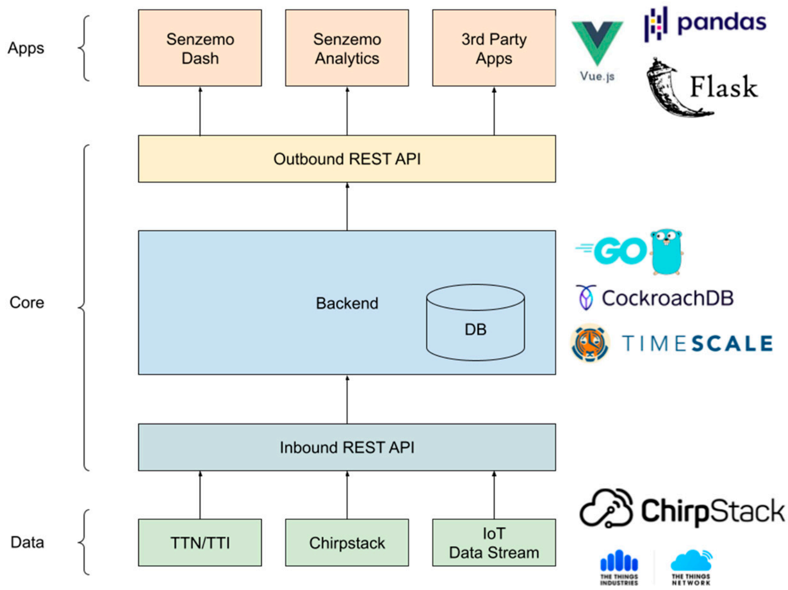


Figure 7. The sensor management platform.

6. The Representational State Transfer Applications Interface (REST API)

The rapid development of Internet of Things (IoT) technologies has allowed the realization and integration of various smart application systems [44]. A core component of the proposed smart nature-based solutions architecture is the REST API. It works under the publish/subscribe design pattern [45] and provides a generic interface based on NGSI-LD (Next Generation Service Interfaces–Linked Data) [46] for third-party applications to access the pilot cities' data resources. The REST API includes multiple data access and security mechanisms to ensure that only authenticated applications can access its resources and is based on the microservice architectural philosophy [47]. Every component has its specific functionality and role in building and operating the REST API. The components have loose coupling with each other to reduce dependencies and complexities. Another decision point for following the microservice architecture was that the specific REST API is cloud-based. Microservices are commonly used in cloud-native applications.

The REST API is built using four major components, as depicted in Figure 8:

- Context broker—Orion LD
- Identity management
- IoT agents connected to sensor network (IP, TTN). (see Figure 2)
- QuantumLeap which is connected to the local databases.

The context broker handles context information management to support the implementation of the NGSI-LD API. For the specific task, the Orion-LD has the most mature implementation of the NGSI-LD API specification. Orion-LD allows context consumers and producers to interact (Figure 9). Context producers vary from a single sensor to a complex system that provides context to the context broker. The context consumer that requests to receive a producer's published data, must subscribe to the specific producer. When the context producer publishes context to the broker, the broker pushes the context to all subscribed consumers.

Identity management, protection of personal data, and data security is a cornerstone of the smart cities concept. All components interacting with the REST API are securely accessed and managed using a unified identity management solution. Keyrock [48] is being utilized to provide user, organization, application, and role management capabilities, defining authorization policies. Keyrock acts as a policy decision point (PDP) [49], which evaluates and issues authorization decisions. Keyrock stores all its data in a MySQL database. The Wilma policy enforcement point (PEP) is being utilized to provide access control to the REST API. The Wilma PEP proxy is positioned between the component that requires access control and the actor who wants to utilize the particular component. It sends/receives the authorization request to the Keyrock and enforces the received decision. All the communication between the internal and external components of the API is encrypted using the transport layer security (TLS) protocol.

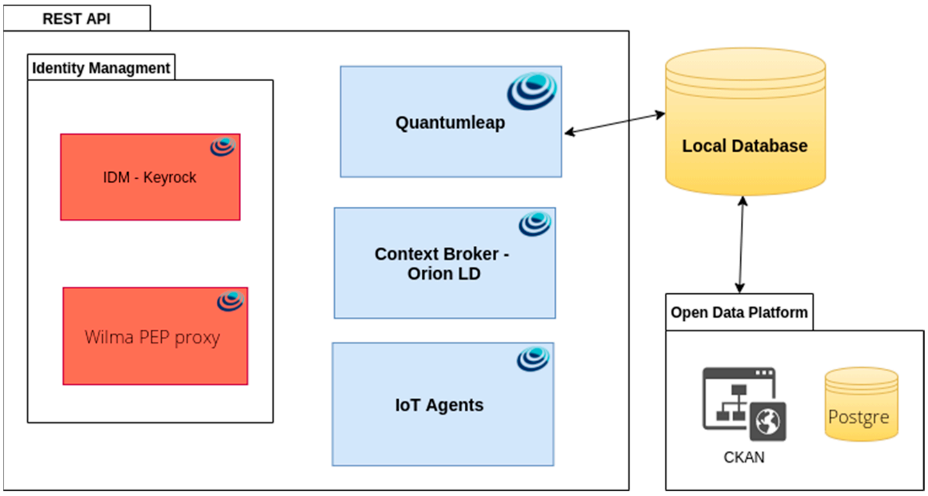


Figure 8. The REST API components.

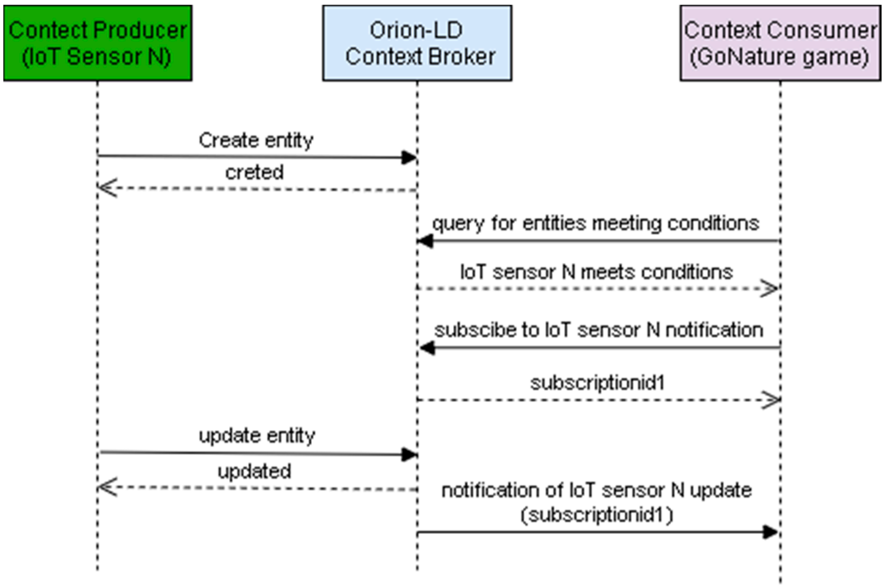


Figure 9. Example API operations (context producer and context consumer).

