sustainability

MDPI

Article

Digital Transformation in the Construction Sector: A Digital Twin for Seismic Safety in the Lifecycle of Buildings

Massimo Lauria [1,*] and Maria Azzalin [2,*]

1 Department of Civil, Energy, Environmental and Material Engineering, Mediterranean University, 89122 Reggio Calabria, Italy
2 Department of Architecture and Territory, Mediterranean University, 89124 Reggio Calabria, Italy
* Correspondence: mlauria@unirc.it (M.L.); maria.azzalin@unirc.it (M.A.)

Abstract: The construction sector is currently undergoing a deep digital transformation resulting from the prioritization of emerging technologies, among which are digital twins. New goals and opportunities are appearing that minimize the impact on a building's lifecycle, reduce economic, environmental, and extra-social costs, optimize energetic performance, decrease energy consumption and emissions, and enhance the durability and service life of buildings and their components. Among the research activities that have led to the development of a maintenance management model (MMM), this paper deals with the digital-twin approach, considering it instrumental to the innovative governance of the building environment from a lifecycle-based and sustainable perspective. It includes paying attention to efficiency in terms of resource use, energy consumption, and the energy performance of buildings, supporting decarbonization processes, and environmental vulnerability due to natural disasters, extreme weather, and seismic events. Its current implementation is presented here. In this scenario, the authors, operating at BIG srl, an academic spinoff of the Mediterranean University of Reggio Calabria, Italy, working together with the startup Sysdev, based in Torino, Italy, the company Berna Engineering srl, based in Reggio Calabria, Italy, and ACCA Software spa, based in Avellino, Italy, introduce the experimental application of the DT4SEM for safety and well-being in buildings, which is specifically oriented to seismic behavior monitoring. The proposal, while highlighting the innovative character of DT approaches, responds to the need for reliable data for increasingly effective forecasts and the control of the seismic behavior of buildings, facilitating informed decision-making for building management while also optimizing maintenance schedules.

Keywords: digital twin; built environment; internet of things; intelligent construction; maintenance; seismic monitoring

Citation: Lauria, M.; Azzalin, M. Digital Transformation in the Construction Sector: A Digital Twin for Seismic Safety in the Lifecycle of Buildings. *Sustainability* **2024**, *16*, 8245. https://doi.org/10.3390/su16188245

Academic Editor: Manuel Duarte Pinheiro

Received: 23 July 2024
Revised: 7 September 2024
Accepted: 10 September 2024
Published: 22 September 2024

1. Introduction

The key enabling technologies (KETs) framework has marked a digital transformation upgrade in many industrial and production sectors [1]. It combines and establishes a strong interaction between research and industry, supporting innovation and operativity and promoting improved digital solutions for processes, products, and services.

It also accompanies the onset of the fourth industrial revolution [2].

Many years on, European digital policies still emphasize digitalization, automation, and interconnection as priorities [3–6], enabling a new phase of digital transformation, as pointed out with the shift from Industry 4.0 to Industry 5.0 [7–9].

In 2021, the EU report "Industry 5.0: Towards More Sustainable, Resilient and Human-Centric Industry" emphasized the need to accelerate the digital and ecological transformation already underway to restore the environment and the economy, focusing on three principles: the centrality of the human, self-sustainability, and resilience [10].

Now, the challenge is to set up a collaborative industry and a super-smart society characterized by the synergy between machines and humans that is able to accompany the transition from digital industry to digital society. This includes an emphasis on digital humanities, which combine emerging digital and computational tools with humanities studies and can be aligned with all sustainable development goals (SDGs) in an interconnected and interrelated way [11].

Similarly, also in the construction sector, a deep but very slow digital transformation is happening, leading to the adoption of emerging technologies as priority instruments.

Furthermore, new goals and opportunities are emerging for the sector: the minimization of its environmental impact and emissions, the reduction of economic and extra-social costs, the optimization of resource use, the improvement of energy performance, and the enhancement of the durability and service life of buildings and components in their lifecycle. The urgency of adopting sustainable processes and the mounting attention being paid to environmental vulnerability due to natural disasters, extreme weather, and seismic events require systemic and scalable innovations to overcome traditional modalities and take full advantage of the digital frontier [12,13].

Among the emerging best-performing innovations, the construction sector recognizes the digital twin, DT, as a paradigm shift. It is considered capable of improving decision-making processes and simulating and supporting sustainable actions at the technical, economic, and procedural levels [14–16].

Its experimentation and widespread application are gaining prominence as it enhances the implementation of many of the goals mentioned above, offering an opportunity to contribute to sustainability in buildings throughout their lifecycle—at the design stage but also in re-thinking, redesigning, and modernizing existing buildings [17–19].

In this scenario, some critical aspects arise in terms of achieving the goals above. These include the availability of data and the ability to collect, format, and process them for a specific need or requirement. These crucial nodes are already highlighted in ISO 15686 Part 7:2017 [20]. The availability of data from the monitoring of in-use conditions is key to enabling more reliable performance control, prediction, and simulation of the lifecycle of buildings. All these opportunities characterize the DT approach and its related potential for optimizing data management [21].

By adopting the background above, the authors investigate the digital-twin approach, considering it instrumental to the innovative governance of the building environments from lifecycle-based and sustainability perspectives. This includes paying general attention to efficiency during resource use and energy consumption, the energy performance of buildings, supporting decarbonization processes, and environmental vulnerability due to natural disasters, extreme weather, and seismic events [22].

The authors, operating at BIG srl, an academic spinoff of the Mediterranean University of Reggio Calabria, together with the startup Sysdev, the company Berna Engineering srl, and ACCA Software spa, here introduce the experimental application and related first results of the digital-twin approach—DT4SEM—regarding safety and well-being in buildings, specifically oriented to the monitoring of seismic behavior.

