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A Digital Twin Framework to Improve Urban Sustainability and Resiliency: The Case Study of Venice

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Abstract: The digital transition is one of the biggest challenges of the new millennium. One of the key drivers of this transition is the need to adapt to the rapidly changing and heterogeneous technological landscape that is continuously evolving. Digital Twin (DT) technology can promote this transition at an urban scale due to its ability to monitor, control, and predict the behaviour of complex systems and processes. As several scientific studies have shown, DTs can be developed for infrastructure and city management, facing the challenges of global changes. DTs are based on sensor-distributed networks and can support urban management and propose intervention strategies based on future forecasts. In the present work, a three-axial operative framework is proposed for developing a DT urban management system using the city of Venice as a case study. The three axes were chosen based on sustainable urban development: energy, mobility, and resiliency. Venice is a fragile city due to its cultural heritage, which needs specific protection strategies. The methodology proposed starts from the analysis of the state-of-the-arts of DT technologies and the definition of key features. Three different axes are proposed, aggregating the key features in a list of fields of intervention for each axis. The Venice open-source database is then analysed to consider the data already available for the city. Finally, a list of DT services for urban management is proposed for each axis. The results show a need to improve the city management system by adopting DT.

Keywords: Digital Twin; urban sustainability; urban resiliency; Venice; digital transition

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1. Introduction

Digital transformation represents one of the most relevant challenges of the new millennium. From the expansion of the Internet of Things (IoT) [1] to the artificial intelligence (AI) revolution, the world is in what we refer to as the beginning of the fifth industrial revolution [2]. Where the third revolution was associated with the increasing deployment of energy resources, as well as the rapid spread of communication media, and the pressing need to prevent a climate catastrophe [3], the fourth revolution seems to be linked to the emergence of new technologies that have revolutionised the world, such as artificial intelligence, genetic editing, and advanced robotics, pushing what has always been considered the limits related to the physical, digital, and biological worlds [4]. While the fourth industrial revolution (Industry 4.0) is still in progress, the fifth industrial revolution (Industry 5.0) is already emerging with a different focus. It introduces a further paradigm of technological development, highlighting the need to introduce an ethical and humane approach to innovations, focusing on human–machine collaboration, sustainability, and social welfare [5].

The digital transition is similarly a priority for European Union (EU) institutions, for which the development of new technologies is acknowledged as a fundamental tool to drive economic growth, enhance public services, and improve the lives of EU citizens. Embracing this transformation is recognised as essential to sustaining high industrial competitiveness and ensuring a prosperous future for the member states (as outlined in the EU Digital Compass and the Digital Decade policy program [6]), stressing that digital skills are a key asset that enables people to use the emerging opportunities created by digital technologies and fully benefit from them.

Among the key factors for ensuring the digital transition, the need to adapt to the rapidly changing technological landscape seems to be a central one. Investments in new digital infrastructures, such as high-speed internet and 5G networks, ensure fast access to digital tools. In addition, digitisation makes it possible to improve the efficiency and effectiveness of public services, including government services. The benefits of this paradigm shift are multiple; e.g., it is the possibility to automate processes not only from a bureaucratic and organisational point of view but also to have a substantial impact on mitigation measures for climate change for achieving sustainable development.

The COVID-19 pandemic has also highlighted the need to adapt the current economic model toward environmental and social sustainability. In December 2019, the President of the European Commission, Ursula von der Leyen, presented the European Green Deal initiative to make Europe the first climate-neutral continent by 2050 [7]. More specifically, Italy emerged as one of the most affected countries by the pandemic, suffering the most from the crisis [8,9]; Italy's gross domestic product (GDP) decreased by 8.9% in 2020, compared to an average decrease in the European Union of 6.2% [10]. Considering the first administrative actions regarding the reduction in February 2020, Italy was the first EU country to be forced to impose a generalised lockdown [11]. The crisis hit the country with numerous criticalities related to economic, social, and environmental aspects, which caused a lower gross domestic product (GDP) growth than other European countries, equal to 7.9% between 1999 and 2019, compared to an average growth of 35.4% in Germany, France, and Spain during the same two decades [12]. Similarly, growth forecasts are limited to 4.7% in 2025, as reported in the Spring 2024 Economic Forecast of the European Union. To face this crisis, Europe has granted Italy an extraordinary financing plan called Next Generation EU (NGEU), which also includes the digitisation of Italian national infrastructures and the development of innovative technological solutions with low environmental impact (according to the principle of DNSH—do no significant harm) and capable of increasing the resilience and sustainability of the Italian environmental, social, and governance (ESG) system.

To the authors' knowledge, nowadays, there is no urban-oriented application of DT systems for historical cities. Therefore, this work proposes a working framework for the development of such technology for the city of Venice. The framework of this research is discussed considering Venice as a case study, but it is exportable to other historical cities using the same hypotheses and working methodology.

2. State-of-the-Art

The digital transition presents societal and security challenges, such as ensuring digital inclusion, protecting data privacy and security, and addressing the ethical implications of emerging technologies. The DT represents a key element for the digital transition. This technology was born in the aerospace sector with the Apollo missions of NASA (National Aeronautics and Space Administration, United States of America), where it was used to reduce mission risks associated with human spaceflight [13]. To date, it is a widely used tool in all those sectors that need complete control of their infrastructures and production processes, such as automotive, avionic, and electronic component production.

The construction sector has also recently begun to approach digital technologies, despite its historical reluctance towards innovation. The adoption of building information modelling (BIM) has acted as a bridge towards the adoption of new digital paradigms, capable of reducing costs, and complexity and providing useful tools to the entire construction chain as well as to end users. The drivers of Construction 4.0 are digital technologies and their mutual interaction [2,14]. The benefits of using tools such as artificial intelligence (AI), machine learning (ML), semantic technologies, big data analytics, blockchain, the Internet of Things (IoT), and cloud computing are clear. As for the fifth industrial revolution, today, we are approaching Construction 5.0, whose fundamental principles see the transparency of information, the human dimension of processes and their chain of transmission, the decentralisation of decision making processes, the possibility of having seamless data flows, automation, interconnection, and interoperability among technologies [5,15].

Digital Twin (DT) is an emerging concept applicable to the construction world, thanks to which it is possible to build a digital replica of any built object, from a single building to a more complex built environment. Starting from the simple monitoring of infrastructure (Digital Shadow), it is possible to analyse and monitor the physical and environmental processes that take place within and around it, simulating plausible scenarios and providing real-time solutions to increase energy sustainability or to ensure conditions of wellbeing, comfort, and safety [11]. A DT may also be able to act directly on the environment, altering the parameters that characterise it, for example by adjusting lighting or air conditioning. However, it can also provide real environmental monitoring strategies (e.g., estimating the tons of CO_2 emitted) or guarantee high standards of safety and efficiency (fault detection and diagnostic-FDD) with forecast and prevision. The three main elements of a DT are access to data, analysis, and forecasting capabilities. The term cognitive DT has also been proposed for such systems, which also includes the ability to “understand” and “interpret” data, evolving on their basis [16]. The interaction with the physical world is made by IoT (Internet of Things) devices, software interfaces to communicate with PLC (programmable logic controllers) belonging to complex systems (HVAC, public lighting, etc.), and by using other source of data such as from Earth Observation (EO) [17]. The adoption of AI and ML techniques is essential during the implementation of modern control and automation systems. The knowledge graph constituted by these systems should include all interactions among the different entities involved in a building realisation (people, plants, and structures). Thanks to this, it is possible to equip a system with semantic intelligence and to provide contextualised descriptions of the processes involved even texturally or verbally [18]. DTs must also be equipped with advanced protection systems to ensure their cybersecurity, such as using different levels of access, encryption, and blockchain [19–22] compliant with GDPR [23]. Finally, given the consistent volume of data stored within DT databases, especially if the scale is moving from a single building to more complex built environments, Big Data management has become an essential component for a DT system [24,25]. An ideal IT system must also be scalable, towards more complex solutions, including the capacity to communicate externally. Figure 1 shows the scalability propriety of DTs, which, starting from a single component or process, includes the possibility to scale up to the system level (monitoring and forecasting the interactions among single components, for example considering all the energy fluxes related to a building) and up to larger urban scale, where each system is interfaced to manage their complexity as a whole (as example to manage energy districts, traffic, or public services).

Several cities are moving towards the adoption of a DT system at the urban level. These include Antwerp, Carouge, Eindhoven, Helsinki, Manchester, Milan, Porto, Glasgow, Birmingham, Herzenberg, and Santander to manage resources and services, such as transport, energy, and water. These cities are looking to evolve towards smart cities via existing

IoT ecosystems and frameworks and are consistent with open standards, such as Open and Agile Smart Cities (OASC) [26]. Specifically, the approaches used are different. Antwerp, for example, uses the ACPaaS platform (Antwerp City Platform as a Service) and the CoT application (City of Things) [27,28]. Carouge has developed three different systems for smart parking, road noise monitoring, and a tourism app [29]. Eindhoven has focused on system interoperability through four main architectures: integrated energy data management (CKAN), FIWARE Orion Context Broker, FIWARE Complex Processing (Proton), and FIWARE Big Data (Cosmos) [30]. Within the city, there are several projects, such as the digitisation of the Brainport region, to support various societal issues, like energy transition, environmental problems, and population growth; the Water Resource Recovery Facility DT, a full-scale operational twin that includes an automated data preprocessing pipeline, a detailed mechanistic full-plant process model, and an interactive user interface, and the EAISI DT Lab to support digital system research and development initiatives. Manchester developed the CityVerve platform and Triangulum H2020 to process live carpark, weather, building energy consumption, and bicycle journey data [31,32]. Milan has developed three different architecture types for parking, buildings/energy, and weather/noise/pollution that contain data from three different projects [33,34]. Porto has created a water management platform, a mobility management platform, an environmental monitoring platform, and a platform for citizens [35].

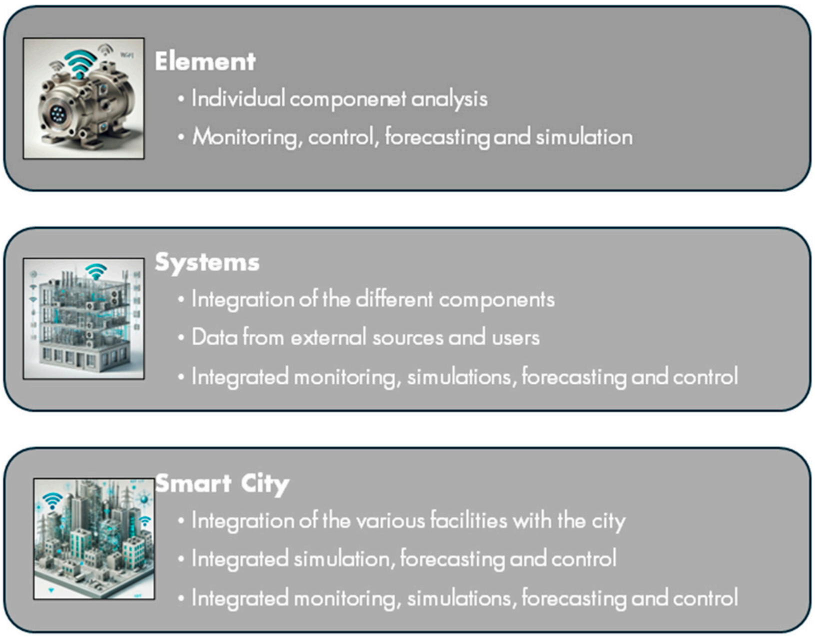

Figure 1. Digital Twin scalability from a single component up to the city level it is possible to use DT systems to monitor, manage, and develop forecasts.

DT represents a key technology to managing sustainable urban development being able to monitor and forecast urban growth and related costs and reduce overall primary resources, such as land, water, and energy usage, as well as guarantee a high level of resiliency monitoring that constantly assesses the risks that a city could be subjected to.

Venice is not only historically relevant for its inestimable cultural heritage but is also particularly fragile, considering its extension on land and over the lagoon [31–33]. Adding up the overall picture of its urban fragilities, i.e., structural, demographic, social, environmental, and climatic, the overall demographic decline of the Italian population, which is quite in line with that generally suffered by all mature economies of the northern hemisphere, finds an unprecedented peak in the historic city of Venice; in fact, the insular city has gone from about 170,000 inhabitants in the first half of the twentieth century to about 49,000 today, with the settlements located within the lagoon area counting no more than 75,000 inhabitants, against the 178,000 of the urban part in the mainland [34]. This phenomenon is due to the ageing population and the rise in short-term rentals and commercial activities that have pushed the younger generation outside the city's historical centre, presenting a serious problem in urban management that must consider innovative solutions to remove urban barriers, manage tourist fluxes, and reduce their impact on the city.

Moreover, Venice is also made from different infrastructures and services that can be managed inside a unique DT system. To ensure consistency and accuracy, the work analyses three different urban axes: mobility, energy, and urban resiliency. The proposed approach allows for increased urban sustainability and resiliency, taking advantage of the interactions between the analysed axes related to energy management and carbon footprint reduction, reduction, and management of traffic (both on land and in waterways), protection from natural disasters and extreme weather conditions, fire protection, control over the land use, urban planning, and citizen safety and security.

A similar intricated scenario, with so many diverse matters to be analysed and compared, both logically and in terms of data and information sources, seems to be very difficult to manage in a single matrix, taking into account all different issues, if not using a Digital Twin approach, not only for comparing all different source of data but also to formulate provisional scenarios both for daily use and in case of any kind of extreme events, such as the cyclical flooding (*acqua alta* in Italian), affecting the city with increasing frequency.

3. Urban DT Key Features

The tool proposed in this research is the DT. According to the creator M. Grieves, a DT is "A virtual representation of a physical object or system that spans its lifecycle and is updated from real-time data. It uses simulation, machine learning and reasoning to help make decisions" [13].

This concept has evolved today with different definitions and interpretations, often contrasting with each other [35]. It is undoubtedly the best solution for the management of complex processes that require timely and accurate control at the same time. A DT system is based on the acquisition of real-time data through sensors, their processing through simulation algorithms based on physical processes or through machine learning (ML) and artificial intelligence (AI) algorithms, and visualisation on web-based information systems [36]. A DT can respond quickly to changes or unforeseen events through a variety of plausible scenarios. DT is, therefore, a methodological approach that focuses on modelling and integrating digital methods and technologies for controlling complex systems. In doing so, DT considers procedural, socioeconomic, and environmental issues; it is, therefore, a true methodological approach for the development of complex projects. It also allows for the visualisation and modification of the operating parameters by the managers and personnel (including external ones) involved in the activities. Given its effectiveness, the DT is now also being applied in other contexts, such as the management of cultural heritage. It is not surprising that following the fire at Notre Dame Cathedral in Paris, the municipality decided to design a DT system to cope with and manage the restoration process of the cathedral in real time, to prevent further accidents [37–39]. At the city level and from a smart city perspective, DTs can be applied in various fields, not only in infrastructures but also in related services, such as health, management systems, and public administrations. As a reference, for the axes related to smart cities, it is possible to the smart city diamond in Figure 2 [40]:

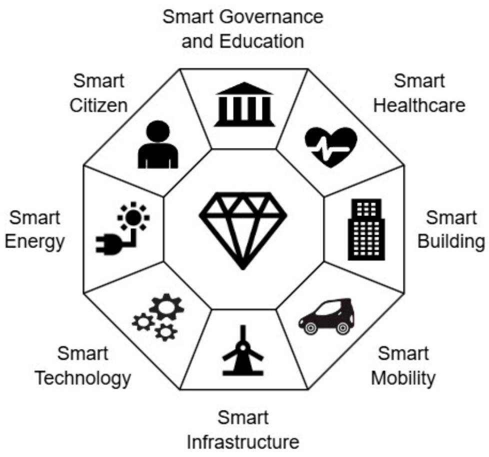

Figure 2. Smart City diamond [40].

The smart city diamond is a conceptual framework that outlines the essential components for developing and managing smart cities. It is based on four key components:

1. Technology: This includes the digital infrastructure, such as IoT devices, sensors, and communication networks, that enable data collection, analysis, and connectivity among various city systems.
2. Data: The collection, management, and utilisation of data are crucial for informed decision making. This encompasses big data analytics, data privacy, and security measures to ensure that the information collected is used effectively and responsibly.
3. People: The involvement of citizens, stakeholders, and government entities is essential. This component focuses on community engagement, public participation, and the role of residents in shaping their urban environment.
4. Governance: Effective governance structures and policies are necessary to manage the complexities of a smart city. This includes regulatory frameworks, collaboration among different levels of government, and strategies for sustainable development.

These can be integrated inside the DT system to develop a holistic approach to urban growth, aiming to enhance the quality of life for residents, while promoting sustainability and efficiency. A DT application from a smart city perspective should, therefore, be able to cover as many areas as possible within the diamond. The United Nations has also moved to support the same issues by bringing the following goals within the SDGs (Sustainable Development Goals) set out in the 2030 agenda for theme no. 11 (Sustainable Communities and Cities, Figure 3) [41]:

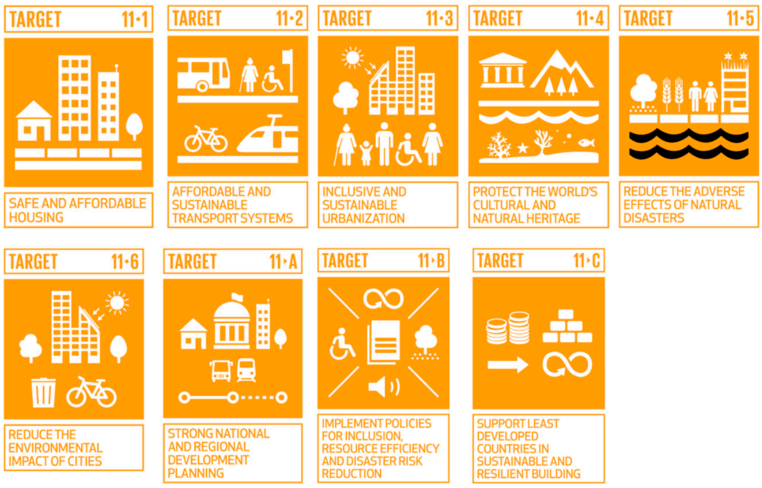

Figure 3. Goals for theme no. 11 Sustainable Communities and Cities of the Sustainable Development Goals proposed by the United Nations (UN).

These objectives include target 11-2 on transport sustainability, which can be reached through DT systems by optimizing travel times and urban mobility by acting on vehicular traffic; target 11-3 on the inclusiveness and sustainability of urbanisation, which can be supported by a DT through the sharing of data and the analysis of future urbanisation policies; target 11-5 for the reduction in adverse effects due to natural disasters, where DT see a central role for their ability in managing and predicting critical scenarios; target 11-6 aimed at reducing the environmental impact of cities, which can make use of the DT system for the real-time and predictive monitoring of urban pollution and wastes through the analysis of data collected by sensors on the territory; and the two targets 11-A and 11-B that can make use of the forecasting capabilities of DT systems both for the design of urban plans, mitigation strategies due to natural disasters, and the ability to analyse and evaluate energy consumption, ensuring the inclusion of all partners involved in the city development process.

Monitorable Data

As a general and non-exhaustive reference, to date, it is possible to create DT systems capable of monitoring the following parameters:

1. Energy: the assessment, monitoring, and forecasting of city energy flows.

- Electricity: Main and secondary electrical devices and loads (up to the single socket), energy produced from distributed renewable sources (photovoltaic plants, cogenerators, wind power, etc.), and electricity stored through batteries or converted to hydrogen for future usage. By monitoring electrical flows, it is possible to optimise consumption and production according to the parameters and preferences of users [42].
- Thermal loads: Air conditioning is one of the main energy consumptions of buildings [43]. By knowing the preferences of users, the internal and external thermohydrometric conditions, the national regulations, and the availability of thermal energy, it is possible to reduce energy loads for air conditioning [44,45]. Moreover, many cities are using district heating to reduce consumption during winter seasons, so they can be connected to a DT system to optimise the load–production profiles [46–49].
- Hydrogen, gas, and other energy vectors: Electricity is not the only energy vector used inside a city, but natural gas, hydrogen (in future), and other energy vectors (wood wastes, biodiesel, etc.) are commonly used to produce power or heat. The control of the flows and the potential benefits of integrating hydrogen into the energy mix can be exploited by using DTs [50]. This would be particularly suitable in cities with a wide availability of water as Venice.

2. Environment: the real-time assessment and monitoring of the main environmental quality parameters.

- Air quality: Monitoring of the main indoor environmental pollutants, including CO_2, VOC, PM_{10}, $PM_{2.5}$, O_3, SOX, H_2S, NOX. Air quality monitoring is essential for the healthiness of environments and cities [51,52].
- Noise: As with air quality, noise must also be monitored in Italy following the D.lgs 42/2017 (Italian legislative decree). Although the decree is inherent to open environments, the risk assessment due to noisy environments also appears in the INAIL (National Institute for Insurance against Accidents at Work) recommendations and is, therefore, one of the risks present in the D.lgs 81/08 on safety in the workplace. Noise monitoring, also due to the presence of machinery and industrial activities, is a fundamental element of an urban DT to increase the safety and comfort of citizens [53,54].

- Lighting: The maintenance of an adequate level of illuminance on public land is required by the Italian D.lgs 81/08, and the recommended levels are expressed in national regulations. In addition to the evaluation of the maintenance of these levels, the proper management of lighting systems includes a reduction in energy consumption, allowing the lights to be switched off or dimmed according to the presence and activities carried out both indoors and outdoors [55–57]. The management and control of lighting systems can also reduce light pollution during nighttime.