Orion-LD has limited data retention capability, so a storage component must be utilized to record historical data. Several components exist that can be used as storage solutions, but their maturity for the implementation of the NGSI-LD is not adequate. The only component with active development and proper implementation of the NGSI-LD API is QuantumLeap. QuantumLeap enables persisting context data into a time-series database, Crate DB [50] or Timescale DB. QuantumLeap provides an interface for querying time-series data stored in either time-series database. Timescale DB is an extension of the Postgres DB [51], which improves the time-series workloads and is conceived as a single-node database. On the contrary, Crate DB is a distributed SQL database designed for high scalability. Crate DB has been selected as the database for the pilot's local database based on its scalability capabilities. Moreover, Crate DB can store binary files (photos, documents, PDFs) in tables.

7. The Local Databases

The entire history of each pilot site is stored in a separate local database. Each local database stores all the measurements from the sensors, GIS data, and data from other sources like European and government databases (e.g., GEOSS), satellites, etc. For each database, all data per pilot city are stored.

A first collection of data from the pilots, specifically dedicated to gathering the necessary information for the creation of a sound and robust knowledge baseline, has been performed. A general framework and guidelines have been provided to collect information from the pilot cities and to systematize the qualitative, quantitative, and spatial data. Heterogeneous information includes data about urban ecosystems, cultural and social variables, pilot needs and challenges, barriers and drivers, local governance systems, and expected impacts/benefits.

Some relevant findings from this phase allow initial comparisons between the various sites:

- Many data and information originally required by the pilot characterization templates are unavailable at the city or pilot area scales, nor are they disaggregated according to gender and other diversity criteria (e.g., age, ethnicity).
- The monitoring of the impacts of the prospected solutions on the regulation of the micro-climate will be of particular interest in pilots presenting extreme weather/thermal conditions (e.g., Castelfranco Veneto, Gzira, and Chania are characterized by the hottest temperatures, intense urban heat islands, and long periods of strong thermal stress during summertime).
- The previous experiences of pilot cities in the implementation of NBSs are rather diverse: Leuven had the most extensive experience with many different types of NBSs, while Gzira reported no past experiences. Novo Mesto indicated only planting trees (the most elementary and often implemented NBS). Skellefteå and Castelfranco had a limited number of experiences, while Dundalk and Chania had moderate experience.
- Skellefteå, Dundalk, Novo Mesto, Chania, and Leuven are strongly experienced in smart city solutions in many fields (energy, mobility, and information and communication technology—ICT). Castelfranco Veneto and Gzira are the pilot cities with the least experience in smart city innovations.
- Among the major socio-economic challenges cited by the pilots, the most recurrent ones are improving dedicated services and social engagement for elderly people due to a rapidly aging population, increasing the attractiveness and inclusiveness of the cities, and addressing gentrification processes or the segregation of unfavored groups (such as immigrants and low-income residents). Despite the quite different socio-economic conditions, the pilots could work together towards similar goals and possibly share methods and solutions.

8. The Health and Well-Being Platform and Key Performance Indicators

8.1. The Health and Well-Being Platform

The health and well-being platform follows the same features for all sites. The following pages are anticipated following consultation with the pilot cities:

1. Landing page map of all pilot sites with information describing each site.
2. Pilot overview page describing the context of the site as well as its local environment.
3. The smart nature-based solutions page, named visionary solutions page, describes all the solutions tabulated in Table 1 in text, images, and 3D renders (where applicable).
4. Biodiversity page, which includes the natural characteristics of each site.
5. Feedback page for user feedback on their health and well-being.
6. Survey page for more specific data collection from the users.

The platform follows a hierarchy based on geographic scale (Figure 10), which best describes the context of the pilot sites. However, the feedback and survey page can work independently of the hierarchy, as pilot cities may choose to prioritize user feedback over the display of results.

Figure 10. The health and well-being platform features and hierarchical page progression.

8.1.1. Landing Page—Pilot Map

The landing page of the dashboard (Figure 11) showcases the pilot map, displaying the different sites included in the research project. Users can interact with the map and explore health and well-being indicators for each city.

The sidebar menu provides convenient navigation options for users, granting them access to three main sections within the dashboard: pilot map, pilot cities dashboard, and sites key performance indicators dashboard.

8.1.2. Overview Page

The overview page disseminates information supplied by each pilot site that best describes the pilot site and its current health and well-being indicators. The overview page serves to give participants a bird's eye view of the pilot site, the solutions, the key performance indicator benchmarks (average values associated with local sociological and environmental data), and the geographic context of other pilot sites (Figure 12).