The proposal, while highlighting the innovative character of DT approaches, responds to the need for reliable data in order to make increasingly effective forecasts about the seismic behavior of buildings. The proposal also contributes to the decarbonization processes of the built environment, controlling and maintaining performance over time and extending a building's useful life, helping with the management of the carbon footprint of building materials and components throughout a building's lifecycle.

The experiment has been carried out on a sample building with a load-bearing reinforced concrete structure. The planned deep restoration includes a prototype of the customized design, installation, and setting of the DT4SEM digital infrastructure.

It synchronizes, on a collaborative platform, the physical building with its virtual as-built digital model, integrating them using a network based on the Internet of Things (IoT), which links 2 gateways and 85 multi-sensor nodes, enabling the proactive monitoring and analysis of seismic behavior over time.

The first results and their discussion, presented below, confirm the potential of the digital-twin approach in enhancing building safety and well-being in buildings, contributing to the durability and service life of buildings.

2. The Digital Turn in Buildings: Current Opportunities and Emerging Potential

The advent of new technologies in the creative processes of architecture confirms the arrival of digital culture to building lifecycle management. This contrasts with the idea that the contribution of these technologies is limited to a mere digital translation of the process.

Mario Carpo [23] defined this process as "the digital turn" and, referring to its evolution, as "the second digital turn". The first changed the ways of making architecture; the second changed the ways of thinking about it [24].

The contemporary arrival of the digital turn alongside environmental issues started the current double transformation—digital and ecological—which has become instrumental in management and renovation strategies at different scales, including landscapes, territories, cities, and buildings.

The interaction of digital assets with climate-change aspects, including vulnerability due to seismic and natural disasters and extreme weather events, has emerged as a key issue. It combines the broader challenges of Agenda 2030 with the need for systemic and scalable sustainable strategies and operational practices [25–29].

As stated by the European Green Deal [30], this means paying more attention to the construction sector and the built environment [31], achieving carbon and climate neutrality within the timeframes of both the 2030 and 2050 scenarios, and guaranteeing safe and secure buildings [32–35].

The DT approach, according to Michael Grieves, who coined the term in 2011, synchronizes two realities—physical objects in real space and virtual objects in virtual space—guaranteeing the mutual exchange of data throughout the entire lifecycle of an object, from design and production to use and disposal [36,37].

Since then, this technological evolution–revolution has been instrumental in the transition from atoms to bits and from the physical to virtual dimension [38].

A survey on the adoption of innovative technologies places DT among the top five emerging trends that will drive technological innovation in the coming decades [39].

Market trends confirm exponential growth and enormous potential [40].

Research activities increasingly validate the technological and innovative role of building lifecycle-based perspectives [41].

The European Commission, in its 2022 Strategic Foresight Report "Twinning the Green and Digital Transitions in the New Geopolitical Context", stimulated the use of DT to revolutionize planning, monitoring, and management at building and urban scales, further improving resilience against hazardous events [42].

The Digital Building Logbook (DBL) establishes the central role of DT approaches in the Operation and Maintenance (O&M) phase, introducing a customized repository of data [43,44].

DT, as a virtual replica of a physical product, allows the simulation of performance over time, experimenting with enhancements without testing on material mock-ups, changing shapes and materials, and evaluating alternative spatial articulations. Furthermore, DT enables intelligent "phygital" constructions that synergically leverage data and information modeling throughout a building's lifecycle [45–47].

The experimental applications of DT aim to structure decision-making processes to reduce environmental impacts, guarantee the comfort and satisfaction of end users, optimize the management of available information, and permit the real-time monitoring and updating of data [48,49]. They also enable the improvement of the durability and adaptability of buildings in their lifecycle, planning management, and maintenance strategies, optimizing performance simulations using machine learning and artificial intelligence [50–52].

Some of these aspects characterize the current experimentation of DT4SEM and introduce further research areas:

- Progressive accuracy and reliability of the "as-built" BIM digital model. This is the graphic and informative model of the existing building, complete with information and technical specifications relating to the assets it contains, as also introduced in the ISO 19650:2024 standard [53–56].
- Pervasive/extensive use of the Internet of Things. This streamlines the effective connection between sensors, software, and ICT technologies, creating an informative infrastructure that activates potential data flows relating to the physical dimensions and performance of buildings. This allows the real-time monitoring and integration of analytics as well as control and simulation functions to develop performance models and data-driven decision-making [57–59].
- Potentiality in applying virtual and augmented reality: integrating artificial intelligence and virtualization for data visualization and subsequent simulation and checks. This permits simulations and the prediction of future performance, preventing anomalies and inefficiencies and permitting changes or improvements at the design stage without having to test on special mock-ups [60,61].

Alongside these themes, others emerge with a focus on more instrumental aspects:

- Widespread use of building information modeling (BIM) [62].
- Combination of BIM and the digital-twin approach as part of the data-generation process and information management for lifecycle planning [63,64].
- Combination of BIM and IoT as a support in implementing simulations and monitoring processes, the application of virtual and augmented reality, and managing information during a building's lifecycle, particularly in the in-use phase [58,59].
- Data information management concerning the O&M phase [65,66].
- Monitoring building structural resistance under seismic forces over time, introducing a thorough transformation in operating practices and simulation and verification tests [67,68].

Despite the interoperability between BIM and structural analysis software being high, intuitive, and direct, it presents some problems at an operative level. Communication between architectural and structural areas and related information transfer often occurs without different disciplines interacting. However, modeling and verification in BIM can bring benefits and facilitate structural calculation through dialogue with the current available FEM (Finite Element Method) software. The challenge of interoperability is to avoid a loss of information following the transfer of elements from one software to another and the removal of manual control [69,70].

Furthermore, strong limitations remain concerning the integration of digital simulation processes with laboratory and mock-up testing. Interoperability implementation is expected to realize and guarantee a continuous exchange between design and structural analysis software, improving the reliability of testing results and the predictive assessments of building behavior over time [71].