3. Water: the monitoring and forecasting of water consumed, collected, and stored.

- Water flows: Measurement and forecast of the water balance among white, black, and grey water. The evaluation of water consumption is useful for identifying any leaks and reducing waste, while maintaining a good quality of the water re-entering into the local ecosystem [58–60].
- Rainwater collection and reuse: Th evaluation of the amount of rainwater that can be used for irrigation or as greywater [61,62]. The monitoring of pollutants and the level of accumulation in basins [63].
- Water quality: The monitoring and control of pollutants in rivers, lakes, groundwater, and seawater for bathing suitability, use of waters for irrigation and for sanity uses [64,65].

4. Green: the monitoring of natural matrices and agriculture.

- Vegetation system: The monitoring of plant essences, irrigation, and the state of health. Through proper monitoring, it is possible to predict pruning and mowing interventions, any risk elements due to weeds or pollutants, optimise water consumption, and provide for the removal of trees at risk of falling [66]. In addition, it is also possible to assess the risk of fires due to the presence of dry areas.
- Agriculture: DT is today used in agriculture to develop virtual models of farming entities to enhance productivity, decision making, and quality. Key applications include the real-time monitoring of variables, like soil health, resource optimisation for water and fertilisers, predictive analytics for forecasting crop issues, precision farming for controlled environments, and machinery management for predictive maintenance [67,68].

5. Safety and Security: the maintenance of high standards of physical and digital security, protection, and prevention of citizens' safety.

- Cyber security: The application of cryptographic standards to protect data flow and storage, separation between the external and internal network, the use of authentication portals, databases on local servers, firewalls, and a separate sensor network not connected to the internet [56,69–72]. Cyber security is a very sensitive topic in urban applications, where accessing the data can cause severe damage on working activities and expose citizens to risk.
- Physical security: The assessment of safety risks inherent in the use of actuators and sensors (unwanted or dangerous actuation) [73,74] and the installation of sensors for physical security (gas leakage [75], flooding [76], seismic [77], short circuit, and electrocution [78], fire [79,80], workers safety [81,82], etc.).
- Management of emergency interventions: The automatic opening of intervention tickets and priority to critical interventions (as an example where is the possibility of injured people) [83]. Real-time analysis of the status of the intervention and data sharing among the various connected emergency services (fire brigade, police, first aid, etc.) [84,85].

6. Maintenance: the monitoring, fault forecasting, and scheduling of maintenance interventions.

- FDD: The monitoring of the operating status of connected systems with predictive capabilities for fault detection and diagnosis (FDD), monitoring also extended to connected sensors and network devices. By monitoring the status of the systems, it is possible to manage maintenance interventions, organise warehouses for spare parts, and keep the systems efficient, with a consequent reduction in inefficiencies and operating costs [86–89].
- Intervention management: the automatic opening of tickets for the maintenance sector to reduce intervention times [90,91].

7. Presence and activities: the monitoring, forecasting, and management of occupation.

- Occupancy: Presence monitoring using dedicated hardware, such as radar sensors and cameras, and other data coming from device usage, lights, computers, etc. [92]. Occupancy data can be used for the evaluation of presence, for medical prevention, as example from COVID SARS cases [93,94], and for the optimisation and reduction in energy consumption [95] due to lighting [96] and air conditioning [97], and to ensure the safety of environments from external intrusions.
- Activity: Evaluating the activity carried out is an additional parameter useful for improving the accuracy of control over air conditioning and lighting systems. Thermal loads and recommended illuminance may vary depending on the type of activity carried out in the environment, an environment that could be used for different and simultaneous activities [98–100].
- Travel: The analysis of people's movements makes it possible to identify the most used services and spaces, highlighting the preferences of citizens [101,102].

8. Wastes and pest control: monitoring and forecasting for pest control and waste produced.

- Pest control: The monitoring of pests (rodents, insects) and IoT capture systems with remote sensors for the identification of pest presence [103,104]. The automation of pest monitoring systems makes it possible to act in time before the creation of out-of-control colonies and their interference with inhabited spaces [105].
- Wastes: The monitoring and evaluation of trash bins through dedicated sensors and the notification of filling, the assessment of the mass of waste produced, and its travel through the territory considering construction waste and special waste [106–108]. The automatic management and evaluation of the wastes produced provide valuable information on environmental pollution and allow to optimisation waste management operations, avoiding the proliferation of animal pest colonies [109].

9. Mobility: the monitoring and forecasting of parking, micro-mobility systems for public and private transport, and charging systems for electric vehicles.

- Parking and micro-mobility: the evaluation and prediction of the number of available spaces through cameras equipped with computer vision and the management of bicycle racks [110–112].
- Transport: the analysis of routes, turnout, and the management of route alternatives based on traffic data and the use of public transport services and roads (or canals in the case of Venice) [113–115].
- Accidents: the automatic identification of accidents and initiation of rescue procedures and automatic warnings on the presence of inefficiencies and automatic generation of route alternatives [116–118].
- Electric charging: the monitoring and forecasting of electricity consumption due to the use of electric charging stations [119–121].

- Routes: the analysis of the shortest routes and reduction in traffic, including vehicular, pedestrian, and naval [122–124].

The list is purely indicative and is based on the state-of-art related to DT systems at different scales, from single buildings and infrastructure up to cities [40,125–131]. Figure 4 summarise all the features, tasks, monitorable data, and targets for an urban DT.

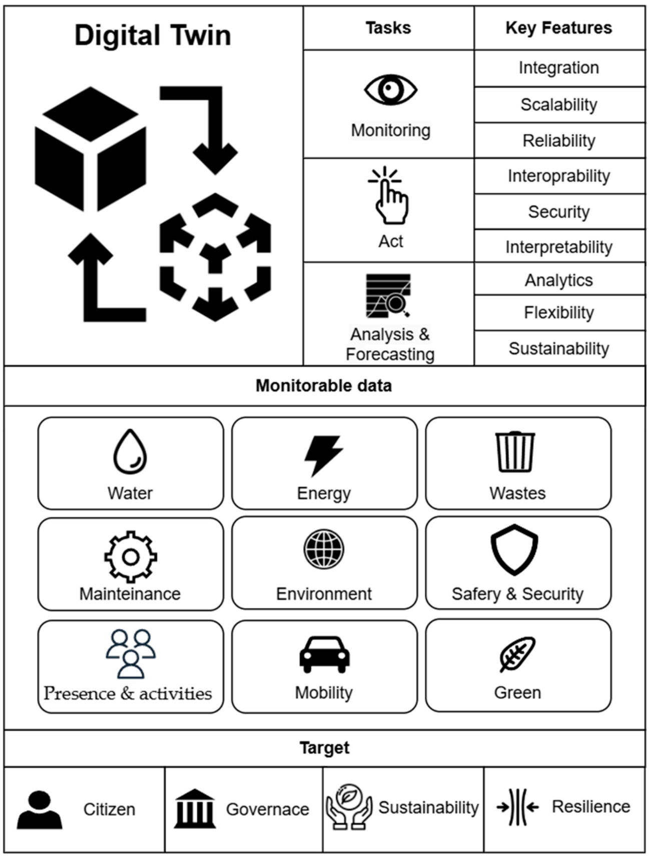

Figure 4. Urban Digital Twin components: tasks, features, data, and targets.

4. Methodological Approach: A Three-Axis Framework for DT Implementation

The complexity of urban management with digital systems requires simplification to avoid overdeveloping too many platforms or tools that would be difficult to manage for a public administration that is just starting to deal with the digital transition. It must be reiterated that the main goal of digital transition is to simplify the process to reduce costs as well as increase resilience and sustainability. Therefore, it is proposed to aggregate all urban activities into three main operative axes based on the main topics of future urban development: energy, mobility, and resilience. These axes must satisfy and comprehend the international framework described in the Sustainable Development Goals and in the smart city diamond [50]. The interexchange of data between these services must be guaranteed as well as the possibility to integrate data flows from actual databases and services already operating inside the city environment. The research also considers the specifical requirement of the city of Venice in terms of cultural heritage conservation [132,133]. Artificial intelligence needs data to obtain the best results [130], and using what is already available can reduce training time and increase the accuracy of forecast and control routines. Digital Twin represents a powerful tool for urban management and future development, but it is necessary to give the developer shared and common methodological frameworks suitable for the specific application. The same principle was proposed in the 14th century by

William of Ockham with Occam's Razor philosophy: "Entia non sunt multiplicanda praeter necessitatem", which translates as "entities must not be multiplied beyond necessity". The same principle should be applied to DT systems.

Moving to the methodological approach used for this research, the following steps have been performed for the development of the three-axial framework:

1. Analysis of the state-of-the-art for DT systems at an urban scale. As outlined in the work of Bauer et al. (2021), various cities are progressing towards the digital transition by developing their own urban DT systems [26]. Many cities are starting to adopt DT systems; however, the application is usually focused on a single topic of urban management.
2. The development of a list of general requirements for the proper development of a DT system, based on guidelines, such as detailed in Luarini's work about smart city planning [40]. Moreover, the international framework for future development was also considered, which focuses on the main fields of intervention to be addressed. In this way, an open-access monitorable database is fundamental to start the assembly of general requirements.
3. The definition and aggregation of the investigation topics detailed in international frameworks and the state-of-the-art can be divided into three main axes: mobility, energy, and residence. A higher number of axes would lead to more different services and platforms being developed, increasing the overall complexity of the resulting DT. Instead, based on the monitorable data study and state-of-the-art, a lower number of services would lead to an excessive simplification that does not suit the international framework for sustainable development.
4. The identification for each axis of a list of fields of intervention can define where it is possible to digitalise the urban environment processes. Then, the fields of interventions are translated into operative services, for which the DT system shall be made. As an example, the field of intervention "monitoring of air quality levels" of the mobility axis shall be contained in the "environmental impact service".
5. The analysis of the data available in the Venice city open-source database.
6. The identification of new data to be integrated into the Venice data portal to establish a DT system. If data related to a specific service are available in the database, then it must be used in the DT system; if no data are available, it is recommended to add new tables to make information available for the citizens, for the future development of the DT system using innovative and secure technologies [133–138], or other uses (as an example for a private company that wants to improve urban quality of life using such data).

The methodological approach proposed is summarised in Figure 5.

The list of the three axes considered for the development of the DT system with their specificities is exposed as follows:

1. City mobility: The management of road and channel infrastructure and traffic analysis, including pedestrian flows, parking, environmental pollution, and a consequent reduction in traffic.
2. Energy: The energy management of city infrastructures and buildings, capable of optimizing and reducing energy consumption, considering the potential beneficial effects of developing local energy communities, and outlining possible future scenarios.
3. Resiliency: The management of emergencies, such as floods, earthquakes, fires, heat islands, waste, city parks, and change detection on new buildings due to urbanisation.

The hypotheses performed in defining the topics managed by the DT system are defined in the following sections. The name "general directives" has been chosen, because they are oriented on defining the direction of the interventions for future urban development and are based on sustainable development goals. As an additional hypothesis, the analysis of water balances and water quality present in infrastructures is excluded from this work and will be the subject of future developments also considering the projects existing in Venice for water management [33,137–141]. The methodology, although generally applicable, was developed using the city of Venice as a case study. Therefore, some specific aspects were considered as cultural heritage conservation, the presence of both waterways and roads, and the exposure to extreme weather events possible in temperate zones.

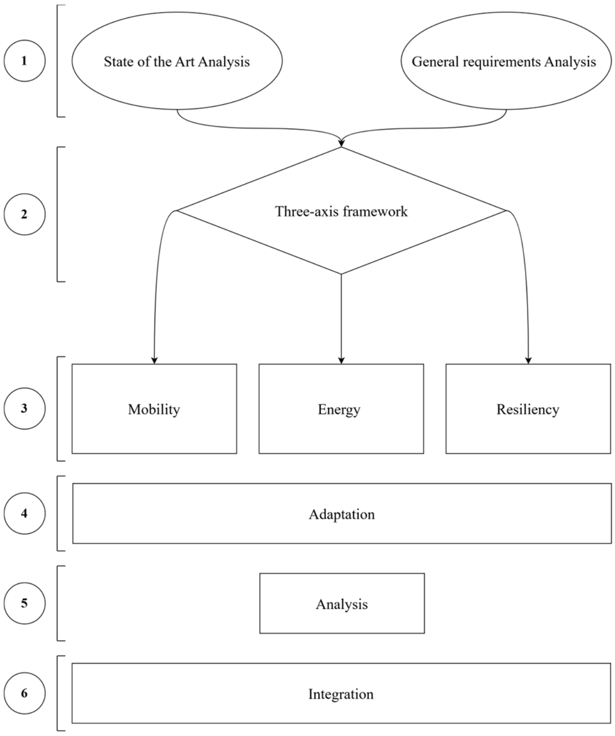

Figure 5. Methodological approach for Digital Twin development.

4.1. General Directives for Mobility Axis

Based on the international guidelines and frameworks previously reported, the main directives that support the development of a DT system to optimise urban mobility are reported as follows:

- Reduction in fossil fuels and traffic in public and private transport: The optimisation of routes with consequent prediction and reduction in traffic and the monitoring of environmental pollutants produced and carbon footprint; the extension of the monitoring service also to maritime traffic within the canals of Venice; the management and scheduling of electric vehicle (EV) charging stations.
- Energy optimisation of on-road systems: the efficiency of public lighting and traffic light systems, point-to-point remote control of public lighting systems, adaptive street and pedestrian lighting, and the evaluation of infrastructure management costs.
- Service management: predictive road lighting by machine learning and real-time data analysis (probabilistic, geo-referenced, and prioritised for critical services), the intelligent monitoring of parking lots, the monitoring of electrical vehicles recharging stations, a reduction in intervention time of emergency and security services (fire brigades, ambulances, police, etc.) through best route identification, data infrastructure shared among different stakeholders (governance, mobility service companies), and intelligent management of traffic light systems based on traffic data.

- Travel: the monitoring of the flows of people (tourists, citizens, and commuters), through and within the different urban areas to identify the most used routes, and the most visited areas, providing indications and guidelines for urban planning.

All data collected in the area must be integrated within a dedicated service within a DT platform for the unified management of city mobility. The system created must be made available both to the public administration, with complete control over the various elements, and to the public through the municipality's open data platform and through a dedicated web portal to give citizens consciousness of the actual traffic and any possible issue related to their mobility inside the city.

Concerning the mobility infrastructure, the network systems used for street lighting, roads, and local traffic management devices (traffic lights, limited traffic zones, etc.) must also be monitored. Moreover, video surveillance systems can be integrated into the DT.

4.2. General Directives for Energy Axis

The approach for the energy axis is the same as for the mobility one. Therefore, based on the international guidelines and the elements reported in the Section 3, the main directives that support the development of a DT system to optimise urban mobility are reported as follows:

- Reduction in fossil fuels: the optimisation and reduction in energy consumption from fossil sources, integration with RES (renewable energy sources), cogeneration, heating by traditional gas boilers, and the management of REC (renewable energy communities); monitoring natural gas and LPG (liquid propane gas) is necessary for assessing carbon emissions.
- Reduction in electricity consumption: referring to air conditioning and lighting systems through increasing the efficiency of electrical devices, the management and control of air conditioning systems, integration with REC and cogeneration systems, adaptive lighting, and the assessment of energy costs; the storage capacity of batteries must be considered for the smart management of energy consumption.
- Preventive and predictive maintenance: ordinary and extraordinary, with active system control by the low-level integration of data to maintain the desired efficiency parameters [86–88,142].
- Smart planning of intervention: based on real consumption data for building upgrading and interventions of the built environment (insulation, fixtures, etc.) and pre-existing energy systems (boilers, air conditioners, etc.) with the capability of forecasting the advantages in terms of energy savings due to the installation of new systems with greater efficiency (geothermal heat pumps, congenators, etc.) and new renewable energy sources (PV, wind, hydrogen, etc.).
- Energy management system: the development of an integrated system able to manage, control, and predict energy consumption through predictive algorithms at different scales (from single building up to districts). All the data collected can be integrated into a unified management system dedicated to city management. It will, therefore, be possible to make this system available both to the public administrators and energy managers, with complete control over the various elements, and to the public through open data.
- Hydrogen systems: the monitoring of hydrogen production, storage, and flows; this element will be necessary in the future for the implementation of natural gas and hydrogen mixtures in pipelines [143,144] and to divide the quota between fossil fuel usage and hydrogen for the assessment of carbon emissions.

The systems to be monitored include the following: MV/LV substations, generators, uninterruptible power supplies, amplifier systems, existing and newly installed photovoltaic systems, public lighting, traffic light systems, special systems, rainwater lifting systems, city video surveillance systems, lighting systems for sports fields and parks, electrical systems serving city markets, cippus and tombstones, boilers, electrolyzes, non-street lighting systems, gas tanks, cogeneration plants, IoT monitoring systems, datacentres, network systems, and all other systems that have energy consumption. Although some systems may have reduced consumption (network systems, IoT, tombstones, amplifier systems, etc.), the sum of all contributions at the city level can make an important contribution to the calculation of energy consumption if summed. It is beyond any doubt that the main components of the main electrical loads must be monitored first, and then, at the second stage, the less demanding systems will be monitored.

To include all energy carriers, the DT system should also be extended to wall-mounted boilers that use methane gas and LPG and, in the future, to hydrogen production and storage systems.

4.3. General Directives for Resiliency Axis

Through the integration of data from building monitoring systems and environmental sensors, DT can provide a complete detailed view of the city considering floods, flooding tides, hydrogeological instability, and fire risk. Data analysis using advanced models can guide climate adaptation strategies and intervention planning to improve the city's resilience to adverse events [17,31–33,37,76,80,85,141,145]. Moreover, DT can be used to detect changes in the urban landscape and to plan future urban development using what-if scenarios and forecasting [125,126,146]. As for the energy axis, the technology can be used for maintenance and building management, as well as to a larger scale, for urban management, tracking restoration, and retrofitting intervention also from a structural and functional point of view [58,79,90,147]. The list of features describing the context of reference for the resiliency axis can be summarised as follows:

- Protection from natural disasters and extreme events: identification and early warning for extreme events (heavy rains, hails, floods, fire, etc.), the assessment of risk area, the management of mitigation strategies, support to emergency planning with what-if analysis, the early identification of heatwaves, the identification of urban heat islands, early warning system, coastal erosion assessment, and the centralisation and monitoring of emergency procedures.
- Monitoring of built environment resilience: the analysis of the displacement map and identification of area subject to hydrogeological instability, maintenance intervention planning, and renovation planning.
- Preservation of cultural heritage and strategic infrastructure: dedicated and more accurate track change analysis, the analysis of pollutants impact on building structures, maintenance and restoration intervention planning, and dedicated what-if analysis for extreme events impact.
- Anthropic impact and urbanisation: air quality and noise monitoring and forecasting, land use assessment, waste and dump monitoring on the territory, urban track-change, comparison with land register plans, what-if analysis for urban planning, and the identification of illegal dumps and unauthorised buildings.

5. Results and Discussion

5.1. Venice City and Open Data

The city of Venice is proposed as a case study for the adoption of an urban DT system. The choice is based on the necessity to protect the natural and cultural heritage of the city as well as its uniqueness as for the presence of a double mobility system, based on waterways and pedestrian roads. The city itself can be divided into two different areas, the historical centre and urban area of Mestre, along the western border of the Venetian lagoon. The historical city, founded at the end of the fifth century on an archipelago of about 118 islets rising less than one meter above sea level, is in the centre of a vast coastal lagoon covering 70,176.4 hectares and morphologically originating from the paleo-delta of several watercourses. The construction technique in such a unique environment, it is based on long wooden piles embedded thickly in the marshy ground, to provide the base for wooden, stone, and brick layer foundations, on which all the buildings and bridges in Venice are subsequently built [132]. The evident fragility of the unique built environment of incredible historical and cultural value, together with the very high naturalistic value of the Venice Lagoon, led UNESCO to inscribe the city and its lagoon on the World Heritage list in 1987 according to the positive report of the International Council on Monuments and Sites (ICOMOS) in 1986 [133].

Venice currently has an open data database supported by the municipality. where public data are regularly published. The database contains information related to management, administration, and resources usage. It is a relational structured query language (SQL) database that is not suitable for managing Big Data, as necessary for DT system [24].

5.2. Mobility Axis

Below is reported the analysis carried out in the mobility axis and based on the analysis of the information available for the Municipality of Venice.

5.2.1. Fields of Intervention

Considering the reference context, it is possible to extrapolate the main fields of intervention by comparison with the international state-of-the-art mobility systems in smart cities [148–150]:

- Evaluation of fossil fuel use by traffic monitoring.
- Monitoring, management, and forecasting of traffic.
- Monitoring, management, and forecasting of public lighting systems.
- Monitoring, management, and forecasting of parking lots.
- Scheduling and management of electric vehicle charging stations.
- Centralisation of traffic light control and data integration with the municipal traffic management centre.
- Integrated management of all assets on a single system equipped with dashboards, satellite data, and monitoring, management, and simulation capabilities.
- Installation of new sensors and devices dedicated to the analysis of the status of roads, streets, and waterways in real time.
- Intelligent and dynamic priority to emergency vehicles.
- Monitoring of air quality levels.
- Monitoring of noise pollution levels.
- Data integration with the other services (energy and resiliency).
- Data availability to citizens and stakeholders.
- Maintaining high cybersecurity standards and a full risk regime.
- Privacy and protection of sensible data.
- Creation of a dedicated ticketing and assistance system.