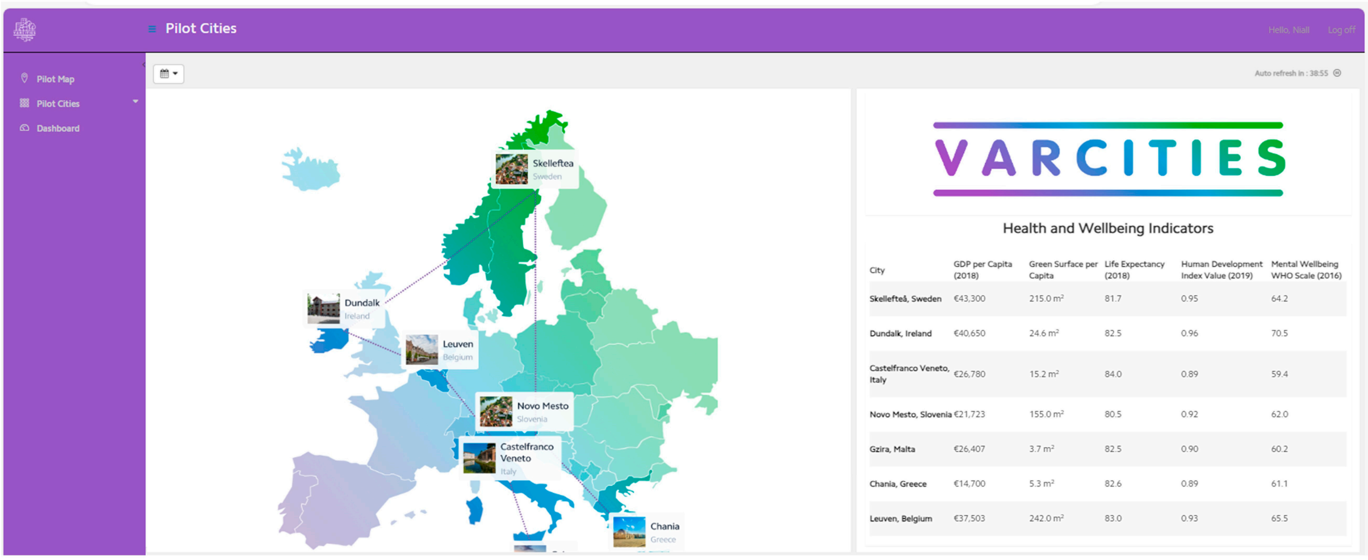


Figure 11. Landing page illustration.

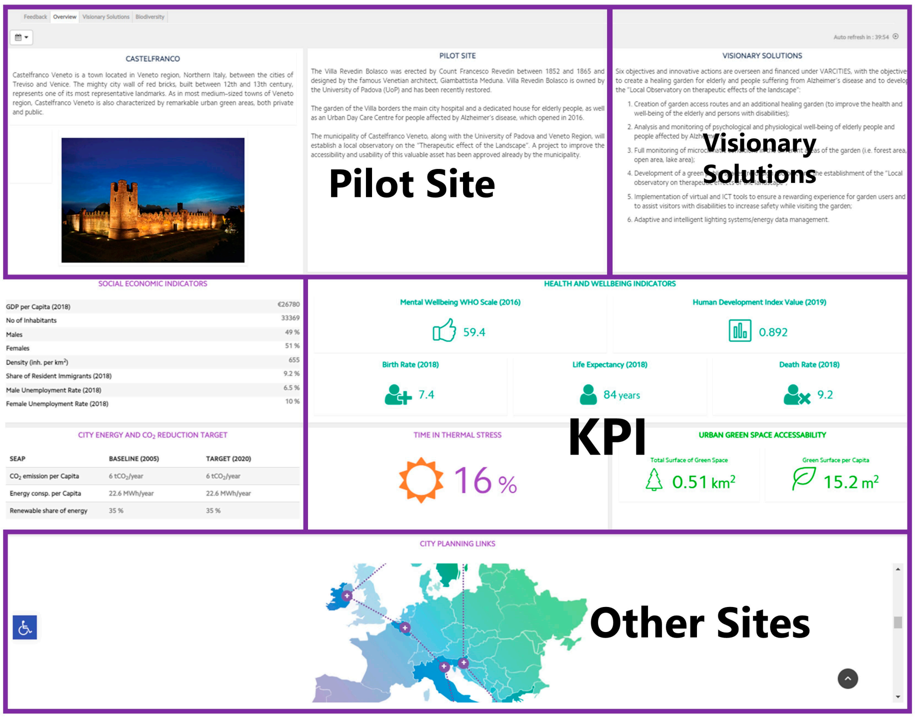


Figure 12. Overview page illustration.

8.1.3. The Visualization of Smart Nature-Based Solutions

Each site has multiple solutions, and for each one a digital twin render and text on the platform have been created. These renders were incorporated into each of the pilot sites' digital twins. An indicative example is illustrated in Figure 13.

Where provided, data from GeoJSON files were incorporated into the models, as shown in the below example of digitized trees in the Castlefranco, IT pilot site (Figure 14).

Figure 13. Dundalk digital twin example: Google Earth above, IES digital twin below.

Figure 14. Castlefranco, IT digital twin example using GeoJSON.

The nature-based solutions page is for users to interact with an immersive digital twin of the area. These digital twins provide a visual representation of sensor locations and showcase the aforementioned solutions (see Table 1).

8.1.4. Biodiversity Page

By navigating the map, users can explore specific regions and understand the ecosystems, habitats, and species that contribute to the area's biodiversity. Moreover, the biodiversity digital twins focus on highlighting sensor locations, and biodiversity data are displayed as shown in Figure 15.

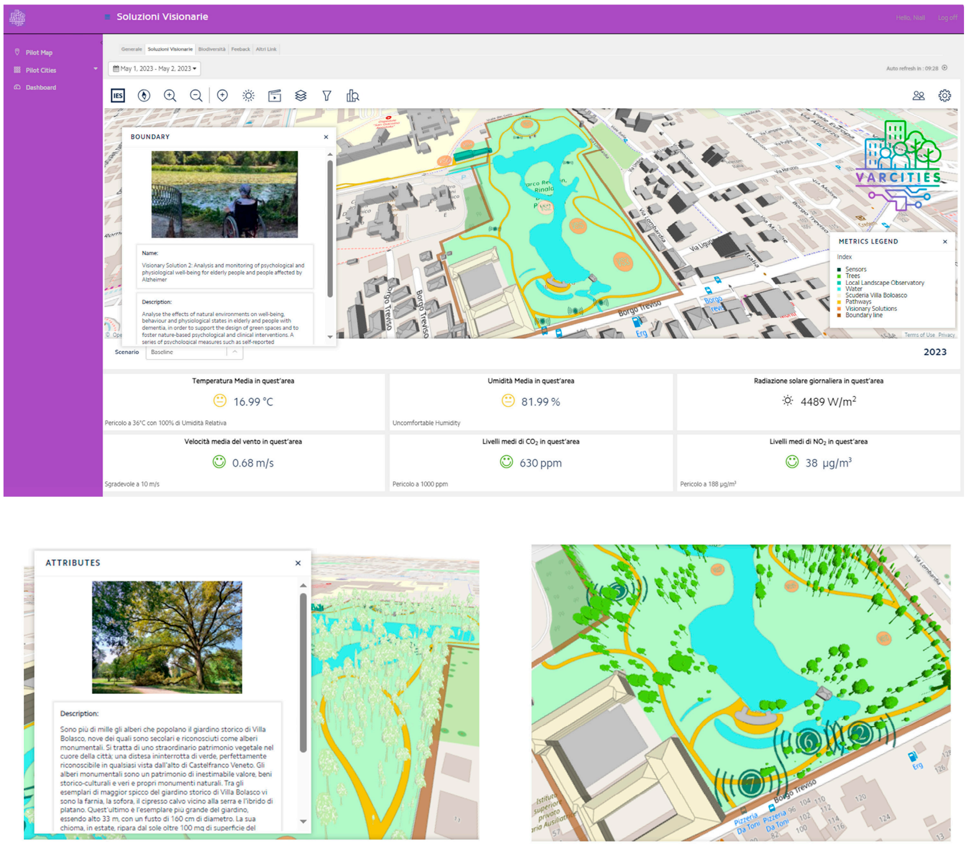


Figure 15. H&WB biodiversity page illustration.