These objectives are unanimously shared by the different scientific disciplines involved in the sustainable management of the built environment, and recognize DT as a potential holistic approach [72,73].

3. Materials and Methods

The potential of DT and its possible implementation lends itself to work concerning the digital-twin approach for seismic and energetical monitoring—DT4SEM—which is an implementation of the maintenance management model (MMM) (Figure 1) [74].

The upgrading introduced here has been developed within research activities dealing with the innovative governance of the built environment, carried out over several years by the authors and recently implemented in the PRESMA Infinity BIM Project (design, execution, and maintenance of the digital model for the digital twin of the "Infinite Building") funded by the Italian Ministry of Economic Development, MISE, and "Digital-twin Approaches for the Innovative Governance of the Built Environment" funded by MUR ex DM 1062/2021 [75].

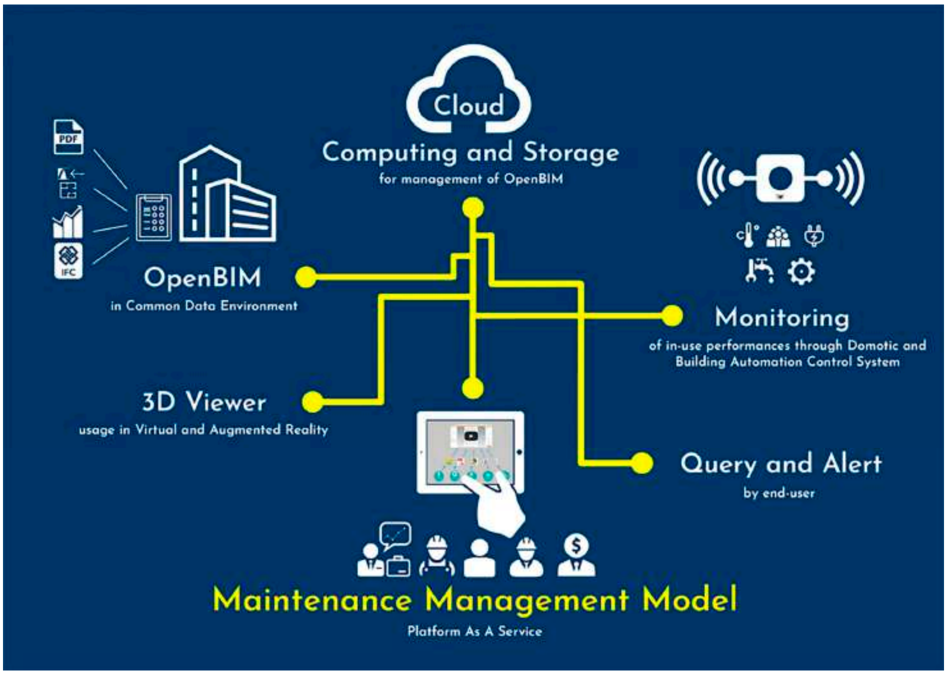


Figure 1. The maintenance management model, MMM by BIG srl.

The initial prototyping, patenting, experimentation, and marketing tasks of the MMM were financed in 2018 with POR Calabria Region funds, and subsequently, in 2021, a two-year loan was obtained from the Smart&Start Italia subsidy program operated by Invitalia Spa (Roma, Italy).

3.1. The Methodological Experimentation Framework

The use of DT4SEM results from an active dialogue between all partners involved, which works synergistically, combining expertise and knowledge.

The authors, as researchers and founding partners of the academic spinoff BIG srl, defined the theoretical and operational framework concerning the DT4SEM approach. The startup Sysdev srl provided the smart-sensor system, its deployment plan, and installation. ACCA Software spa provided the software and platform together with relative informatics competency. Berna Engineering srl carried out a deep renovation of the sample building in late 2022, adding the seismic monitoring as proposed by DT4SEM.

This experimental version takes advantage of the previous deductive approach, already applied to the development of MMM, aimed at defining homogeneous families of properties—characteristics, performance, faults, anomalies, controls, etc.—for interoperable information management in the O&M phase.

Two aspects are strictly functional to this goal, specifically:

- Tools for the collection, structuring, and management of heterogeneous data in an openBIM format: location, use, safety, accessibility, usability, environmental quality, etc.
- Data for the simulation, verification, and prevention of critical and risk events through digital model processing software, monitoring systems, and machine learning.

Moreover, DT4SEM specifically exploits the growth of the market for sensors applied to buildings to ensure the continuous monitoring and analysis of the building's seismic response. Its methodological framework includes the creation of the as-built BIM model of the sample building, sensor deployment plan settings, and linkage with the data-management platform.

The prototype version of DT4SEM, commissioned for this experimental application, now represents the first go-to-market state.

The sample building is in Reggio Calabria, located at Viale della Libertà 28 (Figure 2).

Figure 2. The sample building during the renovation works.

It is a six-story building with a load-bearing structure of reinforced concrete pillars and beams.

The experiment scheduled the installation of a seismic detection sensor system and its integration and linkage into the BIM model. This enabled a dialogue between the physical and digital assets of the building sample through a collaborative platform for the management and visualization of data. It also verifies the replicability and scalability of other sample buildings in different contexts.

3.2. The Architecture of DT4SEM: Digital Twin for Monitoring Seismic Behavior in Buildings

DT4SEM refers to certain distinct but interconnected systems consisting of:

- An as-built BIM model.
- A smart-sensor system and the Internet of Things.
- A collaborative platform of cloud computing and storage.

3.2.1. As-Built BIM Model

The creation of the as-built BIM model, according to the ISO 19650:2024 standard [53], comprises the systematization of the disaggregated and available information and the subsequent application of reverse-engineering approaches, such as scan-to-BIM processes. This allows the survey of all other required as-built parameters concerning the sample building and the integration of those available from its design documentation. The first phase involves an on-site survey, both outside and inside the building, using a Leica BLK 360 Laser Scanner (Figure 3).