5.2.2. Mobility Services

The fields of intervention for the “mobility service” can be aggregated within a reduced number of software services that can coexist and intercommunicate. These services can be provided through different applications dedicated to the various stakeholders with different levels of access to data and interaction. The list of more common services offered is shown below:

- Traffic and parking service: Dedicated to the citizen and public administration, possibly open to third parties. The service scope is to manage and record mobility data (road and maritime), providing information on traffic and parking to control (for public administration) and information (for citizens). Parking lots can be monitored to ensure the effective presence of parking spaces before travel and to avoid circular routes that can increase on-road time and pollution. This assessment can be carried out through image analysis and computer vision, expanding monitoring even on free road stalls [110,111]. This information can then be made available to citizens through mobile apps and variable message signs, as well as being integrated into an application dedicated to parking management for the purchase of parking tickets and payment control. The service will also provide data to the road management service for traffic light control and limited traffic areas. Pedestrian flows can be analysed by the same system and reported within dedicated maps, which, in the case of the insular Venice, can also be significant for designing strategies and policies to counteract over-tourism.
- Environmental impact service: The service will be entrusted to the urban manager and will use traffic data and dedicated sensors (IoT) to calculate the pollution produced by on-road and naval mobility and then monitor its evolution in space and time. The municipal administration will be able to use those data to carry out interventions aimed at reducing environmental and noise pollution or to highlight any critical situations with punctual accuracy on all monitored roads and waterways. Considering the presence of air pollution services managed by ARPA Veneto (Regional Agency for Environmental Prevention and Protection of Veneto region), the data could be integrated between the two databases to increase the accuracy of forecasting. The main pollutants to be monitored are reported in point "#2 Environment" of the list in the "Monitorable Data" section. The analysis of these data will also allow the operator to monitor situations of potential accidents, such as the presence of fires (increase in PM and localised CO_2), gas leakages on the pipeline system, or safety alarms. The electricity consumption data of street lighting can also be integrated into the service with the calculation of the average savings in terms of tons of CO_2 equivalent.
- Roads and waterways management service: The proposed service allows the management and monitoring of all roads, streets, and waterways present in the city: public lighting, traffic light systems, and digital signs. The service shall also be able to propose automatic strategies for the reduction in traffic, automatically controlling road intersections according to the logic of green wave and smart priority (emergency vehicles). Public lighting systems on roads (driveways, cycle, and pedestrian paths), and waterways shall be controlled automatically by the service based on cameras, light meters, and presence sensor data, as well as through sonar, radar, and the GPS localisation system of all circulating public and private vessels. This would allow lights to be automatically reduced according to actual need. Turning off lights is not an option because of safety navigation concerns. However, regulating the light fluxes can reduce the overall energy consumption of lighting systems as well as reduce lighting pollution.

Figure 6 shows the component of the mobility service reported in the previous list.

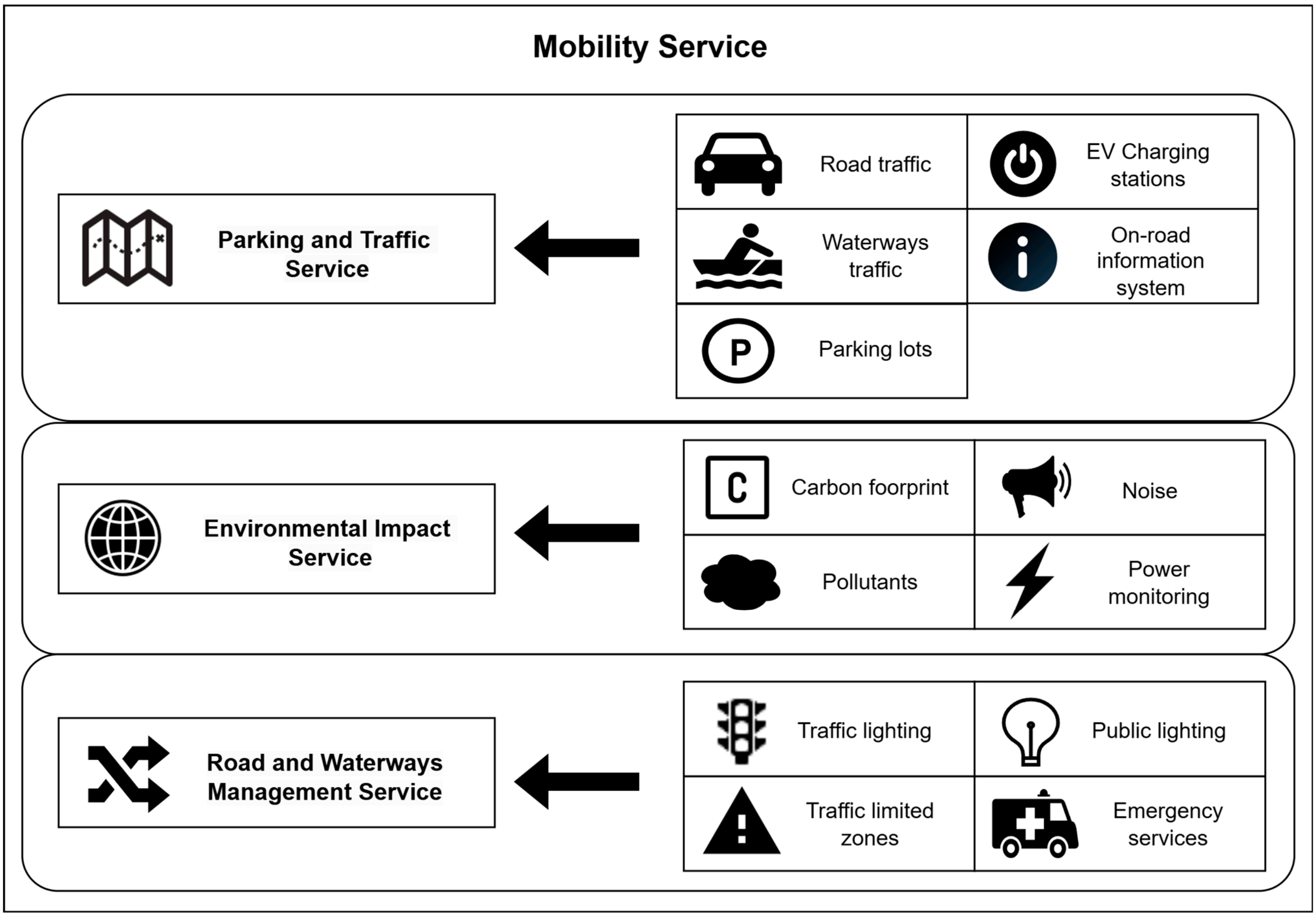

Figure 6. Mobility service components.

5.2.3. Venice Open Data Analysis

Concerning the data available online on the Venice open data portal and considering the service proposed for the management of city mobility, the database has been analysed. As a result, it is necessary to implement new dedicated database tables oriented towards the missing data as well as consider how the available data can be used to implement the different services provided by the DT platform. This analysis showed a lack of information on some of the proposed fields of intervention. As an example, data relating to the general directive of services management are missing. It is, therefore, necessary to develop new datasets to be shared on the Venice open data portal.

Figure 7 shows the data present in the Venice open data database that can be integrated into the DT platform.

5.2.4. Interaction Among Services, General Directives, and Fields of Intervention

Based on the Venice open data database, the assets involved, and the services proposed, it is possible to define the interaction among services, general directives, and fields of intervention aiming at the objective of sustainability and digitisation of city infrastructures. The interaction among different fields of intervention and general directives is reported in Table 1 where the letter "X" indicates an existing relationship.

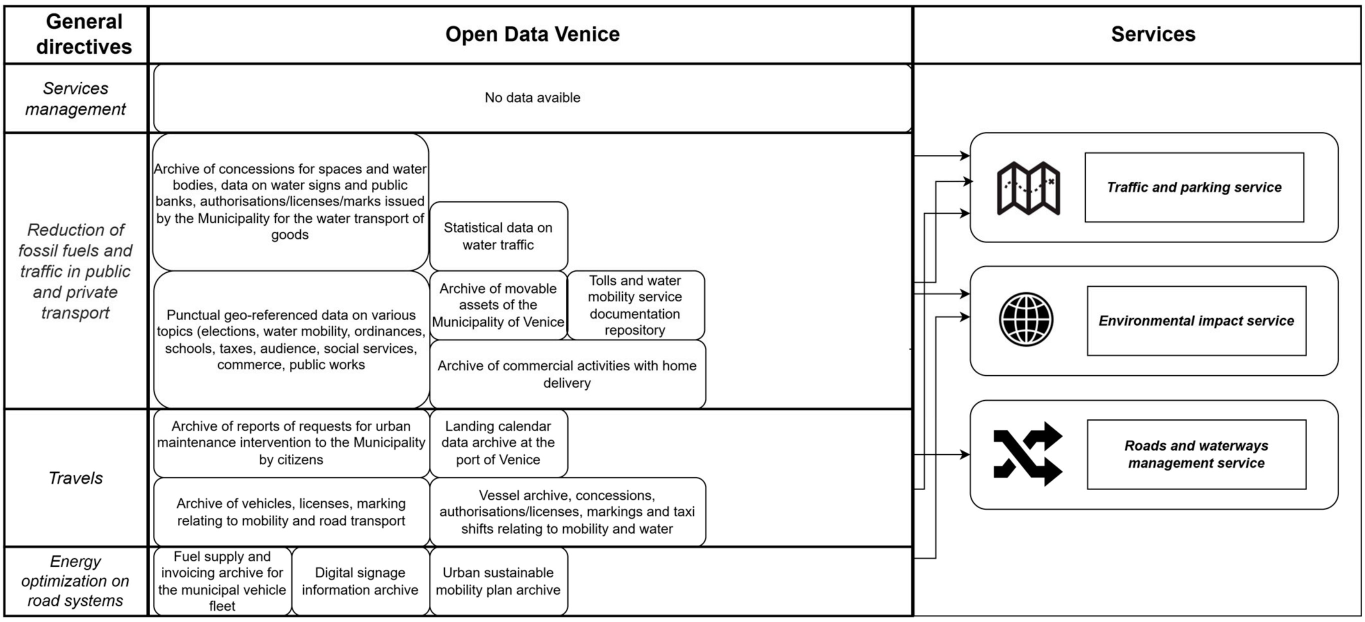

Figure 7. Venice open data analysis, related to general directives and linked by arrows with DT's services related to the mobility axis.

Table 1. Interaction among general directives and fields of intervention for mobility axis.

		General Directives			
		Reduction in Fossil Fuel Use and Traffic in Public and Private Transport	**Energy Optimisation of On-Road Systems**	**Service Management**	**Travel**
N.	**Fields of Intervention**				
1	Evaluation of fossil fuel by traffic monitoring.	X		X	
2	Monitoring, management, and forecasting of traffic.	X		X	X
3	Monitoring, management, and forecasting of public lighting systems.		X	X	
4	Monitoring, management, and forecasting of parking lots.	X		X	X
5	Scheduling and management of electric vehicle charging stations.	X		X	
6	Centralisation of traffic light control and data integration with the municipal traffic management centre.	X	X	X	
7	Integrated management of all assets on a single system equipped with dashboards, satellite data and monitoring, management, and simulation capabilities.	X	X	X	X
8	Installation of new sensors and devices dedicated to the analysis of the status of roads and channels in real time.	X	X		X
9	Intelligent and dynamic priority to emergency vehicles.			X	
10	Monitoring of air quality levels.	X		X	X

Table 1. *Cont.*

		General Directives			
		Reduction in Fossil Fuel Use and Traffic in Public and Private Transport	**Energy Optimisation of On-Road Systems**	**Service Management**	**Travel**
N.	**Fields of Intervention**				
11	Monitoring of noise pollution levels.	X		X	X
12	Data integration with the other services (energy and resiliency).		X	X	X
13	Data availability to citizens and stakeholders.	X			X
14	Maintaining high cybersecurity standards and a full risk regime.	X	X	X	X
15	Privacy and protection of sensible data.	X			X
16	Creation of a dedicated ticketing and assistance system.	X	X	X	X

The interaction among the proposed services and the directives is expressed in Table 2.

Table 2. Interaction among directives and proposed services for the mobility axis.

General Directives	**Services**
Reduction in fossil fuel and traffic in public and private transport	Traffic and parking service Road, streets, and waterways management service
Energy optimisation of on-road systems	Road, streets, and waterways management service
Service management	Traffic and parking service Road, streets, and waterways management service Environmental impact service
Travel	Road, streets, and waterways management service

5.3. Energy Axis

Below is the analysis carried out on the energy axis and based on the investigation of the information available for the Municipality of Venice.

5.3.1. Fields of Intervention

The energy component plays a role of primary importance in city sustainability as also reported in the IEA’s 2022 report on building consumption [151]. DT systems can effectively improve the energy efficiency and environmental sustainability of buildings and systems as demonstrated by the many studies in the literature [130,152–154].

This process can be achieved through the integration of data from the various BMSs (building monitoring systems) and the most advanced BACSs (building automation and control systems) installed on the infrastructures subject to efficiency measures [155–157]. Existing and previous monitoring and control systems may not be compatible with this approach and may need to be updated or replaced [94,158]. Data monitored from individual buildings and infrastructures can be integrated into an urban DT to provide a broader overview from an energy perspective. By creating a basis for the establishment of RED (renewable energy districts) and REC (for example, preferring energy from RES when available or stored in the neighbouring area). The data collected could contain additional information regarding the operating status, the interventions to be carried out, and the real-time efficiency of the various connected devices. Expanding the analysis with additional data (such as efficiencies, operating status, error codes, etc.) can provide a basis for the integration of advanced machine learning and artificial intelligence models able to analyse (through real data) future energy needs, the best efficiency strategies, usage habits, the most reliable systems, and to plan potential RED and REC. The creation of a DT system involves specific design choices and the use of standardised and cutting-edge systems for the analysis, transmission, and processing of data, choices that are easily implemented on the "new", but which require targeted interventions for all "retrofitting" operations. This is a severe issue in the case of Italy and Venice, which possesses one of the oldest built environments in Europe [159].

In addition, given the possibility of real-time and predictive control, DT systems are candidates in response to the needs of full risk about the security of connected systems, providing real-time responses to malfunctions and allowing the automatic creation of service tickets for the maintenance and restoration of buildings and infrastructures.

Including the energy component from methane gas and LPG, the integration of data from boilers can provide information on the state of maintenance, efficiency, and consumption and for the identification of leaks. These data can be integrated with the data of the Single Regional Thermal Cadastre (Directive 2010/31/EU) for the monitoring and control of certification interventions. The same data can also be used as a basis for the installation of new high-efficiency thermal plants (heat pumps) or combined thermal plants (cogeneration) to eliminate fossil fuels other than hydrogen generation and storage systems. The main consumption contribution for a building during the winter period is heating; therefore, the integration of data from REC combined with energy efficiency interventions and the installation of heat pump systems will make it possible in the future to achieve the ambitious goal of zero emissions for 2050 and to increase the energy class of buildings above D by 2030.

Considering the highlighted picture, it is possible to create the following list of fields of intervention for the energy service:

- Assessment and reduction in the use of fossil fuels (methane, LPG).
- Monitoring and forecasting of hydrogen production and storage.
- Monitoring and management of RES with and without storage.
- Monitoring and management of air conditioning systems.
- Use of occupancy data for energy optimisation (lighting and air conditioning).
- Development of Renewable Energy Communities (RECs).
- Centralisation and unification of data from BMS and BACS on a city platform.
- Integrated management of all assets on a single system (with dashboards, satellite data, monitoring, management, and simulation capabilities).
- Installation of new sensors and devices dedicated to the analysis of energy consumption systems (air conditioning, power systems, lighting, handling, elevators, etc.).
- Intelligent and dynamic prioritisation of RES sources.
- Monitoring and control of the operating status of the devices (FDD—fault detection and diagnosis).
- Safety analysis (full-risk assessment).
- Data integration with existing databases and services.

- Accessibility to data to stakeholders.
- Maintaining high cybersecurity standards.
- Privacy protection.
- Scalability of systems, from the single asset to the smart city level.
- Creation of a dedicated ticketing and assistance system.

As additional elements, and dedicated to efficiency measures not directly related to the DT system, the following additional intervention parameters are highlighted:

- Multizone climate management: temperature regulation according to different modes of use and environments.
- Automatic identification analysis of efficiency interventions (replacement of fixtures and installation of thermal coats, insulation, reduction in thermal bridges, use of low-emission paints).
- Replacement of gas heating systems with more efficient systems (heat pumps).
- Installation of new RES plants (photovoltaic, wind, etc.).
- Maintenance of indoor environmental comfort standards.
- Combined interventions for NZEBs (near zero energy buildings).

5.3.2. Energy Services

The fields of intervention highlighted can be aggregated in services dedicated to the energy axis. These sub-services will be able to coexist and communicate with each other as well as allow the various stakeholders access to the data with different levels of authorisation, increasing the resilience of the infrastructures. The list of services offered is shown below:

- Energy service: Dedicated to the citizen and the manager, and possibly open to third parties. The service will be responsible for managing and recording data on production from RES, consumption, and exchange of electricity dedicated to the establishment of REC. Starting from the data monitored within the infrastructures in terms of electricity produced and consumed, it is possible to monitor and optimise energy flows, preferring the renewable quota for the power supply of all the connected systems monitored by the DT. The consumption of individual devices equipped with smart sockets or digital communication interfaces (heat pumps, lights, load lifting motors, etc.) and the electricity produced in real time by the connected RES systems (photovoltaic, wind, etc.) or cogeneration systems can be monitored. Electricity can be fed into the grid, stored on batteries, converted into green hydrogen, or used on-site, preferring its use within neighbouring infrastructures (energy districts) whenever possible, thus saving energy the lost by its transport. The service shall be extended to any private RES systems, providing real-time and predictive data on the energy produced and consumed locally and globally. Any faults or malfunctions can be detected based on the data and transmitted to the management and maintenance to reduce downtime and maintain a high overall efficiency. The monitored data will, therefore, have different levels of authorisation to allow them to be read and written by the managers of the individual connected infrastructures, the stakeholders who will rely on this system, and the municipal administration (which has full access).
- BACS service: The service is dedicated to building managers and will use data from sensors and installed actuators (IoT) to monitor the status of all connected systems belonging to the same building. The manager will be able to use these data to carry out further interventions and maintenance activities, as well as have a complete overview of the operating status of all connected systems. This will make it possible to propose coherent strategies based on the current situation of buildings aimed at reducing environmental pollution, reducing the carbon footprint, increasing sustainability and

resilience, and reducing inefficiencies. The analysis of these data will also make it possible to monitor accidental situations, such as the presence of dangerous failures from a safety point of view (e.g., breakage of elevators) or alarms (interruption of power). The service will also manage the efficiency parameters of the systems starting from electricity consumption and production data, to control and regulate thermal, air conditioning, and lighting systems and all non-critical and regulable systems. Occupancy data for the reduction in consumption (for example dimming lights and regulating air conditioning systems in the event of the absence of people inside the rooms), data on energy stored through storage, and ticketing data can be integrated into the service.

Figure 8 shows the components of the mobility service reported in the previous list.

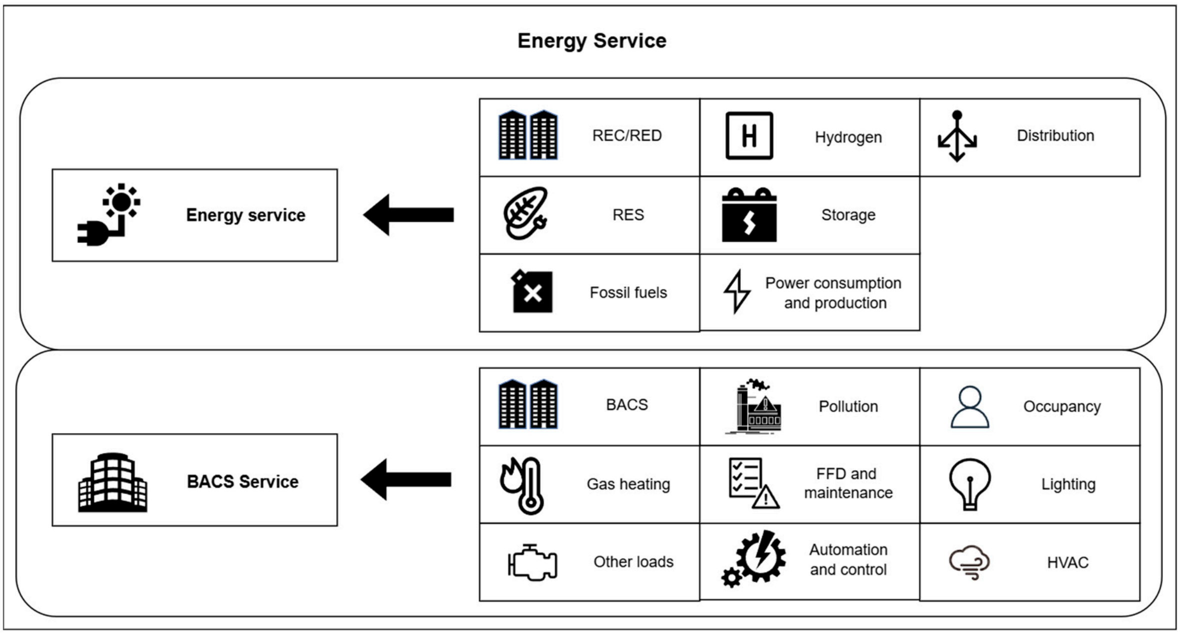

Figure 8. Energy service components.