8.1.5. Feedback and Survey Page

The feedback and survey page feature offers users a platform to provide valuable input and share their experiences when visiting the area. Both pages are available to all pilot sites, with each tab having strengths and weaknesses of the pilot sites' KPIs. The feedback page illustrated in Figure 16 consists of single or multiple questions with interval data inputs. The users can select an icon accompanied by text and express their current mood, physical state, perception of the space they occupied, or any other subjective feedback. By considering user feedback, the lived experiences and perceptions of those interacting with the area are analyzed. This information is important for decision-making, lighting the areas of improvement, and refining strategies and interventions.

The survey page (Figure 17) illustrates how survey feedback can be inputted by the user. This survey is designed by the local pilot site to archive their KPI goals. Although this survey template demonstrates text inputs, the implemented surveys contain mainly multiple-choice questions to facilitate a touchscreen user interface.

8.2. Key Performance Indicators and Data

By designing a KPI-based monitoring and evaluation framework, the pilots can verify the effectiveness of the implemented interventions. The evaluation criteria for the framework are co-developed with citizens, field experts from a diverse range of disciplines, and various stakeholders from different social backgrounds to ensure inclusivity. With the goal of an efficient monitoring and evaluation process, a master list of the KPIs that are measured together with useful details about each one of them has been created. For all these KPIs, information related to the addressed challenges, the expected outcomes, the measurement units, the need for ethical clearance, the related personal data, the geographical scale of the interventions, the calculation methods, and the sources of input data, have been identified, respectively. Some of the KPIs are city-specific, while others are more generic and can be adopted across different cities to be able to compare results at the pre-intervention and post-intervention stages by adopting the same methodology. Table 4 represents the selected indicators, the expected impact, and the related challenge per pilot [8,52].

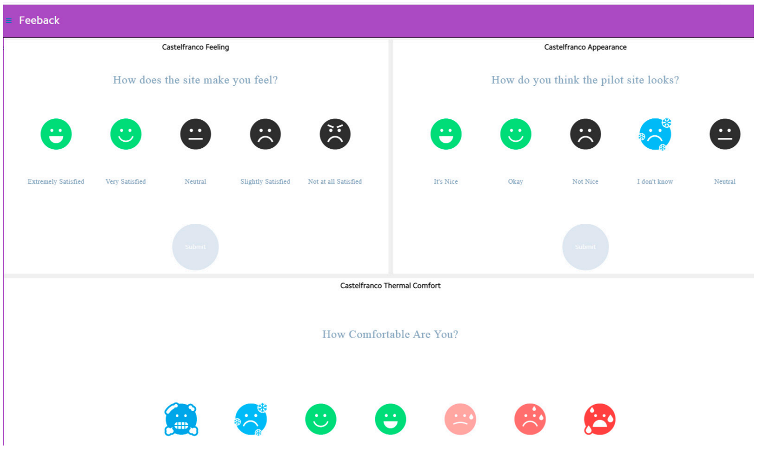


Figure 16. Feedback page for interaction with the citizens.

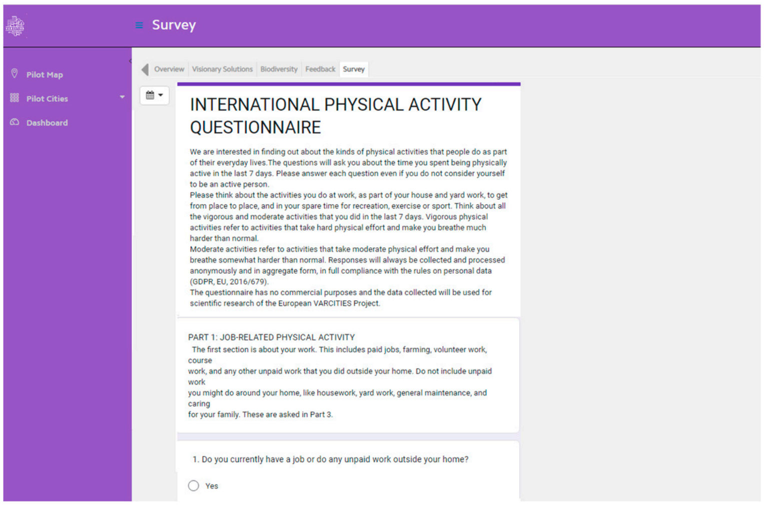


Figure 17. Survey page for interaction with citizens.

Table 4. H&WB KPIs monitored for each pilot city.

Challenge	Expected impact	Indicator	SE	IE	IT	SI	MT	GR	BE
Climate mitigation and adaption	Reduced urban temperature	Decrease in mean or peak daytime local temperatures						x	x
	Improved human comfort	Measures of human comfort			x	x			x
Water management	Improved surface water quality	Water quality indicators (physical)							x
	Reduction in water routed to drainage network	Reduction in water routed to urban sewerage system		x					
	Improved surface water quality	Water quality indicators (chemical, biological)	x						x