Figure 3. The survey phase with a laser scanner.

The two "point clouds" resulting from the laser scanner survey were made independently of each other using the Cyclone Register 360 BLK Edition and then joined together using Autodesk ReCap and cleaned for the modeling phase (Figure 4).

Figure 4. The point cloud.

All different available data in various formats (paper documentation, dwg, pdf, doc files, etc.) and types (administrative, technical, managerial) were formatted and organized for their management and exchange, therefore optimizing their use in the modeling phase.

The first phase of BIM modeling involved the creation of a structural model. Using the point cloud and the AutoCad plans, "grids" corresponding to the pillars and "levels" corresponding to the various floors were generated (Figure 5).

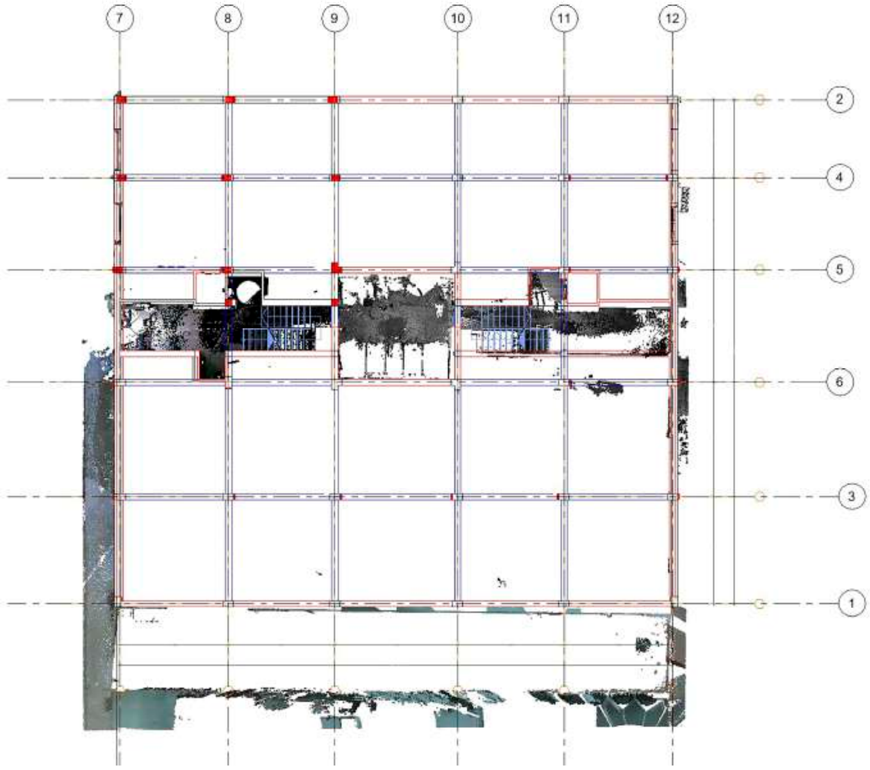


Figure 5. The modeling phase using the point cloud.

Subsequently, a structural and architectonic model was developed (Figure 6).

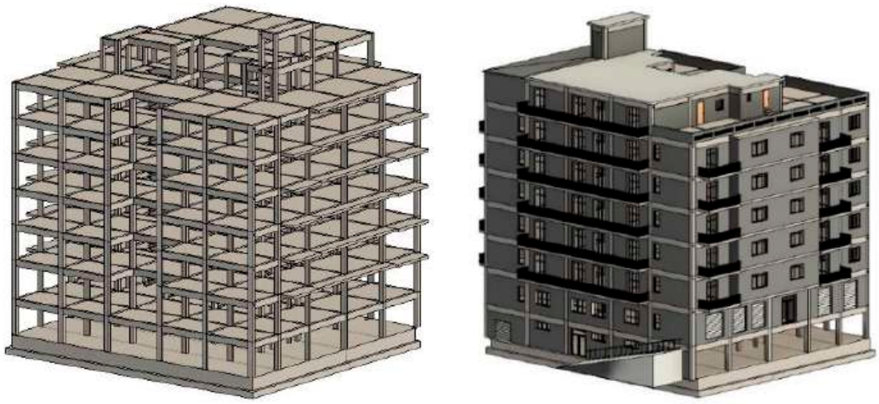


Figure 6. The structural and architectonic as-built of the sample building.

The level of information requirement (LOIN) for the specific information management process (UNI 17412:2021) [76] and the related development level (LOD) were established to clearly define the accuracy required within the BIM model (UNI 11337-4:2017) [77].

The import–export process used openBIM according to the IFC standard (UNI EN ISO 16739:2024) [78]. It was also applied to the transmission and data display during the in-use phase.

In relation to this phase, an important upgrade pointed to the modeling and uploading of the smart sensor as a new BIM object—ifcGUID (Figure 7).