5.3.3. Venice Open Data Analysis

By analysing the data on the Venezia open data portal and focusing on the energy axis, an attempt was made to evaluate the available databases, highlighting potential gaps and areas for integration. These data can be used internally (managers), externally (maintainers, stakeholders), and after agreement with the municipality, shared publicly on the portal. These data can be acquired by the urban DT system, and at the same time, the open data can feed the DT using the following datasets (Figure 9).

5.3.4. Interaction Among Services, General Directives, and Fields of Intervention

The interaction analysis is based on the Venice open data, the assets involved, and the services proposed. This analysis aims to identify how the general directives and fields of intervention cooperate to achieve sustainability and digitisation of city infrastructures.

The interaction among fields of intervention and general directives is reported in Table 3, where the letter "X" indicates an existing relationship.

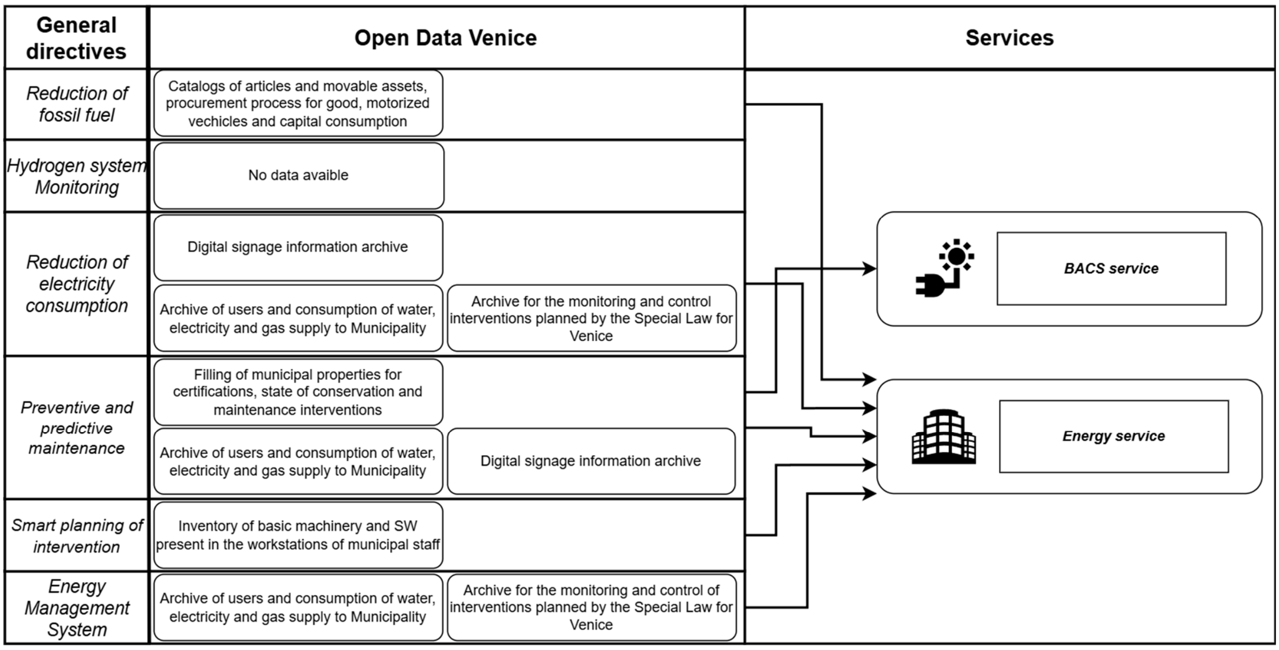

Figure 9. Venice open data analysis, related to general directives and linked by arrows with DT's services related to the energy axis.

Table 3. Interaction among general directives and fields of intervention for energy axis.

		General Directives					
		Reduction in Fossil Fuels	**Reduction in Electricity Consumption**	**Preventive and Predictive Maintenance**	**Smart Planning of Intervention**	**Energy Management System**	**Hydrogen System Monitoring**
N.	**Fields of Intervention**						
1	Assessment of and reduction in the use of fossil fuels.	X			X		
2	Monitoring and forecasting of hydrogen production and storage.			X	X	X	X
4	Monitoring and management of RES with and without storage.	X		X	X	X	X
5	Monitoring and management of air conditioning systems.		X	X		X	
6	Use of occupancy data for energy optimisation.	X	X			X	
7	Development of REC.	X	X			X	X
8	Centralisation and unification of data from BMS and BACS on a city platform.		X	X		X	X
9	Integrated management of all assets on a single system.			X		X	
10	Installation of new sensors and devices dedicated to the analysis of energy consumption systems specific.	X	X		X	X	

Table 3. *Cont.*

		General Directives					
		Reduction in Fossil Fuels	**Reduction in Electricity Consumption**	**Preventive and Predictive Maintenance**	**Smart Planning of Intervention**	**Energy Management System**	**Hydrogen System Monitoring**
N.	**Fields of Intervention**						
11	Intelligent and dynamic prioritisation of RES sources.	X				X	X
12	Monitoring and control of the operating status of the devices.			X	X	X	
13	Safety analysis.			X	X		
14	Data integration with existing databases and services.			X	X	X	X
15	Accessibility to data to stakeholders.	X	X			X	X
16	Maintaining high cybersecurity standards.	X	X	X	X	X	X
17	Privacy protection.	X	X			X	X
18	Scalability of systems, from the single asset to the smart city level.		X	X		X	X
19	Creation of a dedicated ticketing and assistance system.			X		X	
20	Multizone climate management		X			X	
21	Automatic identification analysis of efficiency interventions.	X	X	X	X		
22	Replacement of gas heating systems with more efficient systems.	X	X		X		X
23	Installation of new RES plants.	X	X		X		X
24	Maintenance of indoor environmental comfort standards.				X	X	
25	Combined interventions for NZEBs.		X		X		

The Interaction between the proposed services and the directives is expressed in Table 4.

Table 4. Interaction among directives and proposed services for energy axis.

General Directives	**Services**
Reduction in fossil fuels	Energy service
Reduction in electricity consumption	Energy service
Preventive and predictive maintenance	BACS service
Smart planning of intervention	Energy service BACS service
Energy management system	Energy service BACS service
Hydrogen system monitoring	Energy service

5.4. Resiliency Axis

The following analysis is related to urban resilience, based on the state-of-the-art, open data of the Municipality of Venice, and the satellite data available from the Copernicus service.

5.4.1. Fields of Intervention

Venice is one of the sites recognised by UNESCO World Heritage as a World Heritage Site, and although it is not presently on the list of sites considered at risk [160,161], the risk status was considered during the time. The Venice case was discussed during the UNESCO meeting held in Riyadh, Saudi Arabia in 2023, and after a long debate and observation, the decision taken was not to add the city and its lagoon to the World Heritage in Danger list but to continue the monitoring the city issues, including overtourism and extreme climatic events affecting the city's high fragility due to its construction in the lagoon and the continuous increasing flooding phenomena. The management of resilience is, therefore, presenting specific risks, which extend both to the lagoon area and neighbouring coastland area. This situation involves the need to implement different monitoring systems in the two considered areas, converging data within the same DT system.

The Municipality of Venice comprises the lagoon area, on which the historic city is built, and the coastland area surrounding it. The total area of the municipality is 415.9 km^2, of which 257.73 km^2 is made up of inland waters [162,163].

The presence of the lagoon and its canals in the area comprising the harbour canal system involves a unique hydrological context. Therefore, a detailed analysis of potential risk areas is essential to understand flood risk and to formulate appropriate management strategies. To overcome this problem, the Municipality of Venice, through the Decentralised Functional Centre of the Veneto Region (C.F.D.), constantly monitors the hydrogeological risk and potential issues warnings to the population.

The Municipal Emergency Plan (PCE) produced by the Local Police and Territorial Security Area (APLS) represents a fundamental tool in the field of water resources management and the prevention of hydrogeological risks that can be used as a base for the definition of area where use the DT to monitor rainfall and rivers levels. The areas of particular interest identified by the PRGA (General Flood Risk Plan) and the PA (Flooding Plan) are identified as the floodable areas with very high probability (R4), high probability (R3), and medium probability (R2) of flooding, visible in Figures 10 (PRGA) and 11 (PA).

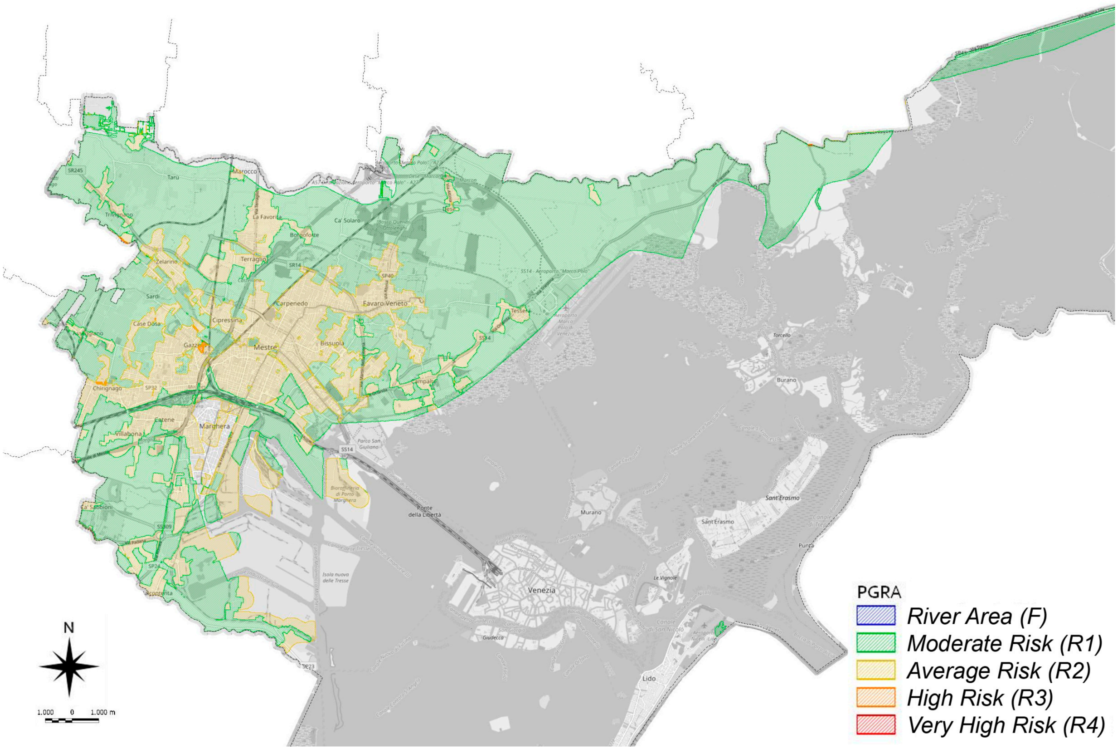

Figure 10. Excerpt from the PRGA (General Flood Risk Plan) of the inland part of the Municipality of Venice [164]. The map shows the risk of flooding related to the river based on 4 different probabilities, from R1 (moderate risk) to R4 (very high risk).

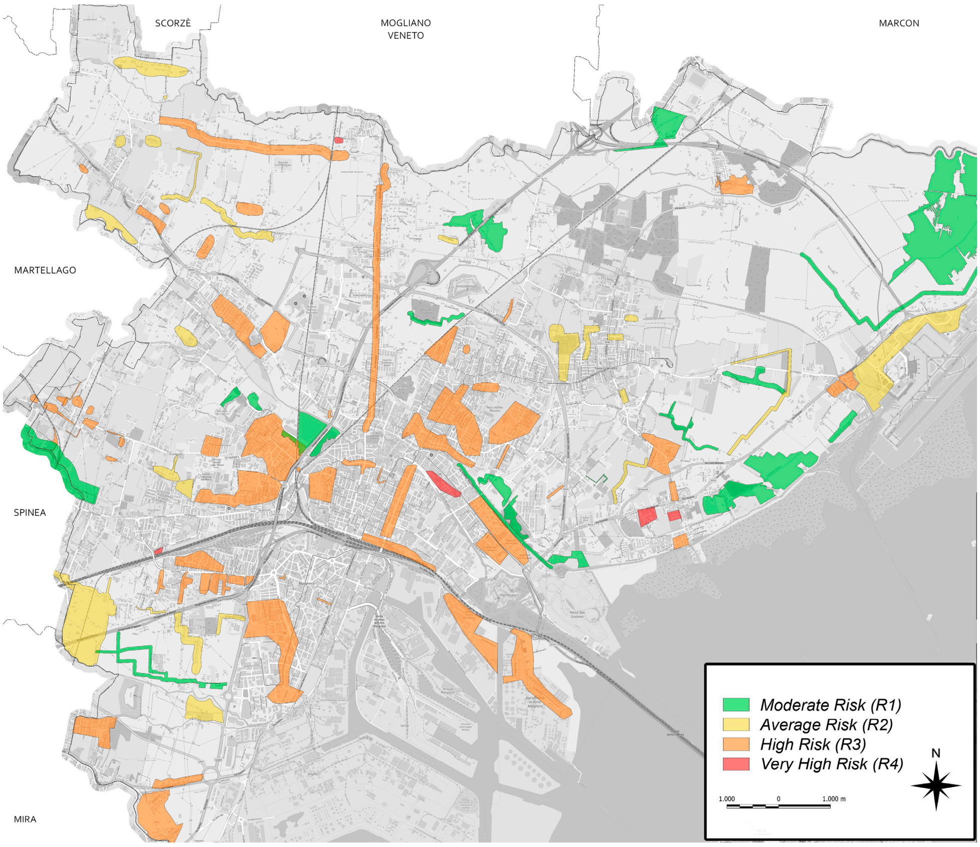

Figure 11. Excerpt from the PA (Flooding Plan) of the inland part of the Municipality of Venice [164]. The map shows the risk of flooding related to rain based on 4 different probabilities, from R1 (moderate risk) to R4 (very high risk).

It must also be considered that the plan concerns only the areas of coastland; the lagoon area is in any case subject to tidal phenomena and is excluded from these documents. The higher-risk areas are mainly distributed near the centre of Mestre and in the industrial zones. Of these areas, the greatest risk belongs to the banks of the river Dese, in the area from Tarù to the river mouth, located in the northern part of the municipal territory. The banks of the Marzengo River are considered at risk of subsidence and overflowing. The considerable extension of areas subject to high flood risk (R3) suggests the need to implement specific risk management strategies to mitigate the potentially significant impact on infrastructure, communities, and the urban environment. Currently, Venice has its own system for the management of flooding in the lagoon area [165], which can be a considered as component for a future DT system.

The fire risk potentially concerns all areas with greenery and the two pine forests in the Lido Island (Alberoni and Ca'Roman pine forests). As a general reference for risk assessment, the dataset offered by the service is taken as a reference Copernicus (Fraction of Green Vegetation Cover 2014-present) that quantifies the spatial extent of the vegetation based upon PROBA-V and Sentinel-3/OLCI data updated on 10 September 2024 (Figure 12) has been reported.

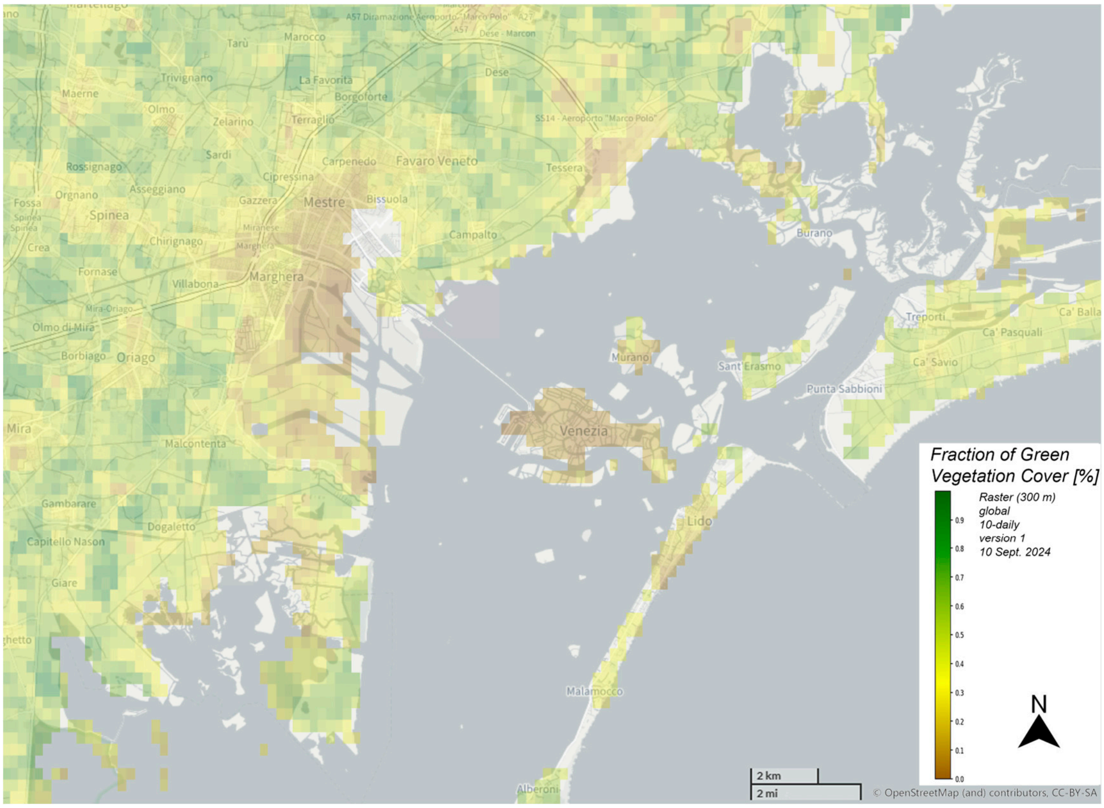

Figure 12. Fraction of green vegetation cover in percentage (generated using European Union's Copernicus Land Monitoring Service information). The image is based on satellite data calculated on 300 square meter pixels and ranges from zero (no vegetation) to 1 (completely covered by plants).

The risk of fires is reduced in the urbanised area due to low vegetative indices but increases in the neighbouring green areas and in the Lido area, where there are extensive green areas shows the displacement map from the SAR (Synthetic Aperture Radar) satellite data taken by the Copernicus European Ground Motion Service (dataset D23-095). The data show an average directional shift towards the southwest of 2 mm/year on the ascending node in the period from 2018 to 2024 (Figure 13). The measures demonstrate a low risk of landslides and subsidence; however, the presence of a service dedicated to the punctual and continuous analysis of the territory can provide an integrative measure for the protection of the city's cultural heritage.

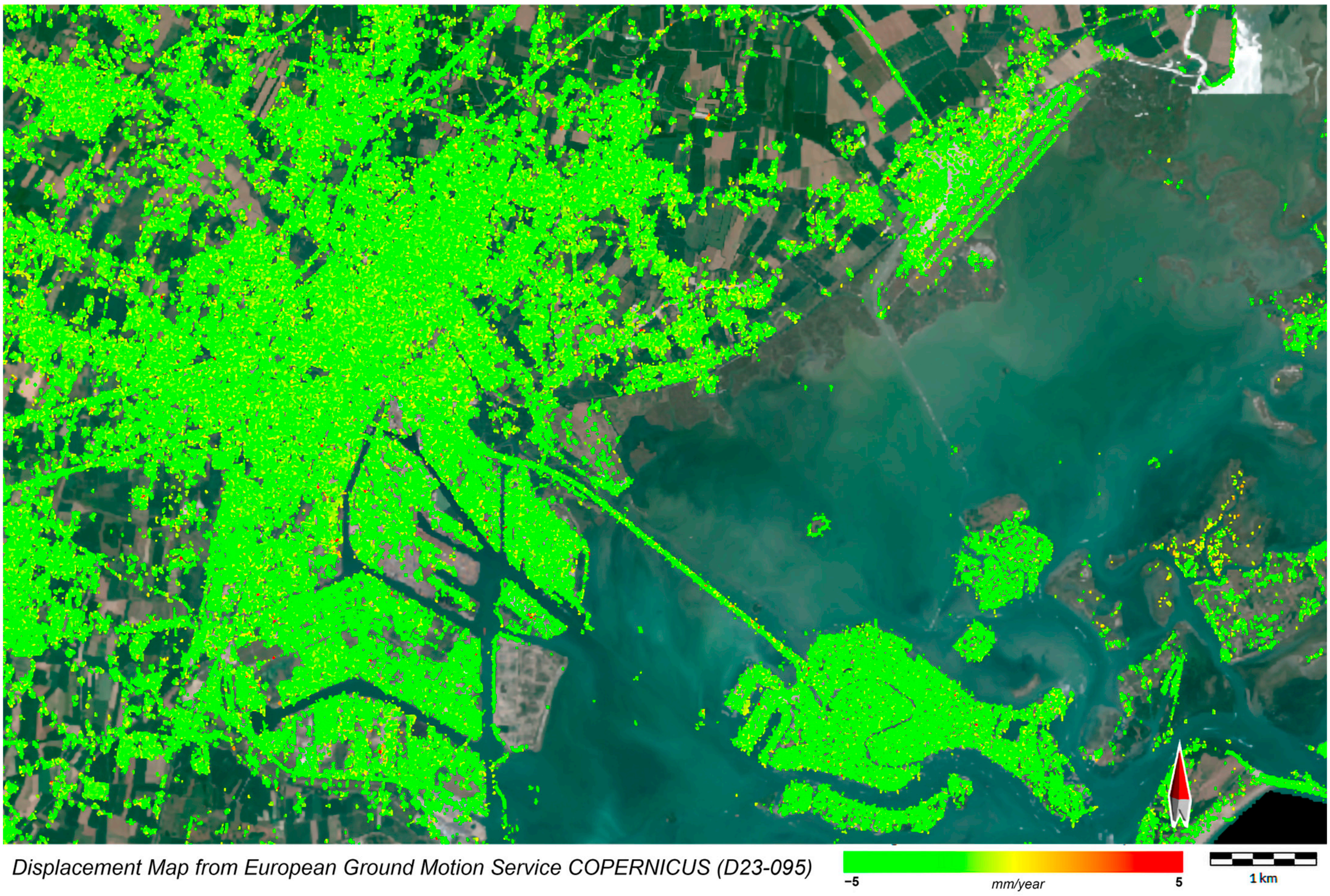

Figure 13. Displacement map from Copernicus satellite SAR data (generated using European Union's Copernicus Land Monitoring Service information).