Table 4. *Cont.*

Challenge	Expected impact	Indicator	SE	IE	IT	SI	MT	GR	BE
Green space management	Increased public green space surface per capita	Surface of public green space per capita					x		
	Increased accessibility of urban green spaces	Accessibility of urban green spaces for the population		x		x	x		x
	Increased recreational or cultural value of green spaces	Recreational or cultural value of green spaces	x	x	x	x	x	x	x
	Increased weighted recreation opportunities	Weighted recreation opportunities				x			
	increased, green-related social services provided to the population	Green-related social services provided to the population				x		x	
	Increased use of green public space facilities	Effectiveness of seating locations		x	x				
	Increased urban biodiversity	Species richness and composition with respect to indigenous vegetation and local/national biodiversity targets	x	x					
	Increased urban biodiversity	Total area of designated sites of local biodiversity importance within the city	x						
	Increased connectivity to existing green infrastructure	Increased connectivity to existing green infrastructure				x			x
	Increased urban biodiversity/increased pollinator species	Pollinator species increase	x						
	Increased urban biodiversity/improved environmental conditions/increase in bird presence	Increase in singing birds in green zones			x				
Air/ambient quality	Improvement of local climatic conditions	Physical air quality indicators: temperature, humidity			x	x		x	x
	Reduction of air pollution	Chemical air quality indicators		x	x	x	x	x	x
	Reduction of air pollution	Air pollution episodes					x		
Urban regeneration	Increased urban biodiversity/increased ecosystem services	Urban green: Index of biodiversity, provision and demand of ecosystem services					x		
	Increased accessibility of green spaces	Accessibility: distribution, configuration, and green space diversity and land use changes				x			
	Increased share of pedestrian areas	Road surface dedicated to pedestrians		x					
Participatory planning and governance	Increased and improved participation	Openness of participatory processes			x				x
Social justice and social cohesion	Greater inclusion of families with babies and individuals with restricted mobility	Accessibility of open public spaces and buildings for families with baby carriages and individuals with restricted mobility			x	x			x

Table 4. *Cont.*

Challenge	Expected impact	Indicator	SE	IE	IT	SI	MT	GR	BE
Public health and well-being	Reduced noise level	Noise reduction rates		x	x		x	x	x
	Increased outdoor presence	No of hours spent outdoors, time people spend in the facility		x			x		x
	Increased health and well-being	Perceived well-being before and after the visit to green spaces		x	x				x
	Improved psychological well-being	Assessment of personal satisfaction with life, emotional competences			x				
	Improved quality of life	Feeling of improving quality of life		x	x	x	x		x
	Reduced loneliness	Social and emotional loneliness perception			x				
	Improved cognitive abilities	Cognitive abilities			x				
	Improved restorativeness	Sense of place and received restorativeness			x				
	Increased residential attachment and satisfaction	Residential attachment and satisfaction			x		x		x
	Reduced behavioral and psychological symptoms in dementia	Behavioral and psychological symptoms of dementia			x				
	Increased outdoor physical activity	Number/share of people being physically active				x		x	x
	Increased outdoor physical activity	Increase in walking and cycling in and around areas of interventions	x	x		x	x	x	x
	Reduced smoking	Smoke cessation due to sports activities in green areas						x	
	Increased outdoor physical activity	Level of physical activity in distances covered and average calories burned			x				
	Improved motor skills among the youth	Improved motor skills among the youth				x			
	Reduction in anxiety levels	Anxiety levels	x		x				
	Increased psychological well-being and/or quality of life: improved positive emotions; reduced negative emotions	Affective status	x		x				
Potential for new economic opportunities and green jobs	Increased job opportunities	No. of jobs created		x		x		x	
	Replication of solutions	Replication of solutions	x	x	x	x	x	x	x
	Savings in healthcare spending	Savings in healthcare spending	x	x			x	x	x

Various methodologies are used to gather the appropriate data needed for the KPI calculation. Real-time data from sensors are employed to monitor air quality, microclimate conditions, noise levels, and the number of visitors in public green spaces. Self-perceived health and well-being data and perceptions on urban nature are collected through the survey page of the H&WB platform while statistical data for each KPI extracted by local databases, citizen' observatories, GEOSS, and EUROSTAT are used to provide useful information to the citizens about their well-being. The outcomes of this analysis are displayed in the H&WB platform and are presented in the relevant KPIs cards (Figure 12).

Through these dashboards, the users' access to advanced graphics and line charts is ensured to provide a comprehensive overview of KPIs associated with the study sites. In Figures 18 and 19, intermitted data are illustrated from the Castelfranco pilot site, demonstrating the data flow from sensors into the H&WB platform. These charts offer a dynamic perspective on the evolution of different KPIs over time, enabling users to identify patterns.

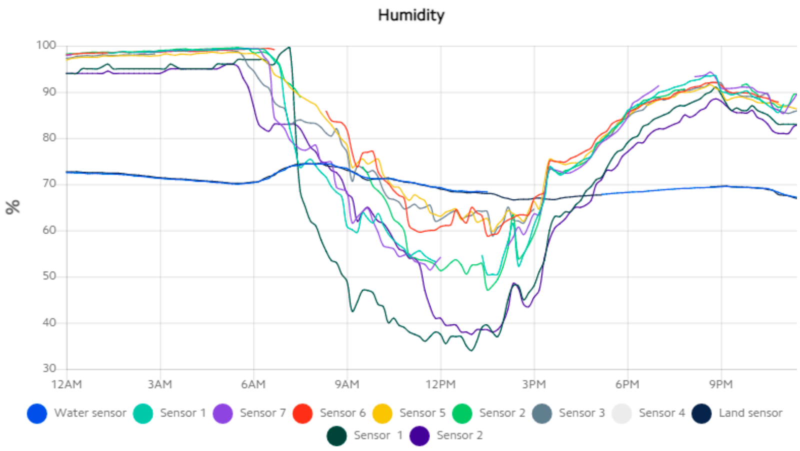


Figure 18. Live API sensor data in Castlefranco dashboards showing the relative humidity in the various points of the garden.

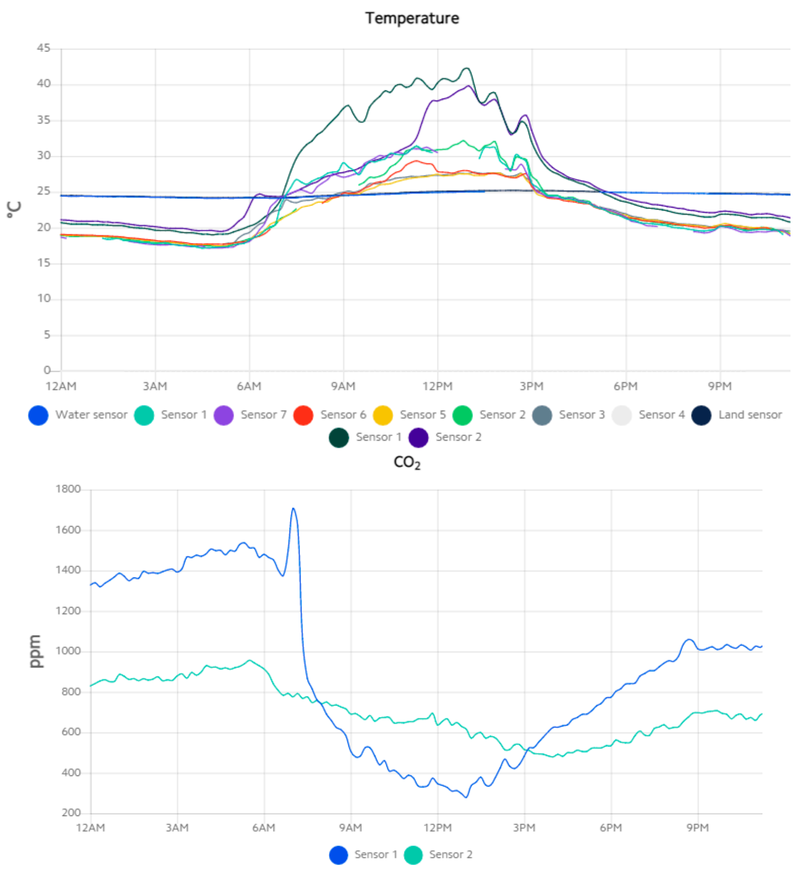


Figure 19. Data flow from sensors to the H&WB platform for air temperature and air quality.