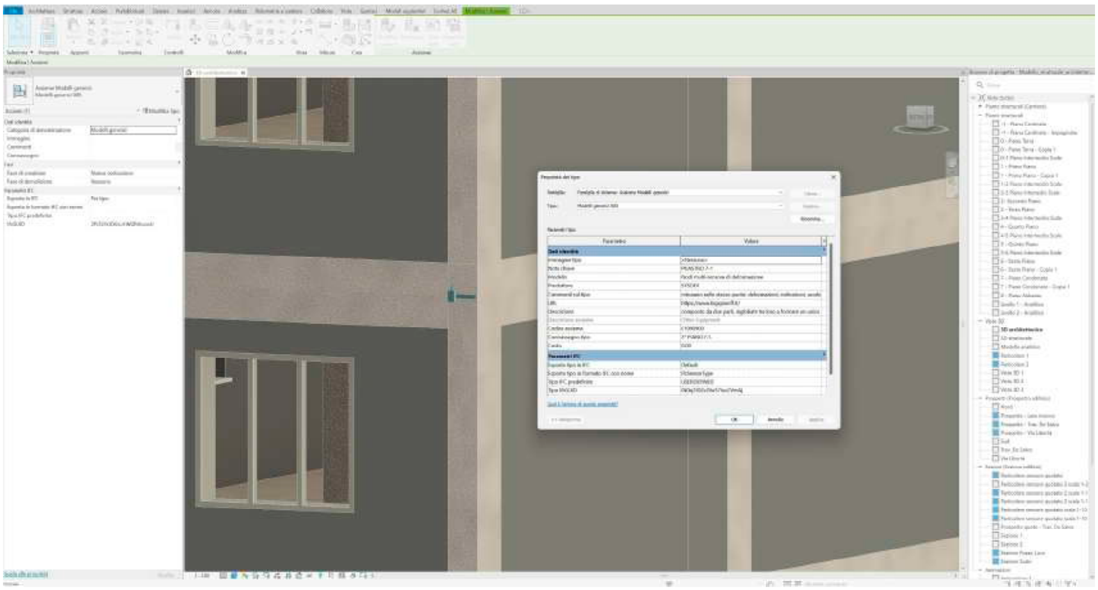


Figure 7. The smart-sensor system as a BIM object.

This allowed dual results: (i) the integration into the BIM workflow visualization of continuous monitoring and analysis of the building's seismic response and (ii) the dialogue with other structural or analysis tools (such as temperature control).

The definition of the new BIM object includes three specific aspects: geometric modeling, the attribution of data, and interoperability properties.

The first defines the 3D sensor geometry within BIM software concerning its size, shape, and position within the structure.

The attribution of data focuses on all possible insertions of sensor properties and installation specifications.

Finally, interoperability goals are finalized to ensure the BIM object sensor is compatible with the standard file formats used in BIM, such as Industry Foundation Classes and IFC, and especially to guarantee data exchange and interoperability with other software or design and structural analysis tools.

Thus, the smart sensor is available as an exportable BIM object—ifcSensorType—in IFC format in the as-built BIM model of the sample building. It is fitted out with properties (e.g., type, manufacturer) and technical parameters (e.g., sensitivity, measurement range) adjournable and implemented over time or integrable with other information such as installation specifications or maintenance data. It is also set to be integrated into the referred smart-sensor deployment plan that is calculated, validated and implemented for the sample building.

3.2.2. Smart-Sensor System and Internet of Things

The smart-sensor system for structural monitoring used in the experiment is SHBox® by Sysdev Srl, Torino, Italy, adopted in collaboration with the research group and applied to building structural elements (Figure 8). Sysdev srl is a startup that develops innovative structural sensor solutions. The ongoing collaboration between the authors, BIG srl and Sysdev srl, in certain operations on bridge monitoring has resulted in an added confirmation of the choice of this smart-sensor system.

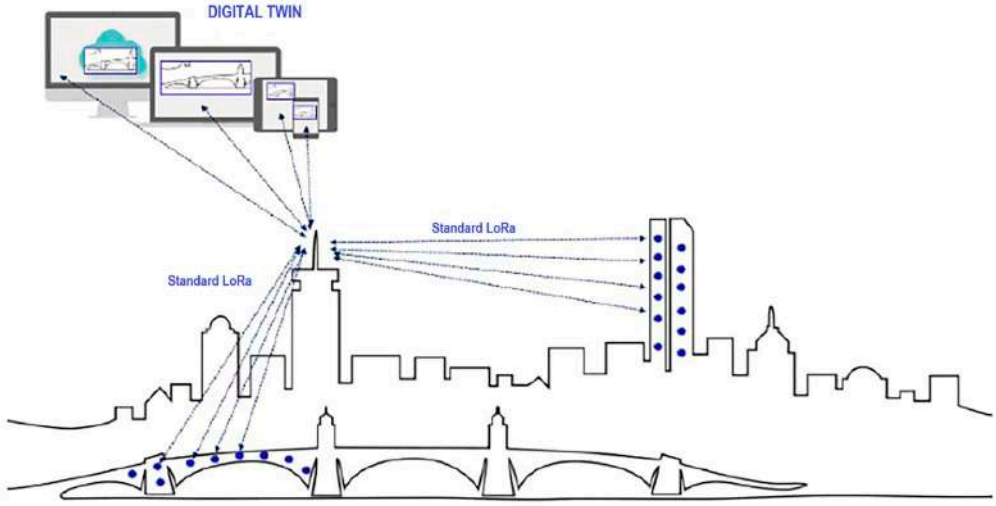


Figure 8. The smart-sensor system.

SHBox® is an innovative and static solution founded on the Internet of Things (IoT) paradigm using multi-sensor nodes connected via wireless technologies, smart metering, remote reading, and management. A network infrastructure allows the central management of data monitoring and its transmission to a centralized platform for processing, storage, and display. Multi-sensor nodes, infrastructure networks, and system software platforms constitute the components of the smart-sensor system.

Each multi-sensor node implements a LoRa transceiver with the referred LoRaWAN protocol. Multi-sensor nodes can, therefore, both connect to LoRa Sysdev networks and roam to public LoRa networks.

In both cases, data are sent to the system software platform for initial processing through algorithm libraries. Subsequently, filtered and aggregated data are retransmitted to the collaborative platform, usBIM.IoT, using the ACCA Software spa that provides the management of DT4SEM.

The network infrastructure is made up of new generation gateways (network access points) that communicate both with multi-sensor nodes through the LoRa protocol and with software platforms via the physical ETHERNET network—3G/4G. The gateway can also be connected to fiber-optic back panels.