The use of DT in combination with satellite data allows for the acquisition, processing, and analysis of multidimensional data in real time, facilitating the proactive management of hydrological dynamics, the assessment of the stability of structures, and the prevention of fires in green areas. Therefore, during DT development, it is also necessary to consider available datasets coming from other sources than the municipality as weather and air quality data. DT systems allow for real-time and predictive monitoring, supporting the safety of connected systems, and facilitating the proactive management of maintenance interventions. In addition, the integration of data from buildings, plants, and monitoring spread throughout the territory can contribute to the assessment of the state of maintenance and the management of phenomena, such as heatwaves and urban heat islands, collaborating in the transition to more sustainable energy sources, supporting the goal of achieving zero emissions by 2050 and improving the energy class of buildings by 2030. The main fields of intervention to promote urban resilience can be listed as follows:

- Monitoring of flooding and rainwater: The DT can be integrated with flooding data for critical infrastructures, concerning the mobility systems most subject to this type of scenario (underpasses), and all those systems subject to obstructions due to the presence of external agents (gratings, rainwater disposal wells, etc.). The management of these systems can be achieved through dedicated sensors supported by weather data and statistical analysis tools (last maintenance, adverse weather) to ensure the fulfilment of all maintenance operations and the correct operation of anti-flooding systems. This process can also integrate data from existing flow meters or through punctual analysis on nodes of interest (underpasses, underground areas, riverbanks, etc.) to ensure high precision and accuracy and display the status of the monitored systems, allowing operators to act in time through targeted interventions, thus reducing critical and dangerous situations, for example by closing a road before its flooding and giving travel alternatives to citizens. The presence of any flooding should be signalled to the operators through automatic alarms able to detect even potentially dangerous situations (i.e., excessive water on the road surface or high water levels on rivers). In addition, the wastewater collection tanks used for the disposal of water of meteoric origin should also be monitored. It is important to install, where necessary, digital road signs for vehicles (traffic lights), depending on the type of alarm and the level of danger. The monitoring data should be integrated centrally with Earth Observation data and transmitted by independent and high-reliability networks (GPRS or SatCom). Using satellites, it is possible to develop a "change detection" analysis capable of detecting the differences between two scans carried out at different times [166–168]. Given the presence of a flooding control system for the historic centre of Venice, these systems should be implemented for the entire area outside the lagoon and interfaced to get information on the water level in the lagoon [140,165,169].

- Fire risk analysis: Using satellite data and "change detection" techniques based on vegetative indices, it is possible to monitor the areas at risk of fire and the possible extension of fires [170–172]. In addition, it is possible to estimate the environmental damage on the territory in terms of area burned and ecosystemic damages. Using visible and hyperspectral bands, it is also possible to identify high-risk areas of fire, such as illegal landfills [173–175].
- Heatwaves and urban heat island: The use of satellite surveys for the evaluation of heatwaves is an advanced methodology that exploits the capabilities of satellites to detect and monitor thermal variations on the Earth's surface. This approach, in combination with medium–long range weather forecasts, provides a precise and detailed assessment of heatwaves, allowing for a timely and targeted response to mitigate the associated risks. The evaluation activities of the heatwaves are based on the processing of the time series of satellite images acquired during the period of interest [176–178]. The urban heat islands are areas subject to higher temperatures than the neighbouring territory due to specific local urban geometry and the building and ground pavement materials used. The raw satellite imagery is then processed to remove any artefacts, correct geometric distortions, and calibrate thermal data to obtain accurate measurements of surface temperatures. Using advanced thermal analysis and anomaly detection algorithms, these areas can be identified. The analysis is carried out by studying the historical average of local temperatures or using pre-established threshold limits. Areas with high temperatures can then be segmented into polygons to create a vector representation of these phenomena and provide the city manager with an accurate and detailed visualisation of the territory, allowing any urban planning interventions aimed at reducing their intensity or size [179–181].
- Urbanisation analysis: Comparing two satellite images with a change detection analysis, it is possible to identify the change in building geometry and identify anomalies by comparison with the land registry database [182–184]. The result is represented by a vector file composed of one or more polygons that shows every intervention made during the period between the images.
- Waste and pest control: Using satellite images and GIS data, it is possible to identify wastes [173–175], track its movements [109], control landfills, and identify illegal

dumps. Pest control can be made by dedicated sensors able to monitor traps and movement and analyse images to obtain information on the fauna present inside urban and agricultural areas. Using these data, specific intervention strategies can be adopted to reduce pest numbers.

- Urban green areas and agriculture: Vegetative index and weather data obtained from EO services can be combined with water data (rivers water levels, meteoric water basins, etc.) to provide information on actual crop status and to plan future interventions to increase water basins and quality, preserving food production and urban green areas also in case of extreme heat [185–187]. The risk is not only related to heat but also cold or hail. Therefore, the development of an automatic alert system can help farmers to save their crops allowing them to act in time. Data can be also obtained from local sensors or dedicated UAVs (unmanned aerial vehicles) [188–191].

5.4.2. Resiliency Services

The fields of intervention listed can be aggregated within a small number of services that can coexist and communicate with each other and with the other axes. These services can be applied to different applications dedicated to various stakeholders with different levels of access to data and interaction.

- Emergency monitoring and coordination service: Through Earth Observation data and meteorological IoT sensors distributed throughout the city, the service allows for the monitoring of weather, providing on-time alerts in case of potentially dangerous situations (fire, flooding, tornadoes, earthquakes, etc.). The data must be updated in real time in the event of extraordinary weather conditions, including intense thunderstorms, strong winds, heatwaves, drought, heavy snowfall, excessive pollutants, hail, and other severe events. The service must also integrate tide forecasting data to monitor the lagoon and surrounding rivers, air quality and noise data, data from ARPA Veneto, NOAA datasets on sea conditions, and any other relevant database. The service will allow citizens to be informed in advance about potential adverse events, giving the competent authorities the time to activate emergency plans as well as monitoring the real-time situation with high precision. Emergencies must be coordinated centrally to quicken response and recovery interventions and to not cause interferences between the various authorities. The service must provide a communication system to allow rapid dissemination of information and must be manned by a control room belonging to the service for civil protection. Using georeferenced data from the hydrogeological risk management service and from the services belonging to the mobility axis (traffic and parking service and road and channels management service), it will be possible to act with real-time information and to make consistent emergency plans based on real data and the road situation. Emergencies must also include extreme heat phenomena that represent a significant risk to public health and agriculture, serious road accidents, landslides, collapses, explosions, and all situations that require timely intervention.
- Infrastructures and land monitoring service: All maintenance interventions and the state of conservation must be planned within this service, which will have to consider separately the protected cultural heritage and the city’s strategic infrastructures. The separation is necessary to ensure the adoption of higher standards relating to data processing for all structures considered components of the World Heritage Sites or that may jeopardise the safety of citizens or the performance of production and services activities. The service must allow the development of what-if scenarios to analyse the impact (economic, social and mobility) due to the execution of the interventions [192]. Data can be acquired through IoT sensors placed on the territory (accelerometers,

Lidar, crack meters, etc.), from the energy axis (BACS service), have a historical origin (last maintenance), or be based on information from citizen reports. FEM models can be used for data analysis [193–195] or FDD [89,196–198] in the case of interventions on structures, or it is possible to use other models for the assessment of costs [199], downtime [200,201], environmental impact [202], life cycle [200,203], and all other parameters of interest by the competent authority. Using hydrological and rainfall data from monitoring stations distributed along watercourses, the lagoon, basins, and flood risk areas, the service will allow us to monitor the level of the rivers, the water flows and tidal movements. Data relating to water quality (pollutants, turbidity, etc.) and soil erosion can also be integrated into the service. It will make it possible to identify potential risk situations related to hydrogeological instability and will allow authorities to take preventive and mitigating actions before the occurrence of accidental events. The service must also consider the maintenance of public land, including gardens, parks, and uncultivated territories owned by the municipality, to ensure the absence of fire risk or the proliferation of pests.

- Urban planning: The service is intended to control the evolution of urban areas and land register discrepancies over time by a track change analysis performed using Earth Observation data. Moreover, using the same data, it will be possible to monitor the presence of unauthorised building interventions, the presence of illegal landfills, and the tracking of waste through the territory. The service must also allow the assessment of the effects due to fire scenarios and potential areas at risk and to draw safety perimeters for preventing any risks for the population. The service must include a toolkit to allow urban planning (districts, roads, gas pipelines, power lines, etc.) according to city expansion through what-if scenarios supported by AI. Finally, by monitoring and forecasting temperatures and climate patterns, the service can identify areas at high health risk due to the presence of heat islands and coordinate targeted interventions to mitigate their effects.

Figure 14 shows the component of the resiliency service reported in the previous list.

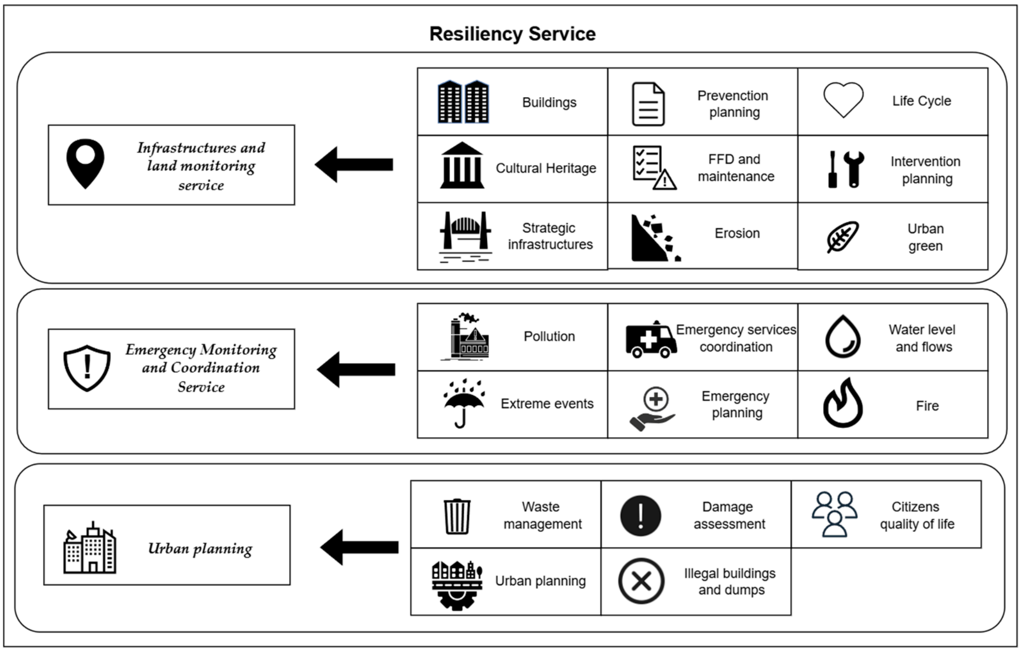

Figure 14. Resiliency service components.

5.4.3. Venice Open Data Analysis

Considering the Venice open data database, there are information pertaining to urban planning, civil protection, cultural heritage management, and urban pollution monitoring. Specifically, it includes datasets of companies participating in public works tenders, requests for urban maintenance interventions, concessions, construction site monitoring, authorisations granted, and statistical data, and georeferenced information on public land authorised use. Additionally, data supporting emergency management are included, such as archives for tracking hydraulic alarms and the recent emergency SMS service IT-Alert, the national public warning system for direct information to the population, which broadcasts useful messages to mobile phones in specific geographical areas in the event of imminent or ongoing serious emergencies or disasters. The IT-Alert message, once transmitted, is received by anyone who is in the area affected by the emergency and has a mobile phone switched on and connected to the telephone cells. The database also contains archival information related to UNESCO-protected cultural heritage through the initiative "#EnjoyRespectVenice", a campaign launched in 2017 to raise awareness for preserving the city's integrity and authenticity through sustainable tourism, while safeguarding residents' daily lives. This initiative was established in response to the challenges posed by overtourism [204–206]. These records provide valuable information for the protection and management of safeguarded assets. The database also includes data on human resources involved in risk prevention and the sustainable urban mobility plan, aimed at improving air quality. As for the other services, the data that can be integrated into the urban DT system are reported in Figure 15.

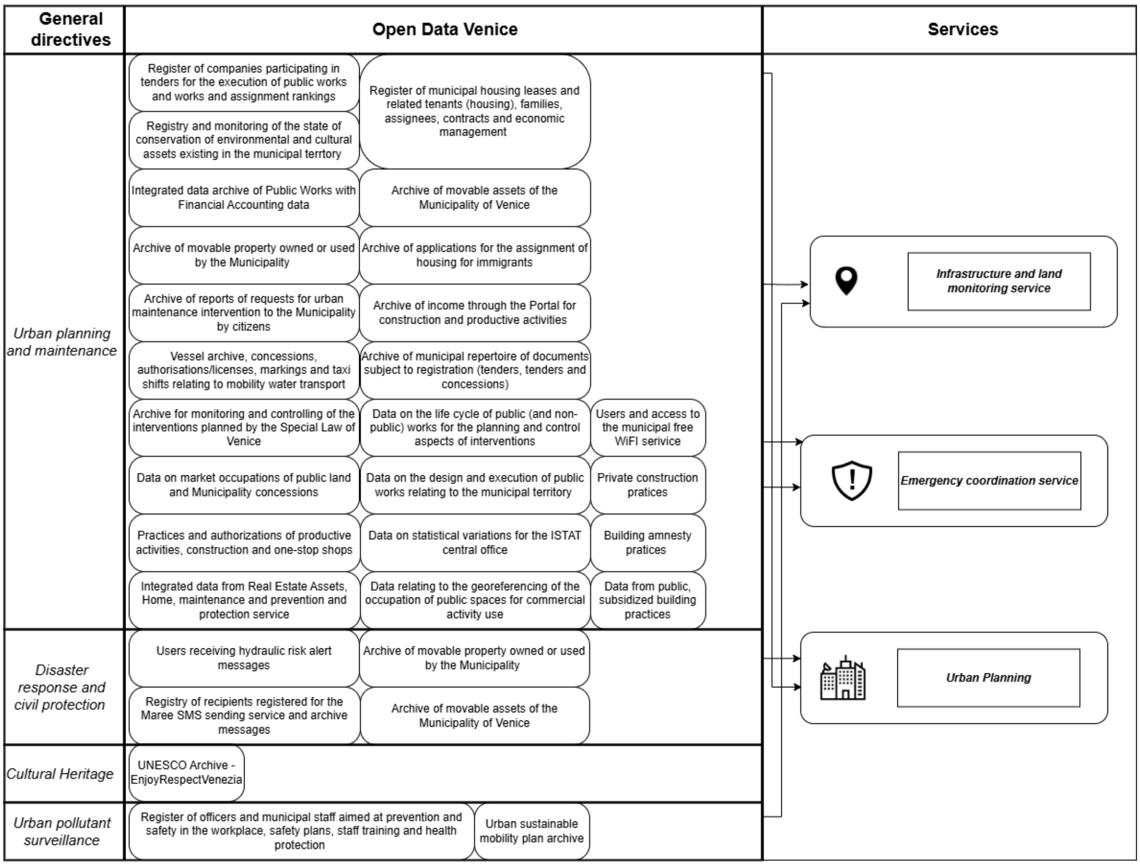

Figure 15. Venice open data analysis, related to general directives and linked by arrows with DT's services related to the resiliency axis.

5.4.4. Interaction Among Services, General Directives, and Fields of Intervention

As for the other axes, the interaction among general directives and fields of intervention has been performed and is reported in Table 5, where the letter "X" indicates an existing relationship.

Table 5. Relationship between general directives and fields of intervention for the resiliency axis.

		General Directives			
		Protection from Natural Disasters and Extreme Events	Monitoring of Built Environment Resilience	Preservation of Cultural Heritage and Strategic Infrastructure:	Anthropic Impact and Urbanisation
N.	**Fields of Intervention**				
1	Monitoring of flooding and rainwater	X		X	X
2	Fire risk analysis	X		X	X
4	Heatwaves and heat island				X
5	Urbanisation analysis	X	X	X	X
6	Waste and pest control				X
7	Urban green and agriculture	X			X

The Interaction among the proposed services and the directives is expressed in Table 6.

Table 6. Interaction among directives and proposed services for the resiliency axis.

General Directives	Services
Protection from natural disasters and extreme events	Emergency monitoring and coordination service Infrastructures and land monitoring service
Monitoring of built environment resilience	Infrastructures and land monitoring service
Preservation of cultural heritage and strategic infrastructure:	Infrastructures and land monitoring service Urban planning
Anthropic impact and urbanisation	Infrastructures and land monitoring service Urban planning

6. Discussion

Developing a DT for a fragile city such as Venice is not a simple task and requires many services to address the high number of urban needs. Moreover, looking at the actual state of the Venice open data database, it is evident that it needs improvements with real-time urban data to feed the DT platform. Applying the framework presented in this study to the database showed the following limitations that must be acknowledged to contextualise the results and outline directions to develop a future urban DT.

6.1. Improvements Related to the Mobility Axis

Regarding the mobility data analysis, the list below evidences possible data sources to be added to the Venice open data database to create a DT that is compliant with the general directives:

- Service Management: the number of individual free and occupied stalls in specific areas of interest, analysis of permanence time and stops on monitored roads and waterways, forecast and real-time data of availability of parking spaces, accidents, disservice time, and smart traffic light location.
- Travel: data relating to sensors location, measurements, and forecast (IAQ, noise, smart lights' location, crowding, public transport usage, parking availability, etc.).
- Reduction in fossil fuels and traffic in public and private transport: traffic analysis data on primary and secondary roads, travel times, carbon footprint due to public and private mobility, average speed on roads, location, and use of EV charging stations.
- Energy optimisation of on-road system: the monitoring of energy consumed for street and waterways, lighting and other devices, and the evaluation of energy consumption on a daily/monthly/annual basis.

6.2. Improvements Related to the Energy Axis

Energy data can be improved with future-proof capabilities, such as information regarding the monitoring of hydrogen storage, production, and consumption, an energetic vector considered a key for future global development and the ecological transition. Additionally, the data currently monitored are not updated in real time. Moreover, properly managing energy loads to meet renewable production and storage is a key factor for ensuring a proper energy balance and optimizing load scheduling. Another critical issue regards the absence of data related to the availability of renewable energy sources and the lack of citizen and local communities' involvement in promoting sustainable behaviours, which is essential for establishing renewable energy communities (RECs).

Considering the fields of interventions and the general directives, Venice open data can take advantage of new data tables related to:

- Reduction in fossil fuels: Energy produced by renewable energy systems (RESs) encompasses the number of installations, types of systems in place, and the energy generated on a daily, monthly, and annual basis. To support the reduction in fossil fuels, it is essential to monitor both average and peak power output over these periods, alongside tracking revenues from energy sales. Additionally, assessing the operational status and geographical location of each installation provides critical insights. Incorporating data on energy storage and the equivalent amount of CO_2 saved further enhances the evaluation process. These comprehensive metrics enable an accurate assessment of how RESs contribute to lowering fossil fuel consumption, highlighting their relevance and positioning within the energy landscape.
- Reduction in electricity consumption: Energy consumption by buildings and facilities involves the detailed tracking of energy used on a daily, monthly, and annual basis, encompassing specific systems, such as air conditioning and indoor lighting. To effectively reduce electricity usage, it is essential to monitor both instantaneous peak power and average power across these timeframes, along with associated energy costs. Additionally, collecting data on the operational status, the purpose of each building, and their locations is necessary to identify areas with significant consumption and determine where energy efficiency measures should be applied. Monitoring the percentage of energy sourced from renewable energy systems (RES) and calculating the equivalent amount of CO_2 produced further enhances the understanding of overall energy performance. By integrating these comprehensive metrics, organisations can accurately assess energy usage patterns, identify high-consumption areas, and implement targeted strategies to minimise consumption and improve overall energy efficiency.