Supplementary, a co-creation process is followed to gather information from stakeholders concerning the KPI visualization. To ensure the information on KPIs is understandable to the citizens, various options of visualization are distributed to stakeholders to gather feedback about their preferences. This feedback denotes a dynamic process of the platform's evolution throughout the project duration.

9. Discussion

The integration of nature-based solutions in smart cities is a significant and challenging topic. The objective is to create systems, in rural and especially urban areas, that optimize natural resources to support a more sustainable approach to global urban challenges.

Data should support this key aspect and be easily accessed and understood by different stakeholders. Particular emphasis should be placed on the user experience, whether that of a specialist or a citizen. In the former case, the information must be not only easily accessible but above all, well coded with appropriate metadata that allows reconstruction of where, how, when, and by whom it was collected. Interoperability is a central point to avoid unnecessary duplication or closed systems and foster synergies between public departments, researchers, or developers. In the second case, ease of access and navigation and a well-designed graphical layout are essential. KPI representation cannot rely on histograms or be accompanied by complex units of measurement but must be through infographics, icons, and comparative examples understandable to non-specialists. And possibly also considering the needs of specific user categories (elderly, children, people with disabilities) to ensure the accessibility of digital services.

The proposed architecture for the web-based data platform allows the freedom to interconnect various components to monitor different parameters of cities and access a variety of key performance indicators. Moreover, it is fully expandable and interoperable to fit different cities' scales. Following the smart cities' communication protocols, a list of sensors with integrated LoRaWAN is incorporated. It is worth noting that sensors are customized to fulfill the specific requirements. For example, the sensor Sensedge Senstick is an award-winning LoRaWAN sensor specially designed for specific applications and pilots. It is designed to generate reliable and quality data in harsh indoor and outdoor environments by monitoring environmental parameters (air temperature, relative humidity, and pressure) as well as solids parameters (temperature, ground moisture). In addition, a bike sensor kit has been designed to cover the monitoring needs of the various pilots where different parameters are measured while the bikes are moving around the city.

Another significant aspect of a smart nature-based solutions data platform is the interaction with the users, visitors of spaces, and citizens. Different approaches are covered by the specific platform, allowing different levels of complexity. Information and data are shown through the GoNature game through a gamification process and VR/AR capabilities. An example of the interaction of the GoNature game with the other platform components is the illustration of air pollution using the sensors management infrastructure and the REST API. GoNature retrieves data regarding the site's air quality, and the user experiences the quality of the air as a visualization of particles and gasses (Figure 20). The user might witness a good, moderate, or bad air quality scenario based on the data received. Depending on the scenario, the user gets informed about the effects of this situation on his/her health. In every case scenario, the user can witness all scenarios to have a measure of comparison [53].

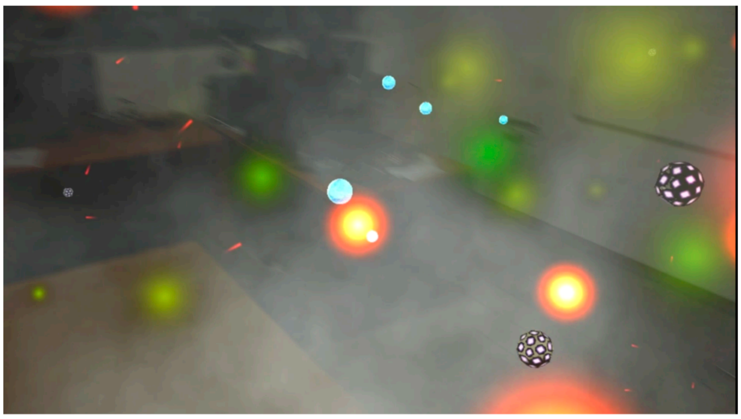


Figure 20. Air pollution visualization example for the GoNature game.

Data visualization and information provided to the citizens from the web-based health and well-being data platform is of critical importance. This procedure was discussed during a series of stakeholder engagement meetings and workshops with local people following Stakeholder Integrated Research STIR [54]. Different alternatives such as faces, bars, diagrams, etc. were presented. A dynamic process was formulated where the data visualization may change according to the user's feedback through a dynamic survey (see Section 8.1.5).

The main question is how these data are exploited to understand the changes performed by the implementation of the pilot sites. For this reason, a common knowledge baseline was created with quantitative and spatial data. The baseline information collected is the following: (a) general information for the regions and cities; (b) climatic data such as temperature, precipitation, and solar radiation, information about urban heat island studies and thermal comfort requirements of the areas; (c) energy aspects related to CO_2 emissions reduction targets of the region, and renewable energy share; (d) green spaces and nature-based solution implementations in the area; (e) socio-economic aspects such as per capita GDP and unemployment rate and Human Development Index; (f) participatory planning and governance and the synthesis of such aspects in each area; (g) health and well-being of the citizens related to birth and death rates, life expectancy, relevant causes of death, subjective well-being related to happiness and perceived health status, and WHO-5 mental well-being index; (h) smart-city-related aspects such as integration of smartness in energy, ICT, and mobility; (i) policy aspects, and (j) market and financing information.

All this information has been stored in a database for comparison between the pilot cities. Indicatively, some information is tabulated in Table 5 concerning the green spaces and in Table 6 for quality of life.

Table 5. Public green space statistics.

	Skellefteå	Dundalk	Castelfranco	Novo Mesto	Gzira	Chania	Leuven
Total surface of green spaces (km^2)	9588.0	3.2	500.0	3.4	1.8	0.3	24.6
Per capita green surface (m^2 per capita)	215.0	24.6 *	15.2	155.0	3.7 *	5.3	242.0 *

* Indicates that the share of municipal/urban green space per capita was calculated by dividing the total surface by the number of inhabitants.