The smart-sensor system operates with two types of multi-sensor nodes that can be used alternatively or in combination with each other.

- Multi-sensor displacement nodes measure at the same point: displacements, inclinations, accelerations (during a seismic event), seismic events, and temperature.
- Multi-sensor deformation nodes measure at the same point: deformations, inclinations, accelerations (during a seismic event), seismic events, and temperature.

In this experiment, multi-sensor deformation nodes were installed, also evaluating factors such as sensitivity, frequency range, and robustness (Figure 9).

The multi-sensor nodes represent the "atomic" elements of the system. They may be equated with the "elements" of a "point cloud" of a digital survey, with some differences: they are dynamic points, constantly updating, but at the same time, they enable the updating of the digital structural model, which has been built and interpolated using them.

Thus, this particular "point cloud" is both the reproduction of the structure system of the sample building and the representation of its dynamic DT. For this reason, the redundancy of multi-sensor nodes, such as the presence (deployment) of multiple nodes close together, does not constitute a duplication but an advance in accuracy and information. For example, a very long beam can take on a non-symmetrical profile if subjected to a load. In this case, deploying multiple multi-sensor nodes along the entire beam allows for a more accurate analysis than a simple average deformation.

Each node can detect potentially dangerous stress events for the building (earthquakes, explosions, impacts, etc.). By recording the progress of the event for its entire duration, the nodes allow the salient parameters to be processed in a summary form that can be immediately used to evaluate the impact on the structure.

MULTI–SENSOR NODE DATA SHEETOF DEFORMATION

It is composed of two parts, incorporated together to form a single object:

- A flexible part, made of plastic material, which incorporates the STRAIN-sensitive element and a Thermal guide for reading TEMPERATURE
- A rigid part (openable watertight container) containing the sensor electronics and the battery interchangeable

DIMENSIONS	FLEXIBLE PART	200x35x0.3mm	Strain sensitive part dimensions: 150 mm	It is completely watertight and sealed and can be painted or covered
	RIGID PART	98x64x47 mm	It is completely watertight and sealed and can be painted or covered with non-metallic materials (so as not to shield the radio emission). It is necessary to leave the cover accessible for battery replacement	

PARAMETER	RANGE	RESOLUTION	NOTE
Deformation (Strain)	+/−2.4%	10 microstrain	Bidirectional measurement performed along the longitudinal axis of the sensor
Temperature	−40°C /+125°C	+/−0.5 °C	Helps compensate for deformation induced by thermal expansion of the substrate
Inclination	–	0.005 °	Performed with triaxial accelerometer
Acceleration	+/−2g	–	Measured only during a seismic event

Seismic event

The sensor provides the following parameters as output:

- Duration of the seismic event, expressed in seconds
- Average frequency of the seismic event, for each axis (XYZ), expressed in Hz.
- Peak acceleration (positive and negative) recorded during the seismic event, for each axis (XYZ), expressed in mG
- Peak displacement (positive and negative) recorded during the seismic event, for each axis (X-YZ), expressed in mm

Simultaneously with the sampling of the acceleration on the 3 axes, a high frequency sampling (125 Hz) of the DEFORMATION is performed, storing the maximum value reached, both positive and negative. Furthermore, at the end of the seismic event, a final reading of the DEFORMATION and INCLINATION is performed to verify the effects of the earthquake on the monitored structure

DRUMS	Non-rechargeable lithium manganese battery with a total capacity of 6 A/h at a voltage of 6V.
DEGREE OF PROTECTION	IP67
OPERATIONAL RANGE	−40°C + 85°C
CERTIFICATIONS	RED 2014/53/EU – ATEX 2014/34/EU

Figure 9. Technical sheet: deformation multi-sensor node.

Thanks to these data, it will be possible to carry out static and continuous structural analysis activities, together with the dynamic detection of extraordinary stresses on the structure in the event of an earthquake or other sudden events (explosions, impacts, etc.).

They create an information infrastructure that activates significant potential data flows relating to the physical dimensions and performance of single parts of buildings.

The multi-sensor nodes are low-energy-consumption-based and powered by multi-year batteries to ensure service continuity. They are simple to install and maintain: no power line is required, and the battery is changed every year.

To avoid overloading the data network and maximize battery life, multi-sensor nodes operate according to an event logic. Each sensor, while carrying out a continuous measurement of the structure on which it is applied, autonomously transmits new data only when it verifies that the new value has significantly deviated from the previous one.

In the absence of events, a message is transmitted at configurable periods.

The smart-sensor system can automatically activate appropriate warning signals if the threshold values of the quantities measured by the multi-sensor nodes are exceeded. This information is made available via the usBIM.IoT platform. It implements supervision and remote control of IoT devices directly from the openBIM model, transforming it into a dynamic and reactive system to the events.

3.2.3. Collaborative Platforms and Cloud Computing and Storage

The collaborative platform is the usBIM.IoT, produced by ACCA Software spa, which is an open and accessible Platform As A Service (PAAS) specifically customized for data management (Figure 10).