- Preventive and predictive maintenance: Gathering comprehensive data on energy efficiency improvements is essential for enhancing overall efficiency. This includes details about the positioning of new sensors and systems installed for activities such as lighting and air conditioning, as well as information on the target areas, cost, timeline, and location of these installations. Additionally, tracking the initial and final energy ratings of the facilities or systems involved allows for continuous monitoring of the long-term benefits of energy saving measures. Monitoring the connected system status, the date of the last maintenance, and the operational condition of these systems facilitate effective planning for future predictive maintenance. By integrating these elements, organisations can effectively evaluate the impact of energy efficiency initiatives, ensure sustained benefits, and optimise the performance of their energy-saving strategies.
- Smart planning of intervention: Energy efficiency interventions encompass various types, such as maintenance, efficiency upgrades, and restoration, each associated with specific costs, timelines, and locations. Detailed information on these interventions includes the starting and final energy classes of the facilities or systems involved, as well as the power installed by renewable energy systems (RES). Monitoring local energy consumption, particularly within renewable energy communities (RECs), is crucial for coordinating energy production and usage. This involves collecting data on energy fed into and drawn from the grid, enabling the optimisation of renewable resource utilisation and contributing to the reduction in overall energy impact. By integrating data on energy efficiency measures with insights from local energy consumption patterns, organisations can effectively plan and implement interventions that enhance energy performance, optimise RES deployment, and achieve sustained energy savings within their communities.
- Energy management system: monitoring of the energy consumed on a local (district/community) level and consequent estimation of the energy injected, stored, and subtracted from the grid.
- Hydrogen system: Including comprehensive information about the monitored installations is fundamental for effective oversight. This encompasses details on the production and storage of hydrogen from renewable energy systems (RES), as well as the placement of new sensors and systems, such as lighting and air conditioning controls. Currently, data on hydrogen production amounts and storage capacities are essential, and future monitoring will extend to hydrogen flows within gas ducts. By integrating information on the positioning and operation of these new sensors and systems with hydrogen-related metrics, organisations can ensure efficient management and optimisation of their energy infrastructure. These elements are vital to enhance renewable resource utilisation, support the expansion of hydrogen infrastructure, and maintain the robust oversight of all energy systems.

6.3. Improvements Related to the Resiliency Axis

Lastly, the DB analysis about resiliency has revealed the lack of some fundamental data for the creation of DT services oriented to urban resiliency. As before, below is a list of possible data to be integrated related to the general directives:

- Urban planning and maintenance: implement a dynamic information system for construction sites, land use, and maintenance using extensive sensor networks that monitor infrastructure, traffic, and city activities; integrate real-time and historical data for predictive simulations to assess the impacts of urban expansion or new constructions; develop a 3D parametric model of buildings, streets, and public properties to enhance planning and visualisation, linking data with the city's physical representation.

- Disaster response and civil protection: enhance data analysis with real-time information on critical conditions to enable effective crisis scenario simulations; establish an instant feedback mechanism for emergency data to ensure timely and efficient responses.
- Cultural heritage: upgrade Venice's open data portal with a real-time database by combining sensor data on building facades (monitoring humidity, movement, integrity, and geometry) with satellite data to reduce errors; create a 3D parametric interactive model of historic buildings to facilitate restoration simulations and prevent damage.
- Urban pollutant surveillance: develop a dynamic mapping system for pollutant sources and correlate pollutant levels with health indicators; utilise a Digital Twin (DT) system to analyse the interactions between climate change, pollution, and public health and propose mitigation actions through simulations.

DT is a key component for the digital and environmental transition and the future development of smart cities. It represents a tool that is expected to be adopted in many cities due to its versatility in terms of planning and management, fulfilling the conceptual structure reported in the smart city diamond [40]. However, without proper optimisation and database architecture, any DT system risks become ineffective because of the lack of data. According to the case study of Venice, its open, public database needs many improvements before it can be effectively used. Specifically, the following elements should be introduced in the form of new data tables: IoT sensor data in real-time aggregated historical analytics and metrics, bidirectional communication interfaces with an API (application protocol interface) to BACS (building automation and control systems), Earth Observation services, and to utility services, forecasting data generated by predictive algorithms to enhance monitoring and responsiveness to extreme events.

The current gaps in the database, as highlighted in the analysis, may significantly hinder the effectiveness of the proposed Digital Twin framework. The absence of real-time data has a severe effect on the capability of analysing traffic, parking availability, and energy consumption, reducing the system's ability to provide accurate forecasts and resource management. Similarly, the lack of comprehensive data on hydrogen production, storage, and integration with renewable energy sources limits progress towards achieving energy sustainability goals. In terms of resiliency, missing information on urban flooding risks, fire hazard mapping, and environmental monitoring constrains the system's capacity for timely and effective disaster response.

Such improvement would represent a significant technological innovation, driving the smarter management of the city. However, considering the huge amount of data that can be daily uploaded to the database, it is fundamental to consider a scalable approach using Big Data technologies to maintain the database responsive also under heavy loads.

As an example, this would be carried out by migrating the database from the current type of structured query language (SQL) to another, more suitable for IoT data, such as NOSQL [134,135] or time-series [136,137], and considering the use of most innovative technologies, such as Kubernetes. Transparent management developed using as a single connection point from an open database would help in coordinating urban efficiency interventions, while engaging stakeholders and citizens through renewable energy communities (RECs), thus promoting community-led and sustainable energy management. Comparable benefits would be acquired in terms of urban mobility, where citizens can access real-time data about traffic, parking lot availability, electrical charging station locations, and information on expected road intervention. Moreover, the open data can also be used to coordinate emergency services and infrastructure management to ensure timely and effective responses to crises. Considering the smart city diamond, this would fit the citizen and governance dimensions, advancing sustainable urban management.

Data and databases are an integral part of any digitisation process, and the use of pre-existing infrastructures can reduce the costs and the time required to develop DT systems. Through communication among databases, it is possible to converge all public data collected and processed for daily use within a single container, making them available not only to public administrations but also to other digital systems at the service of the city and even individual citizens willing to be informed about city management [145–150]. To date, there is no DT for the city of Venice, and the present study stands as a preliminarily conceptual proposal for its future realisation.

7. Conclusions

Applying DT technology to a culturally and naturally invaluable context such as the city of Venice and its Lagoon represents a formidable yet extremely promising challenge. Historic cities are globally recognised as vulnerable and threatened by the effects of climate change, both long-term and through sudden extreme events. Beyond external risks, the natural obsolescence of architectural structures and the devastating impact of mass tourism add further challenges to any historical city administration.

This study proposes a methodology to examine the complex challenges associated with implementing DT systems using the city of Venice as a case study. Starting from an analysis of existing DT applications for urban and building management, a list of general directives inspired by the United Nations' Sustainable Development Goals, the smart city diamond model, and the state-of-the-art DT systems at the urban scale has been defined. Then, a general framework was defined, consolidating the features into three main axes: energy, mobility, and resilience. Only three axes were chosen to avoid excessive complexity for a future management system, which would result in several difficulties in developing the service and in its management by the public administrations. The outlined general directives define the scope and main challenges of each axis. By organizing and aggregating the fields of intervention into services, it is then possible to define the task that the urban DT twin must perform. Finally, the Venice open data database has been analysed to identify already available data and to outline what data should be added to increase its usability by citizens and public administrations. As a result, a concrete approach for DT development has been outlined and applied for the sustainable urban management of the city of Venice. Moreover, the analysis of Venice open data has revealed a significant need for improvements, to provide citizens, governance, and stakeholders with more detailed and useful information on the current state of the city. To develop DT systems for future cities, it will be important to consider what data are already available, what services shall be developed without compromising the overall effectiveness of such systems, and the specificity of the city under analysis. The case study of Venice was chosen due to its fragility and complexity, related to its double extension (both on water and land) and for the presence of inestimable cultural heritage.

Regardless of the complexity inherent to digitalisation processes, as for DT development, some actions are currently undertaken by the city of Venice. As an example, a collaborative initiative, supported by the City of Venice, the VSF Foundation, and various local stakeholders including IUAV University of Venice, has put forward the transformative proposal to reconfigure Venice as a "campus city" [207]. This collective effort is documented in the Memorandum of Understanding for the city of Venice signed by the municipality and the main stakeholders, implying a major stride toward a demographic revitalisation of Venice. This new idea for Venice aims to transform the city into a living laboratory for urban sustainability policies, potentially serving as a model for similar historic cities worldwide (Venice World Sustainability Capital). The importance of such a goal was also underlined by the rector of the IUAV University of Venice in the university's strategic plan for 2023–2027 [208].

Redesigning the future of Venice as a "campus city", in which demographic revitalisation goes hand in hand with the strengthening of academic hospitality, would probably contribute to the revitalisation of the city and, at the same time, make Venice a living laboratory of urban sustainability policies to be exported as a model everywhere in the world [209].

In the future, the research will be oriented on the study of the best strategies for applying DT not just for urban planning and management but also for understanding their complex ethical and social implications, enhancing the human quality of life as outlined by the fifth industrial revolution. In this framework, artificial intelligence, while a powerful tool for data management within an urban DT, must be handled properly, considering that technology, however effective, remains a support for strategic decisions, which should always remain a prerogative of human decision makers.

This study proposes a comprehensive methodology for implementing a DT in Venice, detailing the necessary context and references and highlighting the critical role of digital technologies in enhancing urban sustainability and resilience. We hope this study can serve as a tool for initiatives like those of the VSF Foundation, contributing to the overall revitalisation strategy of Venice and offering a replicable model for other historic cities facing similar challenges.

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References

1. Ashton, K. That Internet of Things Thing. *RFID J.* **2009**, *22*, 97–114.
2. Bai, C.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 Technologies Assessment: A Sustainability Perspective. *Int. J. Prod. Econ.* **2020**, *229*, 107776. [CrossRef]
3. Sezgin, S. The Third Industrial Revolution: How Lateral Power Is Transforming Energy, the Economy, and the World. *Turk. J. Bus. Ethics* **2018**, *11*, 50–52. [CrossRef]
4. Schwab, K. *The Fourth Industrial Revolution, by Klaus Schwab | World Economic Forum*; World Economic Forum: Cologny, Switzerland, 2017.
5. Grabowska, S.; Saniuk, S.; Gajdzik, B. Industry 5.0: Improving Humanization and Sustainability of Industry 4.0. *Scientometrics* **2022**, *127*, 3117–3144. [CrossRef]

6. European Commission. *Communication from the Commission Establishing Union-Level Projected Trajectories for the Digital Targets*; European Commission: Brusselsg, Belgium, 2023.
7. Presidenza del Consiglio dei Ministri Piano Nazionale Di Ripresa e Resilienza. Piano Nazionale Di Ripresa E Resilienza 2021. Available online: https://www.italiadomani.gov.it/content/dam/sogei-ng/documenti/PNRR%20Aggiornato.pdf (accessed on 29 December 2024).
8. Verschuur, J.; Koks, E.E.; Hall, J.W. Global Economic Impacts of COVID-19 Lockdown Measures Stand out in Highfrequency Shipping Data. *PLoS ONE* **2021**, *16*, e0248818. [CrossRef]
9. Vet, J.M.D.E.; Nigohosyan, D.; Ferrer, J.N.; Gross, A.-K.; Kuehl, S.; Flickenschild, M. *Impacts of the COVID-19 Pandemic on EU Industries*; Policy Department for Economic, Scientific and Quality of Life Policies, European Parliament: Strasbourg, France, 2021.
10. Zamfir, I.C.; Iordache, A.M.M. The Influences of Covid-19 Pandemic on Macroeconomic Indexes for European Countries. *Appl. Econ.* **2022**, *54*, 4519–4531. [CrossRef]
11. Cinquepalmi, F. *Towards (R)Evolving Cities Urban Fragilities and Prospects in the 21st Century, the Challenge of Pandemics in Urban Societies*, 1st ed.; Diapress: Florence, Italy, 2021; Volume 1, ISBN 978-88-3338-137-4.
12. Baldwin, R.; Weder, B. *Economics in the Time of COVID-19*; CEPR Press: Washington, DC, USA, 2020.
13. Grieves, M.W. Digital twins: Past, present, and future. In *The Digital Twin*; Crespi, N., Drobot, A.T., Minerva, R., Eds.; Springer: Cham, Switzerland, 2023; pp. 97–121. [CrossRef]
14. Mateev, M. Industry 4.0 and the Digital Twin For Building Industry. *Int. Sci. J. Ind. 4.0* **2020**, *5*, 29–32.
15. Ikudayisi, A.E.; Chan, A.P.C.; Darko, A.; Adedeji, Y.M.D. Integrated Practices in the Architecture, Engineering, and Construction Industry: Current Scope and Pathway towards Industry 5.0. *J. Build. Eng.* **2023**, *73*, 106788. [CrossRef]
16. Yitmen, I. *Cognitive Digital Twins for Smart Lifecycle Management of Built Environment and Infrastructure Challenges, Opportunities and Practices*; CRC Press: Boca Raton, FL, USA, 2023.
17. Cinquepalmi, F.; Piras, G. Earth Observation Technologies for Mitigating Urban Climate Changes. In *Urban Book Series*; Springer International Publishing: Cham, Switzerland, 2023; Volume Part F813.
18. Bourdeau, M.; Zhai, X.q.; Nefzaoui, E.; Guo, X.; Chatellier, P. Modeling and Forecasting Building Energy Consumption: A Review of Data-Driven Techniques. *Sustain. Cities Soc.* **2019**, *48*, 101533. [CrossRef]
19. Teng, S.Y.; Touš, M.; Leong, W.D.; How, B.S.; Lam, H.L.; Máša, V. Recent Advances on Industrial Data-Driven Energy Savings: Digital Twins and Infrastructures. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110208. [CrossRef]
20. Zhang, J.; Tai, Y. Secure Medical Digital Twin via Human-Centric Interaction and Cyber Vulnerability Resilience. *Conn. Sci.* **2022**, *34*, 895–910. [CrossRef]
21. Saad, A.; Faddel, S.; Mohammed, O. IoT-Based Digital Twin for Energy Cyber-Physical Systems: Design and Implementation. *Energies* **2020**, *13*, 4762. [CrossRef]
22. Wang, X.; Yang, J.; Wang, Y.; Miao, Q.; Wang, F.Y.; Zhao, A.; Deng, J.L.; Li, L.; Na, X.; Vlacic, L. Steps Toward Industry 5.0: Building "6S" Parallel Industries with Cyber-Physical-Social Intelligence. *IEEE/CAA J. Autom. Sin.* **2023**, *10*, 1692–1703. [CrossRef]
23. Li, H.; Yu, L.; He, W. The Impact of GDPR on Global Technology Development. *J. Glob. Inf. Technol. Manag.* **2019**, *22*, 1–6. [CrossRef]
24. Hassani, H.; Huang, X.; MacFeely, S. Enabling Digital Twins to Support the UN SDGs. *Big Data Cogn. Comput.* **2022**, *6*, 115. [CrossRef]
25. Sun, M.; Han, C.; Nie, Q.; Xu, J.; Zhang, F.; Zhao, Q. Understanding Building Energy Efficiency with Administrative and Emerging Urban Big Data by Deep Learning in Glasgow. *Energy Build.* **2022**, *273*, 112331. [CrossRef]
26. Bauer, M.; Cirillo, F.; Fürst, J.; Solmaz, G.; Kovacs, E. Urban Digital Twins-A FIWARE-Based Model. *At-Automatisierungstechnik* **2021**, *69*, 1106–1115. [CrossRef]
27. Kartakoullis, A.; Slamnik-Kriještorac, N.; Carlan, V.; Vulpe, A.; Suciu, G.; Iordache, M.; Brenes, J.; Landi, G.; Trichias, K. VITAL-5G: A Novel 5G-Enabled Platform for Vertical Innovations in Transport and Logistics. In Proceedings of the Transportation Research Procedia, Lisboa, Portugal, 14–17 November 2023; Volume 72.
28. Meyer, C.; Gerlitz, L.; Prause, G. Small and Medium-Sized Port Greening Initiatives as Trigger for a Servitisation Port Ecosystem. *Environ. Clim. Technol.* **2023**, *27*, 476–488. [CrossRef]
29. Alshammari, K.; Beach, T.; Rezgui, Y. Cybersecurity for Digital Twins in the Built Environment: Current Research and Future Directions. *J. Inf. Technol. Constr.* **2021**, *26*, 159–173. [CrossRef]
30. Loss, S.; Singh, H.P.; Cacho, N.; Lopes, F. Using FIWARE and Blockchain in Smart Cities Solutions. *Clust. Comput.* **2023**, *26*, 2115–2128. [CrossRef]
31. Maragno, D.; Dall'omo, C.F.; Pozzer, G.; Musco, F. Multi-Risk Climate Mapping for the Adaptation of the Venice Metropolitan Area. *Sustainability* **2021**, *13*, 1334. [CrossRef]
32. Linkov, I.; Fox-Lent, C.; Keisler, J.; Sala, S.D.; Sieweke, J. Risk and Resilience Lessons from Venice. *Environ. Syst. Decis.* **2014**, *34*, 378–382. [CrossRef]

33. Schlumberger, J.; Ferrarin, C.; Jonkman, S.N.; Diaz Loaiza, M.A.; Antonini, A.; Fatorić, S. Developing a Framework for the Assessment of Current and Future Flood Risk in Venice, Italy. *Nat. Hazards Earth Syst. Sci.* **2022**, *22*, 2381–2400. [CrossRef]
34. Fondazione Gianni Pellicani. *Ri-Pensare Venezia: Primo Focus*, 1st ed.; Fondazione Gianni Pellicani: Venice, Italy, 2023; Volume 1.
35. Tomczyk, M.; van der Valk, H. Digital Twin Paradigm Shift: The Journey of the Digital Twin Definition. In Proceedings of the International Conference on Enterprise Information Systems, ICEIS-Proceedings, Virtual, 25–27 April 2022; Volume 2.
36. VanDerHorn, E.; Mahadevan, S. Digital Twin: Generalization, Characterization and Implementation. *Decis. Support. Syst.* **2021**, *145*, 113524. [CrossRef]
37. Guibaud, A.; Mindeguia, J.C.; Albuerne, A.; Parent, T.; Torero, J. Notre-Dame de Paris as a Validation Case to Improve Fire Safety Modelling in Historic Buildings. *J. Cult. Herit.* **2023**, *65*, 145–154. [CrossRef]
38. Gros, A.; Guillem, A.; De Luca, L.; Baillieul, É.; Duvocelle, B.; Malavergne, O.; Leroux, L.; Zimmer, T. Faceting the Post-Disaster Built Heritage Reconstruction Process within the Digital Twin Framework for Notre-Dame de Paris. *Sci. Rep.* **2023**, *13*, 5981. [CrossRef] [PubMed]
39. Cinquepalmi, F.; Cumo, F. Using digital twin models (dtm) for managing, protecting and restoring historical buildings. *Conserv. Sci. Cult. Herit.* **2022**, *22*, 425–445. [CrossRef]
40. Laurini, R. Towards Smart Urban Planning through Knowledge Infrastructure. In Proceedings of the Ninth International Conference on Advanced Geographic Information Systems, Applications, and Services, Nice, France, 19–23 March 2017.
41. Sampedro, R. The Sustainable Development Goals (SDG). *Carreteras* **2021**, *4*, 9. [CrossRef]
42. Zhang, X.; Shen, J.; Saini, P.K.; Lovati, M.; Han, M.; Huang, P.; Huang, Z. Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications. *Front. Sustain. Cities* **2021**, *3*, 663269. [CrossRef]
43. *IEA Global Status Report for Buildings and Construction 2019—Analysis*; IEA: Paris, France, 2019.
44. Simonsson, J.; Atta, K.T.; Schweiger, G.; Birk, W. Experiences from City-Scale Simulation of Thermal Grids. *Resources* **2021**, *10*, 10. [CrossRef]
45. Zheng, X.; Shi, Z.; Wang, Y.; Zhang, H.; Tang, Z. Digital Twin Modeling for District Heating Network Based on Hydraulic Resistance Identification and Heat Load Prediction. *Energy* **2024**, *288*, 129726. [CrossRef]
46. Casella, E.; Khamesi, A.R.; Silvestri, S.; Baker, D.A.; Das, S.K. HVAC Power Conservation through Reverse Auctions and Machine Learning. In Proceedings of the 2022 IEEE International Conference on Pervasive Computing and Communications, PerCom 2022, Pisa, Italy, 21–25 March 2022.
47. Wang, M.; Wang, Z.; Geng, Y.; Lin, B. Interpreting the Neural Network Model for HVAC System Energy Data Mining. *Build. Environ.* **2022**, *209*, 108449. [CrossRef]
48. Pang, Z.; O'Neill, Z.; Chen, Y.; Zhang, J.; Cheng, H.; Dong, B. Adopting Occupancy-Based HVAC Controls in Commercial Building Energy Codes: Analysis of Cost-Effectiveness and Decarbonization Potential. *Appl. Energy* **2023**, *349*, 121594. [CrossRef]
49. Nikdel, L.; Janoyan, K.; Bird, S.D.; Powers, S.E. Multiple Perspectives of the Value of Occupancy-Based HVAC Control Systems. *Build. Environ.* **2018**, *129*, 15–25. [CrossRef]
50. Jiang, Y.; Shen, X. Construction and Application of Digital Twin in Hydrogen Production System of Alkaline Water Electrolyzer. *Gaodianya Jishu/High Volt. Eng.* **2022**, *48*, 1673–1683. [CrossRef]
51. Topping, D.; Bannan, T.J.; Coe, H.; Evans, J.; Jay, C.; Murabito, E.; Robinson, N. Digital Twins of Urban Air Quality: Opportunities and Challenges. *Front. Sustain. Cities* **2021**, *3*, 786563. [CrossRef]
52. Ariansyah, D.; Isnan, M.; Rahutomo, R.; Pardamean, B. Digital Twin (DT) Smart City for Air Quality Management. *Procedia Comput. Sci.* **2023**, *227*, 524–533. [CrossRef]
53. Yang, S.; Kim, S.; Sungah, K. BIM-Based Design Automation Tool and Digital Twin Interoperability-Case of the Next Generation Noise Barrier Tunnel. *KIBIM Mag.* **2021**, *11*, 31–41.
54. Miller, C. What's in the Box?! Towards Explainable Machine Learning Applied to Non-Residential Building Smart Meter Classification. *Energy Build.* **2019**, *199*, 523–536. [CrossRef]
55. Lv, Z.; Gander, A.J.; Lv, H. Digital Twins of Sustainable City. In *Encyclopedia of Sustainable Technologies*; Elsevier: Amsterdam, The Netherlands, 2024.
56. Barcik, P.; Coufalikova, A.; Frantis, P.; Vavra, J. The Future Possibilities and Security Challenges of City Digitalization. *Smart Cities* **2023**, *6*, 137–155. [CrossRef]
57. Piper, W.; Sun, H.; Jiang, J. Digital Twins for Smart Cities: Case Study and Visualisation via Mixed Reality. In Proceedings of the IEEE Vehicular Technology Conference, Beijing, China; London, UK, 26–29 September 2022; Volume 2022.
58. Ramos, H.M.; Kuriqi, A.; Besharat, M.; Creaco, E.; Tasca, E.; Coronado-Hernández, O.E.; Pienika, R.; Iglesias-Rey, P. Smart Water Grids and Digital Twin for the Management of System Efficiency in Water Distribution Networks. *Water* **2023**, *15*, 1129. [CrossRef]
59. Wei, Y.; Law, A.W.K.; Yang, C. Real-Time Data-Processing Framework with Model Updating for Digital Twins of Water Treatment Facilities. *Water* **2022**, *14*, 3591. [CrossRef]
60. Sheng, D.; Lou, Y.; Sun, F.; Xie, J.; Yu, Y. Reengineering and Its Reliability: An Analysis of Water Projects and Watershed Management under a Digital Twin Scheme in China. *Water* **2023**, *15*, 3203. [CrossRef]