Table 6. Average scores at the country level for the question "How satisfied are you with your life these days?" from the European Quality of Life Survey 2016. The European countries with the highest scores are Denmark, Finland, and Sweden (7.9–8.2), and the ones with the lowest are Albania and Greece (4.9–5.3).

Subjective Well-Being How Satisfied Are you with Your Life These Days?			Status		Gender		Age Group		Income	
			Employed	Unemployed	Female	Male	18–24	Over 65	1-Quartile	4-Quartile
SE	Skelleftea	7.9	8	7.9	8	7.8	7	8.3	7.6	8.3
IE	Dundalk	7.7	7.9	7.5	7.7	7.7	7.8	7.7	7.1	8.2
IT	Castelfranco	6.6	6.8	6.4	6.6	6.6	7.1	6.4	5.7	7
SI	Novo Mesto	6.9	7.1	6.6	6.9	6.8	8	6.3	6.1	7.5
MT	Gzira	7.6	7.8	7.3	7.6	7.6	7.9	7.3	7.1	7.9
EL	Chania	5.3	5.6	5.1	5.3	5.2	6.7	4.9	4.5	5.8
BE	Leuven	7.3	7.5	7.1	7.3	7.3	7.6	7.4	6.8	7.6

10. Conclusions and Future Prospects

The need for nature-based solutions in the current world that faces constant environmental pressure, societal imbalance, and economic challenges is undeniable. It is well recognized that nature-based solutions are a way to protect, restore, and sustainably manage the environment to increase resiliency and tackle social problems. Doing so is essential for biodiversity and overall human well-being and health. The intersection of nature-based solutions with smart cities creates great potential for future cities. Data platforms already developed for smart cities and communication protocols should be fully exploited to support quantifying the impact of nature-based solutions on urban health and well-being. In particular, citizens' growing expectation of integrated experiences should not be underestimated. Nowadays, the increase in apps and digital services (e.g., in the transport, leisure, and shopping sectors) that integrate and merge with the physical world (hence the word "phygital") makes the boundaries between systems increasingly blurred. Phygital allows the blending of the physical with the digital world. This already happens, for example, in monitoring and interaction with domestic energy systems (i.e., building automation, demand side management) and it has been already proven how, for example, in the tourist sector, the phygital phenomenon represents a radical change in the personal and social behavior of tourists, influencing the decision-making process [55].

Therefore, having an effective support tool for the phygital world means contributing to a rewarding and satisfying experience. It is expected that in the design and management of innovative public spaces, this is going to have significant importance as it expands possibilities and interaction with sensors and apps and supports understanding of critical issues such as climate change and risks for citizens, thus prompting behavioral changes [56] However, it is still scarcely present in NBS: while walking in a city we all experience that public green and parks influence the local microclimate and our well-being, but at this moment, how much, when, and how is not a piece of accessible information.

The web-based data platform designed and analyzed in the present paper provides a robust basis for different research aspects. The first one is the integration of various sensors related to the implementation of nature-based solutions in cities targeting to cover a range of key performance indicators. The specific research supports the creation of databases and baselines for future projections and evaluation. Another aspect is integrating different scales of nature-based solution implementation in one platform. This research aspect allows comparing scales' performance and supports the development of the necessary knowledge related to the future rehabilitation of outdoor spaces. The scale aspect is essential and should not be underestimated, implying the need for investment and funding mechanisms.

Finally, the interoperability and expandability of the proposed platform and the ability to include more areas and more data provide the ability to interconnect data not only from urban but also from expanded peri-urban or even more rural areas, creating a significant advantage for the role of nature-based solutions in other important domains such as soil remediation and agriculture by examining these aspects in an integrated manner.

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Abbreviations

H&WB	Health and well-being
VS	Visionary solutions
KPI	Key performance indicator
GPS	Global positioning system
LIDAR	Light detection and ranging
ICT	Information and communication technology
iSCAN	Intelligent control and analysis
NBS	Nature-based solutions
GIS	Geographic information system
3D	Three-dimensional
API	Application programming interface
GDPR	General data protection regulation
iCD	Intelligent community design
iCIM	Intelligent community information model
IoT	Internet of Things
PCB	Printed circuit board
PCBA	Printed circuit board assembled
HW	Hardware
FW	Firmware
JSON	JavaScript object notation
REST	Representational state transfer
PDP	Policy decision point
PM	Particulate matter
dB	Decibel, measurement of noise
Pa	Pascal, measurement of pressure
TN	Things Network
AR&VR	Augmented and virtual Reality
POI	Points of interest
NGSI-LD	Next Generation Service Interfaces–Linked Data
PEP	Policy enforcement point
STK	Stakeholder
TLS	Transport layer security

Appendix A

Table A1. Overview of the sensors installed per pilot city.

Sensors	Measuring	Quantity	Communication Protocol	Link as Reference	Access Date
			Skellefteå-SE		
Sensedge Senstick	T_{air} (°C), relative humidity (%), air pressure	5	LoRaWAN	https://senzemo.com/	11 October 2023
Elsys ELT-2	T_{air} (°C), relative humidity (%)		LoRaWAN	https://www.elsys.se/	
Decentlab DL-ATM22	T_{air} (°C), relative humidity (%), wind speed, wind direction	1	LoRaWAN	https://cdn.decentlab.com/download/datasheets/Decentlab-DL-ATM22-datasheet.pdf	11 October 2023
Milesight-iotEM500-UDL or Elsys ELT Ultrasonic	Distance	2	LoRaWAN	https://www.elsys.se/	11 October 2023
Milesight 5G AIOT Pro	Counting people	2	LoRaWAN	https://www.milesight.com/product/5g-aiot-pro-bullet-plus	11 October 2023
Sensedge Traffic Counter	Number of visitors	3	LoRaWAN	https://senzemo.com/	11 October 2023

Table A1. Cont.