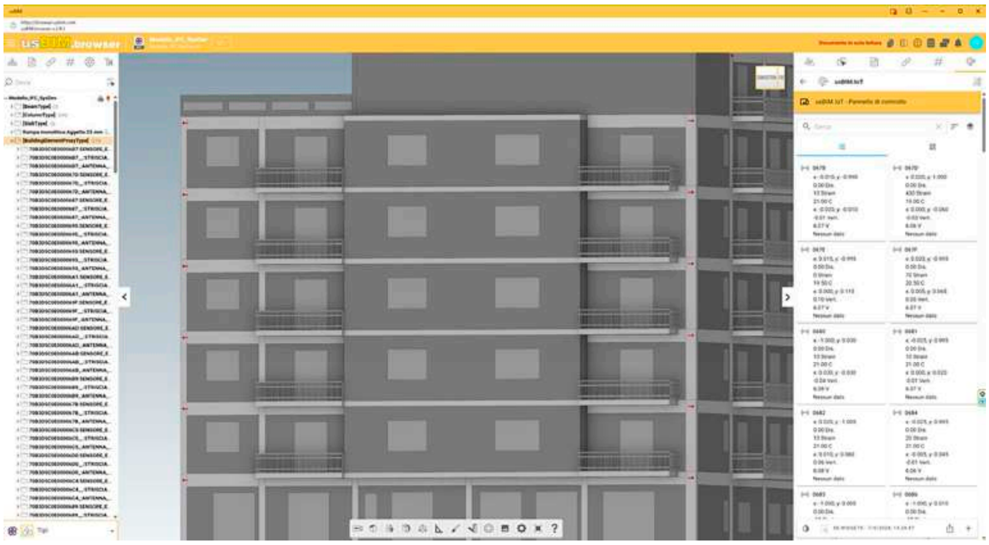


Figure 10. The collaborative platform.

It provides data collection, analysis, and visualization concerning the current DT4SEM experiment. It is usable online, directly by browser, by various operators (owners, managers, administrators, technicians and professionals, end users, etc.), allowing the management of openBIM models in a single common-data environment (CDE).

It also provides cloud computing and storage that makes mass memory available for archiving and managing BIM models and monitoring historical data.

Guaranteeing the historical storage of all detected data allows the differentiation of the visualization and analysis criteria based on the current and past state. Moreover, by integrating virtual and augmented reality, it is possible to use the openBIM 3D model for data visualization, subsequent simulations, and checks through specifically dedicated guided and customized navigation paths coherently with the functional localization and indication of active reports.

Thus, the platform is the management and control center of the LoRa data-collection network. It is the digital support where the dynamic virtual model of the physical reality monitored by the multi-sensor nodes takes shape and where data are collected.

The data from multi-sensor nodes may be evaluated individually but can also be dynamically re-aggregated via interpretive physical models. These models can refer directly to libraries of aggregation algorithms already provided and immediately usable. They can also be customized to the user's needs and operational requirements.

The platform's analytical tools process and interpret the data, identifying patterns, anomalies, and potential structural problems, and permitting automated alerts and maintenance schedules based on sensor data. At the same time, the platform's digital viewer tools allow real-time visualization of sensor data on the BIM model, granting intuitive and mainstream monitoring and evaluation even for non-expert end users.

Through the platform, it is possible to interact directly with a single node and check and change the operating parameters of the network sectors (served by the gateways).

In particular:

- Communications and user access take place via advanced cryptographically protected protocols (LoRa, TSL).
- Device firmware is protected from access and cloning by the processor.
- Access to data and a preliminary analysis of the state of the structures are simple, fast, and timely.
- The graphical interface is multi-device and multi-user, accessible from a browser in all its functions.
- The user interface is configurable based on different needs.
- Specific queries may be launched from end users, and dynamic chat activated between various operators with advanced team working functions and online meetings.

Moreover, the collaborative platforms of DT4SEM also guarantee:

- Maximum reliability in the conservation of historical data of the structures (the data are replicated on data centers located on two different continents).
- Complete continuity of service, even in the face of periodic maintenance and update interventions (SLA equal to 99.9%, failor over system).
- Ability to manage a very large number of data (dynamically scalable databases).
- Integrated management of the 3D visualization network.
- Integrated management of machine-learning algorithms for statistical and predictive analysis.
- Total scalability of the system, capable of supporting any expansion of both the number of sensors deployed and the number of users.
- The data-management platform facilitates automated alerts and maintenance scheduling based on sensor data.

3.3. The Deployment Plan of Multi-Sensor Nodes and Gateways

The deployment plan is the allocation of the smart sensors and gateways on the building sample according to a project properly designed by experts in load-bearing structures.

In this experiment, the deployment plan has provided the installation of 2 gateways and 85 multi-sensor nodes based on the LoRaWAN protocol (Figure 11).

The gateways and the multi-sensor nodes have been positioned and configured to ensure the most appropriate coverage of the building, carrying out monitoring and analysis both at the structural element and building scale.

The latter accounts for the analysis referring to a single element or a single zone. The coordinated processing of multiple measurements allows in-depth evaluation to be carried out on the entire building with the opportunity to compare its real behavior with theoretical simulation models.

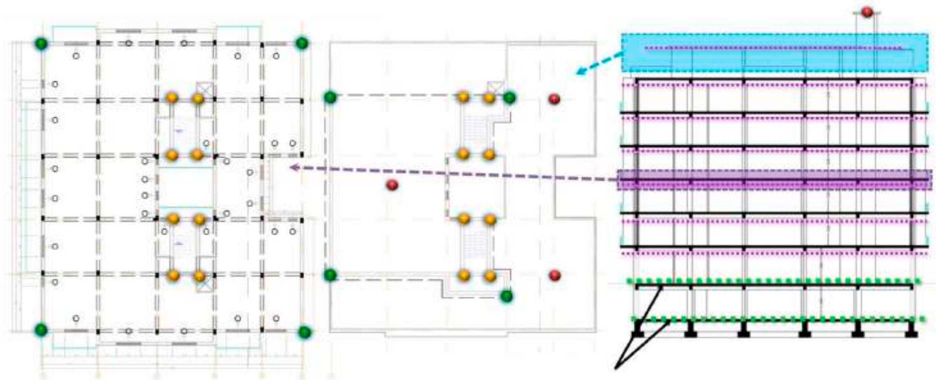
The new generation gateways and the network access points were installed both on the ground floor and on the terrace. They communicate with the multi-sensor nodes and the software platform via the 3G/4G physical ETHERNET network (Figure 12).

Each multi-sensor node is identifiable through 3D BIM coordinates. They were applied after analyzing the structure, geometry, and properties of the salient structural elements according to the point-cloud concept and the relative principle of redundancy.