61. Cesco, S.; Sambo, P.; Borin, M.; Basso, B.; Orzes, G.; Mazzetto, F. Smart Agriculture and Digital Twins: Applications and Challenges in a Vision of Sustainability. *Eur. J. Agron.* **2023**, *146*, 126809. [CrossRef]
62. Ramos, H.M.; Morani, M.C.; Carravetta, A.; Fecarrotta, O.; Adeyeye, K.; López-Jiménez, P.A.; Pérez-Sánchez, M. New Challenges towards Smart Systems' Efficiency by Digital Twin in Water Distribution Networks. *Water* **2022**, *14*, 1304. [CrossRef]
63. Girotto, C.D.; Piadeh, F.; Bkhtiari, V.; Behzadian, K.; Chen, A.S.; Campos, L.C.; Zolgharni, M. A Critical Review of Digital Technology Innovations for Early Warning of Water-Related Disease Outbreaks Associated with Climatic Hazards. *Int. J. Disaster Risk Reduct.* **2024**, *100*, 104151. [CrossRef]
64. Loos, R.; Gawlik, B.M.; Locoro, G.; Rimaviciute, E.; Contini, S.; Bidoglio, G. EU-Wide Survey of Polar Organic Persistent Pollutants in European River Waters. *Environ. Pollut.* **2009**, *157*, 561–568. [CrossRef] [PubMed]
65. Semyachkov, A.I.; Semyachkov, K. Al Digital Model of Groundwater Technogenesis as an Element of Sustainable Development of the Urban Environment. *Sustain. Dev. Mt. Territ.* **2022**, *14*, 362–369. [CrossRef]
66. Zhao, D.; Li, X.; Wang, X.; Shen, X.; Gao, W. Applying Digital Twins to Research the Relationship Between Urban Expansion and Vegetation Coverage: A Case Study of Natural Preserve. *Front. Plant Sci.* **2022**, *13*, 840471. [CrossRef] [PubMed]
67. Peladarinos, N.; Piromalis, D.; Cheimaras, V.; Tserepas, E.; Munteanu, R.A.; Papageorgas, P. Enhancing Smart Agriculture by Implementing Digital Twins: A Comprehensive Review. *Sensors* **2023**, *23*, 7128. [CrossRef] [PubMed]
68. Ariesen-Verschuur, N.; Verdouw, C.; Tekinerdogan, B. Digital Twins in Greenhouse Horticulture: A Review. *Comput. Electron. Agric.* **2022**, *199*, 107183. [CrossRef]
69. Laufs, J.; Borrion, H.; Bradford, B. Security and the Smart City: A Systematic Review. *Sustain. Cities Soc.* **2020**, *55*, 102023. [CrossRef]
70. Murthy Pedapudi, S.; Vadlamani, N. A Comprehensive Network Security Management in Virtual Private Network Environment. In Proceedings of the Proceedings-International Conference on Applied Artificial Intelligence and Computing, ICAAIC 2022, Salem, India, 9–11 May 2022.
71. Burhan, M.; Rehman, R.A.; Khan, B.; Kim, B.S. IoT Elements, Layered Architectures and Security Issues: A Comprehensive Survey. *Sensors* **2018**, *18*, 2796. [CrossRef] [PubMed]
72. Pimple, N.; Salunke, T.; Pawar, U.; Sangoi, J. Wireless Security-An Approach Towards Secured Wi-Fi Connectivity. In Proceedings of the 2020 6th International Conference on Advanced Computing and Communication Systems, ICACCS 2020, Coimbatore, India, 6–7 March 2020.
73. Eckhart, M.; Ekelhart, A. Digital Twins for Cyber-Physical Systems Security: State of the Art and Outlook. In *Security and Quality in Cyber-Physical Systems Engineering*; Springer: Berlin/Heidelberg, Germany, 2019.
74. Zhao, T.; Foo, E.; Tian, H. A Digital Twin Framework for Cyber Security in Cyber-Physical Systems. *arXiv* **2022**, arXiv:2204.13859.
75. Wang, D.; Shi, S.; Lu, J.; Hu, Z.; Chen, J. Research on Gas Pipeline Leakage Model Identification Driven by Digital Twin. *Syst. Sci. Control Eng.* **2023**, *11*, 2180687. [CrossRef]
76. Ghaith, M.; Yosri, A.; El-Dakhakhni, W. Synchronization-Enhanced Deep Learning Early Flood Risk Predictions: The Core of Data-Driven City Digital Twins for Climate Resilience Planning. *Water* **2022**, *14*, 3619. [CrossRef]
77. Mokhtari, F.; Imanpour, A. A Digital Twin-Based Framework for Multi-Element Seismic Hybrid Simulation of Structures. *Mech. Syst. Signal Process.* **2023**, *186*, 109909. [CrossRef]
78. Mansour, D.E.A.; Numair, M.; Zalhaf, A.S.; Ramadan, R.; Darwish, M.M.F.; Huang, Q.; Hussien, M.G.; Abdel-Rahim, O. Applications of IoT and Digital Twin in Electrical Power Systems: A Comprehensive Survey. *IET Gener. Transm. Distrib.* **2023**, *17*, 4457–4479. [CrossRef]
79. Almatared, M.; Liu, H.; Abudayyeh, O.; Hakim, O.; Sulaiman, M. Digital-Twin-Based Fire Safety Management Framework for Smart Buildings. *Buildings* **2024**, *14*, 4. [CrossRef]
80. Zhang, X.; Jiang, Y.; Wu, X.; Nan, Z.; Jiang, Y.; Shi, J.; Zhang, Y.; Huang, X.; Huang, G.G.Q. AIoT-Enabled Digital Twin System for Smart Tunnel Fire Safety Management. *Dev. Built Environ.* **2024**, *18*, 100381. [CrossRef]
81. Berti, N.; Finco, S.; Guidolin, M.; Battini, D. Towards Human Digital Twins to Enhance Workers' Safety and Production System Resilience. In Proceedings of the IFAC-PapersOnLine, Yokohama, Japan, 9–14 November 2023; Volume 56.
82. Paul, A.; Pulani, S.; Maheswari, J.U. Digital Twin Framework for Worker Safety Using RFID Technology. In Proceedings of the International Symposium on Automation and Robotics in Construction, Chennai, India, 3–9 July 2023.
83. Wang, E.; Tayebi, P.; Song, Y.T. Cloud-Based Digital Twins' Storage in Emergency Healthcare. *Int. J. Networked Distrib. Comput.* **2023**, *11*, 75–87. [CrossRef]
84. Moyaux, T.; Liu, Y.; Bouleux, G.; Cheutet, V. An Agent-Based Architecture of the Digital Twin for an Emergency Department. *Sustainability* **2023**, *15*, 3412. [CrossRef]
85. Meschini, S.; Accardo, D.; Locatelli, M.; Pellegrini, L.; Tagliabue, L.C.; Di Giuda, G.M. BIM-GIS Integration and Crowd Simulation for Fire Emergency Management in a Large, Diffused University. In Proceedings of the International Symposium on Automation and Robotics in Construction, Chennai, India, 3–9 July 2023.

86. Yan, K.; Zhong, C.; Ji, Z.; Huang, J. Semi-Supervised Learning for Early Detection and Diagnosis of Various Air Handling Unit Faults. *Energy Build.* **2018**, *181*, 75–83. [CrossRef]
87. Zenebe, T.M.; Midtgård, O.M.; Völler, S.; Cali, Ü. Machine Learning for PV System Operational Fault Analysis: Literature Review. In Proceedings of the Communications in Computer and Information Science, Grimstad, Norway, 11–13 October 2022; Volume 1616.
88. Hussain, M.; Memon, T.D.; Hussain, I.; Memon, Z.A.; Kumar, D. Fault Detection and Identification Using Deep Learning Algorithms in Induction Motors. *CMES-Comput. Model. Eng. Sci.* **2022**, *133*, 435–470. [CrossRef]
89. Ciaburro, G. Machine Fault Detection Methods Based on Machine Learning Algorithms: A Review. *Math. Biosci. Eng.* **2022**, *19*, 11453–11490. [CrossRef]
90. Yitmen, I.; Alizadehsalehi, S.; Akıner, İ.; Akıner, M.E. An Adapted Model of Cognitive Digital Twins for Building Lifecycle Management. *Appl. Sci.* **2021**, *11*, 4276. [CrossRef]
91. El Mokhtari, K.; Panushev, I.; McArthur, J.J. Development of a Cognitive Digital Twin for Building Management and Operations. *Front. Built Environ.* **2022**, *8*, 856873. [CrossRef]
92. Hobson, B.W.; Lowcay, D.; Gunay, H.B.; Ashouri, A.; Newsham, G.R. Opportunistic Occupancy-Count Estimation Using Sensor Fusion: A Case Study. *Build. Environ.* **2019**, *159*, 106154. [CrossRef]
93. Eyiokur, F.I.; Kantarcı, A.; Erakın, M.E.; Damer, N.; Ofli, F.; Imran, M.; Križaj, J.; Salah, A.A.; Waibel, A.; Štruc, V.; et al. A Survey on Computer Vision Based Human Analysis in the COVID-19 Era. *Image Vis. Comput.* **2023**, *130*, 104610. [CrossRef]
94. Lv, Z.; Chen, D.; Lv, H. Smart City Construction and Management by Digital Twins and BIM Big Data in COVID-19 Scenario. *ACM Trans. Multimed. Comput. Commun. Appl.* **2022**, *18*, 1–21. [CrossRef]
95. Anand, P.; Deb, C.; Yan, K.; Yang, J.; Cheong, D.; Sekhar, C. Occupancy-Based Energy Consumption Modelling Using Machine Learning Algorithms for Institutional Buildings. *Energy Build.* **2021**, *252*, 111478. [CrossRef]
96. Ding, Y.; Chen, W.; Wei, S.; Yang, F. An Occupancy Prediction Model for Campus Buildings Based on the Diversity of Occupancy Patterns. *Sustain. Cities Soc.* **2021**, *64*, 102533. [CrossRef]
97. Wang, C.; Pattawi, K.; Lee, H. Energy Saving Impact of Occupancy-Driven Thermostat for Residential Buildings. *Energy Build.* **2020**, *211*, 109791. [CrossRef]
98. Kim, E. Interpretable and Accurate Convolutional Neural Networks for Human Activity Recognition. *IEEE Trans. Ind. Inf.* **2020**, *16*, 7190–7198. [CrossRef]
99. Yuan, L.; Andrews, J.; Mu, H.; Vakil, A.; Ewing, R.; Blasch, E.; Li, J. Interpretable Passive Multi-Modal Sensor Fusion for Human Identification and Activity Recognition. *Sensors* **2022**, *22*, 5787. [CrossRef] [PubMed]
100. Cengiz, A.B.; Birant, K.U.; Cengiz, M.; Birant, D.; Baysari, K. Improving the Performance and Explainability of Indoor Human Activity Recognition in the Internet of Things Environment. *Symmetry* **2022**, *14*, 2022. [CrossRef]
101. Ibrahim, M.R.; Haworth, J.; Cheng, T. Understanding Cities with Machine Eyes: A Review of Deep Computer Vision in Urban Analytics. *Cities* **2020**, *96*, 102481. [CrossRef]
102. Kothadiya, D.; Chaudhari, A.; Macwan, R.; Patel, K.; Bhatt, C. The Convergence of Deep Learning and Computer Vision: Smart City Applications and Research Challenges. In Proceedings of the 3rd International Conference on Integrated Intelligent Computing Communication & Security (ICIIC 2021), Bangalore, India, 6–7 August 2021; Volume 4.
103. Cardoso, B.; Silva, C.; Costa, J.; Ribeiro, B. Internet of Things Meets Computer Vision to Make an Intelligent Pest Monitoring Network. *Appl. Sci.* **2022**, *12*, 9397. [CrossRef]
104. Kiobia, D.O.; Mwitta, C.J.; Fue, K.G.; Schmidt, J.M.; Riley, D.G.; Rains, G.C. A Review of Successes and Impeding Challenges of IoT-Based Insect Pest Detection Systems for Estimating Agroecosystem Health and Productivity of Cotton. *Sensors* **2023**, *23*, 4127. [CrossRef] [PubMed]
105. Civantos, E.; Thuiller, W.; Maiorano, L.; Guisan, A.; Arajo, M.B. Potential Impacts of Climate Change on Ecosystem Services in Europe: The Case of Pest Control by Vertebrates. *Bioscience* **2012**, *62*, 658–666. [CrossRef]
106. Chen, Z.; Huang, L. Digital Twin in Circular Economy: Remanufacturing in Construction. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Vienna, Austria, 18–21 May 2020; Volume 588.
107. Fang, B.; Yu, J.; Chen, Z.; Osman, A.I.; Farghali, M.; Ihara, I.; Hamza, E.H.; Rooney, D.W.; Yap, P.S. Artificial Intelligence for Waste Management in Smart Cities: A Review. *Environ. Chem. Lett.* **2023**, *21*, 1959–1989. [CrossRef]
108. Khan, A.U.R.; Ahmad, R.W. A Blockchain-Based IoT-Enabled E-Waste Tracking and Tracing System for Smart Cities. *IEEE Access* **2022**, *10*, 86256–86269. [CrossRef]
109. Moral, P.; García-Martín, Á.; Escudero-Viñolo, M.; Martínez, J.M.; Bescós, J.; Peñuela, J.; Martínez, J.C.; Alvis, G. Towards Automatic Waste Containers Management in Cities via Computer Vision: Containers Localization and Geo-Positioning in City Maps. *Waste Manag.* **2022**, *152*, 59–68. [CrossRef] [PubMed]
110. Zou, Y.; Ye, F.; Li, A.; Munir, M.; Hjelseth, E.; Sujan, S.F. A Digital Twin Prototype for Smart Parking Management. In *eWork and eBusiness in Architecture, Engineering and Construction, Proceedings of the 14th European Conference on Product and Process Modelling, ECPPM 2022, Trondheim, Norway, 14–16 September 2022*; CRC Press: Boca Raton, FL, USA, 2023.

111. Liu, Y.; Pan, S.; Folz, P.; Ramparany, F.; Bolle, S.; Ballot, E.; Coupaye, T. Cognitive Digital Twins for Freight Parking Management in Last Mile Delivery under Smart Cities Paradigm. *Comput. Ind.* **2023**, *153*, 104022. [CrossRef]
112. Shang, K.; Zhang, Y.; Zhang, F. Architecture of Smart Parking Lot Based on Digital Twin Technology. *Beijing Hangkong Hangtian Daxue Xuebao/J. Beijing Univ. Aeronaut. Astronaut.* **2023**, *49*, 2029–2038. [CrossRef]
113. Chaalal, E.; Guerlain, C.; Pardo, E.; Faye, S. Integrating Connected and Automated Shuttles with Other Mobility Systems: Challenges and Future Directions. *IEEE Access* **2023**, *11*, 83081–83106. [CrossRef]
114. García-Luque, R.; Toro-Gálvez, L.; Moreno, N.; Troya, J.; Canal, C.; Pimentel, E. Integrating Citizens' Avatars in Urban Digital Twins. *J. Web Eng.* **2023**, *22*, 913–938. [CrossRef]
115. Kaewunruen, S.; Xu, N. Digital Twin for Sustainability Evaluation of Railway Station Buildings. *Front. Built Environ.* **2018**, *4*, 430624. [CrossRef]
116. Lv, Z.; Guo, J.; Singh, A.K.; Lv, H. Digital Twins Based VR Simulation for Accident Prevention of Intelligent Vehicle. *IEEE Trans. Veh. Technol.* **2022**, *71*, 3414–3428. [CrossRef]
117. Li, Y.; Zhang, W. Traffic Flow Digital Twin Generation for Highway Scenario Based on Radar-Camera Paired Fusion. *Sci. Rep.* **2023**, *13*, 642. [CrossRef]
118. Fujishima, M.; Takagi, M.; Yokoya, M.; Nakada, R. Digital Twins for Streamlining Road-Traffic Flow. *NTT Tech. Rev.* **2023**, *21*, 32–37. [CrossRef]
119. Korotunov, S.; Tabunshchyk, G.; Arras, P. Utilization of a Digital Twin for an Electric Vehicles Smart Charging Station for Future Use with Engineering Students. In *Artificial Intelligence and Online Engineering*; Auer, M.E., El-Seoud, S.A., Karam, O.H., Eds.; REV 2022 Lecture Notes in Networks and Systems; Springer: Cham, Switzerland, 2022; Volume 524. [CrossRef]
120. Francisco, A.M.B.; Monteiro, J.; Cardoso, P.J.S. A Digital Twin of Charging Stations for Fleets of Electric Vehicles. *IEEE Access* **2023**, *11*, 125664–125683. [CrossRef]
121. Farina, A.; Frosolini, M.; Petri, M.; Pratelli, A. Design of an Evacuation and Addressing System in Case of Emergency or Accident in the Port Area of Bastia. In Proceedings of the European Modeling and Simulation Symposium, EMSS, Rome, Italy, 19–21 September 2022.
122. Martelli, M.; Virdis, A.; Gotta, A.; Cassara, P.; DI Summa, M. An Outlook on the Future Marine Traffic Management System for Autonomous Ships. *IEEE Access* **2021**, *9*, 157316–157328. [CrossRef]
123. Li, Y.; Liu, W.; Zhang, Y.; Zhang, W.; Gao, C.; Chen, Q.; Ji, Y. Interactive Real-Time Monitoring and Information Traceability for Complex Aircraft Assembly Field Based on Digital Twin. *IEEE Trans. Ind. Inf.* **2023**, *19*, 9745–9756. [CrossRef]
124. Zhang, C.; Tian, X.; Zhao, Y.; Li, T.; Zhou, Y.; Zhang, X. Causal Discovery-Based External Attention in Neural Networks for Accurate and Reliable Fault Detection and Diagnosis of Building Energy Systems. *Build. Environ.* **2022**, *222*, 109357. [CrossRef]
125. Jiang, F.; Ma, L.; Broyd, T.; Chen, W.; Luo, H. Digital Twin Enabled Sustainable Urban Road Planning. *Sustain. Cities Soc.* **2022**, *78*, 103645. [CrossRef]
126. Ye, X.; Du, J.; Han, Y.; Newman, G.; Retchless, D.; Zou, L.; Ham, Y.; Cai, Z. Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda. *J. Plan. Lit.* **2023**, *38*, 187–199. [CrossRef] [PubMed]
127. Dembski, F.; Wössner, U.; Letzgus, M.; Ruddat, M.; Yamu, C. Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany. *Sustainability* **2020**, *12*, 2307. [CrossRef]
128. Bononi, L.; Donatiello, L.; Longo, D.; Massari, M.; Montori, F.; Stacchio, L.; Marfia, G. Digital Twin Collaborative Platforms: Applications to Humans-in-the-Loop Crafting of Urban Areas. *IEEE Consum. Electron. Mag.* **2023**, *12*, 38–46. [CrossRef]
129. Shaharuddin, S.; Abdul Maulud, K.N.; Syed Abdul Rahman, S.A.F.; Che Ani, A.I. Digital Twin for Indoor Disaster in Smart City: A Systematic Review. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences-ISPRS Archives, online, 5–6 October 2022; Volume 46.
130. Gugliermetti, L.; Cumo, F.; Agostinelli, S. A Future Direction of Machine Learning for Building Energy Management: Interpretable Models. *Energies* **2024**, *17*, 700. [CrossRef]
131. Soe, R.M. Smart Twin Cities via Urban Operating System. In Proceedings of the ACM International Conference Proceeding Series, New Delhi, India, 7–9 March 2017; Volume Part F128003.
132. Foscari, A. Ateneo Veneto Rivista di Scienze Lettere ed Arti, Anno CXCV, 3rd ed.Ateneo Veneto: Venice, Italy, 2009; Volume 8/2, ISBN 978-1110103003.
133. ICOMOS. *UNESCO World Heritage List n. 394, Venice and Its Lagoon*. Available online: https://whc.unesco.org/en/list/394/ (accessed on 29 December 2024).
134. Bathla, G.; Rani, R.; Aggarwal, H. Comparative Study of NoSQL Databases for Big Data Storage. *Int. J. Eng. Technol.* **2018**, *7*, 83–87. [CrossRef]
135. Corbellini, A.; Mateos, C.; Zunino, A.; Godoy, D.; Schiaffino, S. Persisting Big-Data: The NoSQL Landscape. *Inf. Syst.* **2017**, *63*, 1–23. [CrossRef]
136. Botha, I. Time Series Forecasting in the Artificial Intelligence Milieu. *J. Econ. Financ. Sci.* **2022**, *15*, a836. [CrossRef]
137. Shah, B.; Jat, P.M.; Sasidhar, K. Performance Study of Time Series Databases. *Int. J. Database Manag. Syst.* **2022**, *14*, 1–13. [CrossRef]