Sensors	Measuring	Quantity	Communication Protocol	Link as Reference	Access Date
		Dundalk-IE			
Imbuildings People Counter	Number of visitors	4	LoRaWAN	https://www.imbuildings.com/lorawan-people-counter/	9 October 2023
Enginko LoRaWAN Single-Phase Energy Meter	Solar panel energy production	1	LoRaWAN	https://enginko.com/en/solutions/mono-phase-metering-mcf-lw12met/	9 October 2023
ENL-AIR-X Outdoor Air Quality Monitor	Outdoor Air Quality Sensor	1	LoRaWAN	https://www.alliot.co.uk/product/enlink-air-x/	9 October 2023
Polysense WXS8800-362021	Noise	1	LoRaWAN	https://www.polysense.net/page180?product_id=235	9 October 2023
Milesight EM310-UDL	Number of bicycles	4	LoRaWAN	https://www.kerlink.com/product/wanesy-wave/	9 October 2023
LDDS75 LoRaWAN	Water level	1	LoRaWAN	https://www.dragino.com/products/distance-level-sensor/item/161-ldds75.html	9 October 2023
Sensedge Senstick	T_{air} (°C), relative humidity (%), Air pressure	5	LoRaWAN	https://senzemo.com/	9 October 2023
Sensedge Traffic Counter	Number of visitors	3	LoRaWAN	https://senzemo.com/	9 October 2023
		Leuven-BE			
Renkforce WH2600	T_{air} (°C), relative humidity (%), wind, air pressure, rain, solar radiation, UV index	1	Wi-Fi	https://www.conrad.com/p/renkforce-renkforce-wh2600-wireless-digital-weather-station-forecasts-for-12-to-24-h-1267654	2 September 2023
Noise	dB	2	LTE-M (4G)	https://munisense.com/measuring-noise	2 September 2023
Traffic sensor	Number of cyclists in the area, pedestrians	1		-	
Air quality sensor	CO_2 Nitrogen oxide, NOx PM2.5 PM10	1		-	
Sensedge Senstick	T_{air} (°C), relative humidity (%), air pressure	1	LoRaWAN	https://senzemo.com/	2 September 2023
Sensedge Traffic Counter	Number of visitors	3	LoRaWAN	https://senzemo.com/	2 September 2023

Table A1. Cont.

Sensors	Measuring	Quantity	Communication Protocol	Link as Reference	Access Date
		Novo mesto-SI			
Sensedge Senstick	T_{air} (°C), relative humidity (%), Air pressure	10	LoRaWAN	https://senzemo.com/	13 October 2023
LoRa people counter	No. of visitors	4	LoRaWAN	https://lora-alliance.org/lora_products/people-counter/	13 October 2023
Air quality/microclimatic conditions	T_{air} (°C), Barometric pressure, Relative Humidity (%), PM1, PM2.5, PM10, O_3, CO, NO_2, SO	2	LoRaWAN	https://www.uradmonitor.com/products/	13 October 2023
FitBit5	Optical heart rate monitor, accelerometer, GPS, Oxygen saturation, light sensor	20	BT, Wi-Fi	https://www.fitbit.com/global/us/products/trackers/charge5	13 October 2023
Sensedge Traffic Counter	number of visitors	3	LoRaWAN	https://senzemo.com/	13 October 2023
		Castelfranco-IT			
ENL-AIR-X Outdoor Air Quality Monitor	Outdoor Air Quality Sensor	2	LoRaWAN	https://www.alliot.co.uk/product/enlink-air-x/	26 September 2023
Sensedge Senstick	T_{air} (°C), relative humidity (%), Air pressure	10	LoRaWAN	SENSEDGE: SENSTICK Microclimate SMC30	26 September 2023
Decentlab DL_PYR	Total Solar Radiation Sensor	7	LoRaWAN	https://www.decentlab.com/products/total-solar-radiation-sensor-for-lorawan	26 September 2023
Decentlab DL-ATM22	Wind speed, wind direction, and temperature sensor	3	LoRaWAN	https://www.decentlab.com/products/wind-speed-wind-direction-and-temperature-sensor-for-lorawan	26 September 2023
IOTSENS Sound Monitor	dB, noise levels	2	LoRaWAN	https://www.iotsens.com/en/product/sound-monitor/	26 September 2023
Sensedge Traffic Counter	Number of visitors	3	LoRaWAN	https://senzemo.com/	26 September 2023
		Chania-GR			
Bike sensor kits	T_{air} (°C), relative humidity (%), PM, Sound, GPS, Smart Grip (heart rate)	45	WiFi/LoRaWAN—API/JSON	http://www.cyclopolis.gr/index.php/en	15 October 2023
Fixed station sensor kits	T_{air} (°C), relative humidity (%), Sound, NO, NO_2, O_3, SO_2, NH_3, CO, CO_2, TVOC, CL_2	4	Cloud—API/JSON	http://www.cyclopolis.gr/index.php/en	15 October 2023
Sensedge Traffic Counter	Number of visitors	3	LoRaWAN	https://senzemo.com/	15 October 2023
Sensedge Senstick	T_{air} (°C), relative humidity (%), air pressure		LoRaWAN	https://senzemo.com/	15 October 2023
Power management system of Mobile Urban Living Room	Energy produced, energy stored, energy consumed	1	Wi-Fi	http://www.cyclopolis.gr/index.php/en	15 October 2023

Table A1. Cont.

Sensors	Measuring	Quantity	Communication Protocol	Link as Reference	Access Date
		Malta-MT			
IoT Sensors					
Sensedge Senstick	T_{air} (°C), relative humidity (%), air pressure	5	LoRaWAN	https://senzemo.com/	12 September 2023
Senstate Urban air quality monitor	PM1.0, PM2.5, PM4.0, PM10, AQI	10	LoRaWAN	https://senstate.com/products/senstate-urban-air-quality-station/	12 September 2023
Sensedge Traffic Counter	Number of visitors	3	LoRaWAN	https://senzemo.com/	12 September 2023
Data Logger					
Thiesclima Ultrasonic Anemometer	Wind speed and direction	2	N/A	https://www.thiesclima.com/pdf/en/Products/Wind-Ultrasonic-Anemometer/?art=809	12 September 2023
Vaisala AQT400, (Datalogger, handheld device)	NO_2 (ppm) SO_2 (ppm) CO (ppm) O_3 (ppm) PM2.5 (µg/m^3) PM10 (µg/m^3) T_{air} (°C) Relative air humidity (%)) Air Pressure (mbar)	10	N/A	https://www.vaisala.com/sites/default/files/documents/AQT400_Series_Datasheet_B211581EN_0.pdf	12 September 2023
Svantek SV 977 Class 1 Sound & Vibration Level Meter	dB	1	N/A	https://svantek.com/products/svan-977-class-1-sound-vibration-level-meter/	12 September 2023
Metrocount RoadPod VT	Car count	6	N/A	https://metrocount.com/products/roadpod-vehicle-tube-classifier/	

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