138. Adiono, T.; Marthensa, R.; Muttaqin, R.; Fuada, S.; Harimurti, S.; Adijarto, W. Design of Database and Secure Communication Protocols for Internet-of-Things-Based Smart Home System. In Proceedings of the IEEE Region 10 Annual International Conference, Proceedings/TENCON, Penang, Malaysia, 5–8 November 2017; Volume 2017.
139. Gentilcore, D. The Cistern-System of Early Modern Venice: Technology, Politics and Culture in a Hydraulic Society. *Water Hist.* **2021**, *13*, 375–406. [CrossRef]
140. Umgiesser, G. The Impact of Operating the Mobile Barriers in Venice (MOSE) under Climate Change. *J. Nat. Conserv.* **2020**, *54*, 125783. [CrossRef]
141. Pham, H.V.; Dal Barco, M.K.; Cadau, M.; Harris, R.; Furlan, E.; Torresan, S.; Rubinetti, S.; Zanchettin, D.; Rubino, A.; Kuznetsov, I.; et al. Multi-Model Chain for Climate Change Scenario Analysis to Support Coastal Erosion and Water Quality Risk Management for the Metropolitan City of Venice. *Sci. Total Environ.* **2023**, *904*, 166310. [CrossRef] [PubMed]
142. Zhang, R.; Hong, T. Modeling of HVAC Operational Faults in Building Performance Simulation. *Appl. Energy* **2017**, *202*, 178–188. [CrossRef]
143. Neacsa, A.; Eparu, C.N.; Stoica, D.B. Hydrogen–Natural Gas Blending in Distribution Systems—An Energy, Economic, and Environmental Assessment. *Energies* **2022**, *15*, 6143. [CrossRef]
144. Zhang, H.; Zhao, J.; Li, J.; Yu, B.; Wang, J.; Lyu, R.; Xi, Q. Research Progress on Corrosion and Hydrogen Embrittlement in Hydrogen–Natural Gas Pipeline Transportation. *Nat. Gas Ind. B* **2023**, *10*, 570–582. [CrossRef]
145. Cinquepalmi, F. The Copernicus Programme: Europe's Eye on Urban Areas. In *Abitare la Terra–Dwelling on Earth Quaderni 2*; Portoghesi, P., Ed.; Gangemi: Rome, Italy, 2020; Volume 2, pp. 12–15, ISBN 9788849238983.
146. Corrado, C.R.; DeLong, S.M.; Holt, E.G.; Hua, E.Y.; Tolk, A. Combining Green Metrics and Digital Twins for Sustainability Planning and Governance of Smart Buildings and Cities. *Sustainability* **2022**, *14*, 12988. [CrossRef]
147. Salem, T.; Dragomir, M. Options for and Challenges of Employing Digital Twins in Construction Management. *Appl. Sci.* **2022**, *12*, 2928. [CrossRef]
148. Goumiri, S.; Yahiaoui, S.; Djahel, S. Smart Mobility in Smart Cities: Emerging Challenges, Recent Advances and Future Directions. *J. Intell. Transp. Syst. Technol. Plan. Oper.* **2023**, 1–37. [CrossRef]
149. Müller-Eie, D.; Kosmidis, I. Sustainable Mobility in Smart Cities: A Document Study of Mobility Initiatives of Mid-Sized Nordic Smart Cities. *Eur. Transp. Res. Rev.* **2023**, *15*, 36. [CrossRef]
150. Tahmasseby, S. The Implementation of Smart Mobility for Smart Cities: A Case Study in Qatar. *Civ. Eng. J.* **2022**, *8*, 2154–2171. [CrossRef]
151. International Energy Agency International Energy Agency (IEA) World Energy Outlook 2022. Available online: https://www.iea.org/reports/world-energy-outlook-2022/executive-summary (accessed on 22 September 2024).
152. Lin, Y.; Li, B.; Moiser, T.M.; Griffel, L.M.; Mahalik, M.R.; Kwon, J.; Alam, S.M.S. Revenue Prediction for Integrated Renewable Energy and Energy Storage System Using Machine Learning Techniques. *J. Energy Storage* **2022**, *50*, 104123. [CrossRef]
153. Ramesh, T.; Prakash, R.; Shukla, K.K. Life Cycle Energy Analysis of Buildings: An Overview. *Energy Build.* **2010**, *42*, 1592–1600. [CrossRef]
154. Agostinelli, S.; Cumo, F.; Nezhad, M.M.; Orsini, G.; Piras, G. Renewable Energy System Controlled by Open-Source Tools and Digital Twin Model: Zero Energy Port Area in Italy. *Energies* **2022**, *15*, 1817. [CrossRef]
155. Yang, B.; Lv, Z.; Wang, F. Digital Twins for Intelligent Green Buildings. *Buildings* **2022**, *12*, 856. [CrossRef]
156. Villa, V.; Chiaia, B. Digital Twin for Smart School Buildings: State of the Art, Challenges, and Opportunities. In *Handbook of Research on Developing Smart Cities Based on Digital Twins*; IGI Global Scientific Publishing: Hershey, PA, USA, 2021.
157. Deng, M.; Menassa, C.C.; Kamat, V.R. From BIM to Digital Twins: A Systematic Review of the Evolution of Intelligent Building Representations in the AEC-FM Industry. *J. Inf. Technol. Constr.* **2021**, *26*, 58–83. [CrossRef]
158. Cho, Y.; Kim, J. A Study on Setting the Direction of Digital Twin Implementation for Urban Regeneration Business. *Int. J. Adv. Appl. Sci.* **2022**, *9*, 147–154. [CrossRef]
159. Ascione, F.; De Masi, R.F.; Mastellone, M.; Ruggiero, S.; Vanoli, G.P. Improving the Building Stock Sustainability in European Countries: A Focus on the Italian Case. *J. Clean. Prod.* **2022**, *365*, 132699. [CrossRef]
160. Giuffrida, A. Italy Bans Cruise Ships from Venice Lagoon after Unesco Threat, The Guardian, 2021, July 13. Available online: https://www.theguardian.com/world/2021/jul/13/italy-bans-cruise-ships-from-venice-lagoon-after-unesco-threat (accessed on 29 December 2024).
161. Ryan, J.; Silvanto, S. The World Heritage List: The Making and Management of a Brand. *Place Brand. Public Dipl.* **2009**, *5*, 290–300. [CrossRef]
162. Venice Municipality Superfici Amministrative. Available online: https://www.comune.venezia.it/sites/comune.venezia.it/files/immagini/statistica/tabella_superfici_agg2020.pdf (accessed on 16 September 2024).
163. Cavalli, R.M. Capability of Remote Sensing Images to Distinguish the Urban Surface Materials: A Case Study of Venice City. *Remote Sens.* **2021**, *13*, 3959. [CrossRef]

164. Agostini, M.; Cammerata, F. PA Risk Map Venice; Venice, Italy. 2023. Available online: https://www.comune.venezia.it/sites/comune.venezia.it/files/documenti/sue/nta_in_salvaguardia.pdf (accessed on 29 December 2024).
165. Pirazzoli, P.A.; Umgiesser, G. The Projected "MOSE" Barriers against Flooding in Venice (Italy) and the Expected Global Sea-Level Rise. *J. Mar. Environ. Eng.* **2006**, *8*, 247–261.
166. Abbott, B.N.; Wallace, J.; Nicholas, D.M.; Karim, F.; Waltham, N.J. Bund Removal to Re-Establish Tidal Flow, Remove Aquatic Weeds and Restore Coastal Wetland Services-North Queensland, Australia. *PLoS ONE* **2020**, *15*, e0217531. [CrossRef]
167. Steinmann, R.; Seydoux, L.; Campillo, M. AI-Based Unmixing of Medium and Source Signatures From Seismograms: Ground Freezing Patterns. *Geophys. Res. Lett.* **2022**, *49*, e2022GL098854. [CrossRef] [PubMed]
168. Patel, A.; Vyas, D.; Chaudhari, N.; Patel, R.; Patel, K.; Mehta, D. Novel Approach for the LULC Change Detection Using GIS & Google Earth Engine through Spatiotemporal Analysis to Evaluate the Urbanization Growth of Ahmedabad City. *Results Eng.* **2024**, *21*, 101788. [CrossRef]
169. Alberti, T.; Anzidei, M.; Faranda, D.; Vecchio, A.; Favaro, M.; Papa, A. Dynamical Diagnostic of Extreme Events in Venice Lagoon and Their Mitigation with the MoSE. *Sci. Rep.* **2023**, *13*, 10475. [CrossRef]
170. Lee, K.; Kim, B.; Park, S. Evaluating the Potential of Burn Severity Mapping and Transferability of Copernicus EMS Data Using Sentinel-2 Imagery and Machine Learning Approaches. *GIsci Remote Sens.* **2023**, *60*, 2192157. [CrossRef]
171. Stoof, C.R.; Kok, E.; Cardil Forradellas, A.; van Marle, M.J.E. In Temperate Europe, Fire Is Already Here: The Case of The Netherlands. *Ambio* **2024**, *53*, 604–623. [CrossRef] [PubMed]
172. Tonbul, H.; Colkesen, I.; Kavzoglu, T. Forest Fire and Burn Severity Analysis in Cefalù Region of Italy Using Sentinel-2 Imagery. In Proceedings of the International Symposium on Applied Geoinformatics (ISAG), Istanbul, Turkey, 7–9 November 2019.
173. Mei, A.; Baiocchi, V.; Mattei, S.; Zampetti, E.; Pai, H.J.; Tratzi, P.; Ragazzo, A.V.; Cuzzucoli, A.; Mancuso, A.; Bearzotti, A.; et al. Conceptualization of a satellite, uas and ugv downscaling approach for abandoned waste detection and waste to energy prospects. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.-ISPRS Arch.* **2023**, *48*, 287–293. [CrossRef]
174. Slonecker, T.; Fisher, G.B.; Aiello, D.P.; Haack, B. Visible and Infrared Remote Imaging of Hazardous Waste: A Review. *Remote Sens.* **2010**, *2*, 2474–2508. [CrossRef]
175. Lavender, S. Detection of Waste Plastics in the Environment: Application of Copernicus Earth Observation Data. *Remote Sens.* **2022**, *14*, 4772. [CrossRef]
176. Ricciardi, G.; Callegari, G. Digital Twins for Climate-Neutral and Resilient Cities. State of the Art and Future Development as Tools to Support Urban Decision-Making. In *Urban Book Series*; Springer International Publishing: Cham, Switzerland, 2023; Volume Part F813.
177. Gustin, M.; McLeod, R.S.; Lomas, K.J. Forecasting Indoor Temperatures during Heatwaves Using Time Series Models. *Build. Environ.* **2018**, *143*, 727–739. [CrossRef]
178. Kim, M.K.; Yu, D.G.; Oh, J.S.; Byun, Y.H.; Boo, K.O.; Chung, I.U.; Park, J.S.; Park, D.S.R.; Min, S.K.; Sung, H.M. Performance Evaluation of CMIP5 and CMIP6 Models on Heatwaves in Korea and Associated Teleconnection Patterns. *J. Geophys. Res. Atmos.* **2020**, *125*, e2020JD032583. [CrossRef]
179. Ghosh, A.; Hafnaoui, R.; Mesloub, A.; Elkhayat, K.; Albaqawy, G.; Alnaim, M.M.; Mayhoub, M.S. Active Smart Switchable Glazing for Smart City: A Review. *J. Build. Eng.* **2024**, *84*, 108644. [CrossRef]
180. Tang, Y.; Gao, F.; Wang, C.; Huang, M.M.; Wu, M.; Li, H.; Li, Z. Vertical Greenery System (VGS) Renovation for Sustainable Arcade-Housing: Building Energy Efficiency Analysis Based on Digital Twin. *Sustainability* **2023**, *15*, 2310. [CrossRef]
181. Qi, Y.; Li, H.; Pang, Z.; Gao, W.; Liu, C. A Case Study of the Relationship Between Vegetation Coverage and Urban Heat Island in a Coastal City by Applying Digital Twins. *Front. Plant Sci.* **2022**, *13*, 861768. [CrossRef]
182. Javed, A.; Kim, T.; Lee, C.; Oh, J.; Han, Y. Deep Learning-Based Detection of Urban Forest Cover Change along with Overall Urban Changes Using Very-High-Resolution Satellite Images. *Remote Sens.* **2023**, *15*, 4285. [CrossRef]
183. Wang, H.; Lv, X.; Zhang, K.; Guo, B. Building Change Detection Based on 3D Co-Segmentation Using Satellite Stereo Imagery. *Remote Sens.* **2022**, *14*, 628. [CrossRef]
184. Shen, L.; Lu, Y.; Chen, H.; Wei, H.; Xie, D.; Yue, J.; Chen, R.; Lv, S.; Jiang, B. S2looking: A Satellite Side-Looking Dataset for Building Change Detection. *Remote Sens* **2021**, *13*, 5094. [CrossRef]
185. El Hachimi, J.; El Harti, A.; Lhissou, R.; Ouzemou, J.E.; Chakouri, M.; Jellouli, A. Combination of Sentinel-2 Satellite Images and Meteorological Data for Crop Water Requirements Estimation in Intensive Agriculture. *Agriculture* **2022**, *12*, 1168. [CrossRef]
186. Veysi, S.; Naseri, A.A.; Hamzeh, S.; Bartholomeus, H. A Satellite Based Crop Water Stress Index for Irrigation Scheduling in Sugarcane Fields. *Agric. Water Manag.* **2017**, *189*, 70–86. [CrossRef]
187. Soni, A.K.; Tripathi, J.N.; Ghosh, K.; Sateesh, M.; Singh, P. Evaluating Crop Water Stress through Satellite-Derived Crop Water Stress Index (CWSI) in Marathwada Region Using Google Earth Engine. *J. Agrometeorol.* **2023**, *25*, 539–546. [CrossRef]
188. Shafi, U.; Mumtaz, R.; García-Nieto, J.; Hassan, S.A.; Zaidi, S.A.R.; Iqbal, N. Precision Agriculture Techniques and Practices: From Considerations to Applications. *Sensors* **2019**, *19*, 3796. [CrossRef] [PubMed]

189. Chamara, N.; Islam, M.D.; Bai, G.F.; Shi, Y.; Ge, Y. Ag-IoT for Crop and Environment Monitoring: Past, Present, and Future. *Agric. Syst.* **2022**, *203*, 103497. [CrossRef]
190. Jiang, J.; Atkinson, P.M.; Chen, C.; Cao, Q.; Tian, Y.; Zhu, Y.; Liu, X.; Cao, W. Combining UAV and Sentinel-2 Satellite Multi-Spectral Images to Diagnose Crop Growth and N Status in Winter Wheat at the County Scale. *Field Crops Res.* **2023**, *294*, 108860. [CrossRef]
191. Maimaitijiang, M.; Sagan, V.; Sidike, P.; Daloye, A.M.; Erkbol, H.; Fritschi, F.B. Crop Monitoring Using Satellite/UAV Data Fusion and Machine Learning. *Remote Sens.* **2020**, *12*, 1357. [CrossRef]
192. Sharif, S.A.; Hammad, A.; Eshraghi, P. Generation of Whole Building Renovation Scenarios Using Variational Autoencoders. *Energy Build.* **2021**, *230*, 110520. [CrossRef]
193. Posada, H.; Chacón, R.; Ramonell, C. I-Twin. Computational Twin Connectors for I-profiles. Towards Unforeseen Interoperability of Digital Tools. *Ce/Pap.* **2023**, *6*, 445–451. [CrossRef]
194. Fareeza, F.; Krishna Veni, S.; Rambabu, C.; Yanore, T.Z.; Rajkumar, P. Future Energy Source for Remote IoT Systems Using MEMS-Based Piezoelectric Energy Harvesting Devices. *J. Phys. Conf. Ser.* **2021**, *1979*, 012067. [CrossRef]
195. Scuro, C.; Alì, G.; Demarco, F.; Porzio, S. Development of a Structural Health Monitoring System with IoT Smart Nodes Based on Mathematical Model of Inverted Pendulums Equipped with Accelerometers. *Int. J. Mason. Res. Innov.* **2022**, *7*, 624–649. [CrossRef]
196. Meyer, A. Vibration Fault Diagnosis in Wind Turbines Based on Automated Feature Learning. *Energies* **2022**, *15*, 1514. [CrossRef]
197. Palacios, I.; Placencia, J.; Muñoz, M.; Samaniego, V.; González, S.; Jiménez, J. MQTT Based Event Detection System for Structural Health Monitoring of Buildings. In *Emerging Research in Intelligent Systems*; Botto-Tobar, M., Cruz, H., Díaz Cadena, A., Durakovic, B., Eds.; CIT 2021. Lecture Notes in Networks and Systems; Springer: Cham, Switzerland, 2022; Volume 405. [CrossRef]
198. Komarizadehasl, S.; Huguenet, P.; Lozano, F.; Lozano-Galant, J.A.; Turmo, J. Operational and Analytical Modal Analysis of a Bridge Using Low-Cost Wireless Arduino-Based Accelerometers. *Sensors* **2022**, *22*, 9808. [CrossRef] [PubMed]
199. Sharma, S.; Ahmed, S.; Naseem, M.; Alnumay, W.S.; Singh, S.; Cho, G.H. A Survey on Applications of Artificial Intelligence for Pre-Parametric Project Cost and Soil Shear-Strength Estimation in Construction and Geotechnical Engineering. *Sensors* **2021**, *21*, 463. [CrossRef] [PubMed]
200. Mastrucci, A.; Marvuglia, A.; Benetto, E.; Leopold, U. A Spatio-Temporal Life Cycle Assessment Framework for Building Renovation Scenarios at the Urban Scale. *Renew. Sustain. Energy Rev.* **2020**, *126*, 109834. [CrossRef]
201. Maia, I.; Kranzl, L.; Müller, A. New Step-by-Step Retrofitting Model for Delivering Optimum Timing. *Appl. Energy* **2021**, *290*, 116714. [CrossRef]
202. Nesticò, A.; Marca, M. La Urban Real Estate Values and Ecosystem Disservices: An Estimate Model Based on Regression Analysis. *Sustainability* **2020**, *12*, 6304. [CrossRef]
203. Mulero-Palencia, S.; Álvarez-Díaz, S.; Andrés-Chicote, M. Machine Learning for the Improvement of Deep Renovation Building Projects Using As-Built Bim Models. *Sustainability* **2021**, *13*, 6576. [CrossRef]
204. Bertocchi, D.; Camatti, N. Tourism in Venice: Mapping Overtourism and Exploring Solutions. In *A Research Agenda for Urban Tourism*; Edward Elgar Publishing: Cheltenham, UK, 2022.
205. Bertocchi, D.; Camatti, N.; Giove, S.; van der Borg, J. Venice and Overtourism: Simulating Sustainable Development Scenarios through a Tourism Carrying Capacity Model. *Sustainability* **2020**, *12*, 512. [CrossRef]
206. Kryczka, M. Overtourism vs. Sustainable Development of Tourism. Attempts to Handle Overtourism Following the Example of Venice. *Stud. Perieget.* **2019**, *2*, 43–61.
207. Regione Del Veneto; Comune Di Venezia; Università Ca' Foscari Venezia; Università Iuav Di Venezia; Accademia Di Belle Arti Venezia; Conservatorio Di Musica Benedetto Marcello Venezia; Fondazione Venezia Capitale Mondiale Della Sostenibilità. Venezia Città Campus. Italy. 2023. Available online: https://www.iuav.it/sites/default/files/2024-05/Venezia-Citt--Campus.pdf (accessed on 29 December 2024).
208. Università Iuav di Venezia. *Piano Strategico 2023–2027*; Università Iuav di Venezia: Venice, Italy, 2024; Available online: https://www.iuav.it/sites/default/files/2024-10/piano-strategico-2023_2027_completo.pdf (accessed on 29 December 2024).
209. Benno, A. Un nuovo Campus per la città = A new Campus for the city. In *WA VE 2022 Workshop Architettura Venezia*; Iorio, A., Calogero, L., Eds.; Anteferma Edizioni: Venice, Italy, 2024; Volume 1, ISBN 979-1259530479.