Figure 11. The installed multi-sensor nodes

Figure 12. The installed gateway

They were allocated on the surface of the artifact to be monitored by gluing with rapid structural acrylic adhesive. For correct installation, the surface was adequately smoothed and prepared, removing external layers that were not perfectly integral to the body of the product, as well as cleaning away grease and dirt (Figures 13–15).



Description	No. Points	Plans	Total Points
Measuring Points on Floors	3	1	3
Measuring Points on Rigid Elements	8	7	56
Measure Points on Vertices and Shape Changes	4	7	28
Measuring Point on the Apice of the Building	1	1	1
Total			**88**
Acceleration to the Campaign Plan (optional)	4	0	4
Minimum sections to be monitored	Integrative sections to be monitored		

Figure 13. The deployment plan

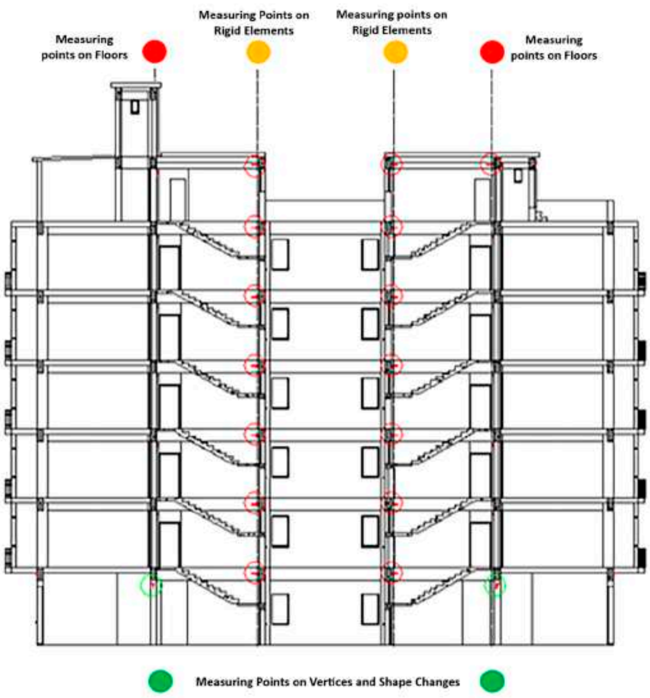


Figure 14. The deployment plan. Section of the sample building.

Address	Liberty Avenue 28, Reggio Calabria
Intervention	First intervention 20/11/2023–23/11/2023. Second intervention 12/02/2024–15/02/2024
date Installer	Earthy Plants on behalf of Sysdev
Gateways installed	2 – Kerlink Wirenet Station and Kerlink Istation
Gateways replaced	0
Multi-sensor nodes installed	n. 85 of type LR-SS (Multi-sensor nodes relevant for temperature, inclination, acceleration in case of seismic event and deformation)
Multi-sensor nodes replaced	No. 14
Configuration end date	02/19/2024
Multi-sensor node configuration	

Parameter	Unit of measure	Value	Notes
Acquisition interval	Seconds	14,400 (4 hours)	
Periodic Send Interval (HEARTBEAT)	Minutes	1,440 (24 hours)	
Strain activation threshold (for the foreseen models) (2)	microstrain	30,000	
Tilt threshold	Sexagesimal degrees	1	
Earthquake acceleration start threshold	mG	63	
Earthquake time threshold (1)	seconds	5	The value 255 deactivates the earthquake measurement
MMF earthquake frequency	percentage	90	
Earthquake acceleration end threshold	mG	63	

The multi-sensor node calibration procedure and setting was performed since the month of May 2024, at the end of the redevelopment works underway on the building, to avoid the continuous recording of non-standard information caused by construction site activities.

Figure 15. The installed deformation multi-sensor node

Gluing was mandatory for the multi-strain sensor node because the strain-sensitive part (black band) had to adhere perfectly to the surface of the structural element being monitored. In this regard, every possible air bubble underneath the strip was appropriately eliminated. Multi-sensor nodes are self-aligning. It is not necessary to align exactly with the Earth's vertical, as required by conventional inclinometers. It is also not necessary to reset the measurement bridge of the strain gauge, as required by conventional strain sensors.

4. Results

The installation of DT4SEM infrastructure was carried out between November 2023 and April 2024 at the end of a deep renovation of the building sample. This was to avoid recording non-standard information caused by construction site activities during the allocation and subsequent setting phases.

Following installation, since May 2024, a precise and efficient calibration procedure of the multi-sensor nodes and relative settings has been provided.

Furthermore, in-depth tests were also begun in order to verify the quality of the sensor node settings. The software platform was tested and configured to process data collected by the installed multi-sensor nodes. Once the check was completed, four sensors were not aligned and were unable to communicate with the platform. Therefore, they were replaced. Since then, verifications and setting tests have yielded positive results.

They have also confirmed the total scalability of the system, guaranteeing its capability of supporting any expansion of both the number of sensors deployed and the number of users.

Operation activation of DT4SEM and the related monitoring functionalities will follow shortly. It will definitely begin working when the site closes, all activities are completed, and the deep renovation project is settled, potentially in autumn 2024.

The last operation scheduled will be the installation of two 1905-cm monitors in the entrance hall of the two stairwells for real-time visualization of the data monitoring and DT navigation. They will show technicians and end users the real-time operating status of sensors and gateways, display the data values detected by the sensors and the operating temperature, and indicate the last alert issued relating to the recording of seismic events.

DT4SEM experimentation has reached the Technology Readiness Level 9 (TRL9): a system proven through successful operations in an operating environment and ready for full commercial deployment (Figure 16). The development process started at TRL6—technology demonstrated in the relevant environment [74]—and progressed through to an intermedium TRL8—system is complete and qualified [75].

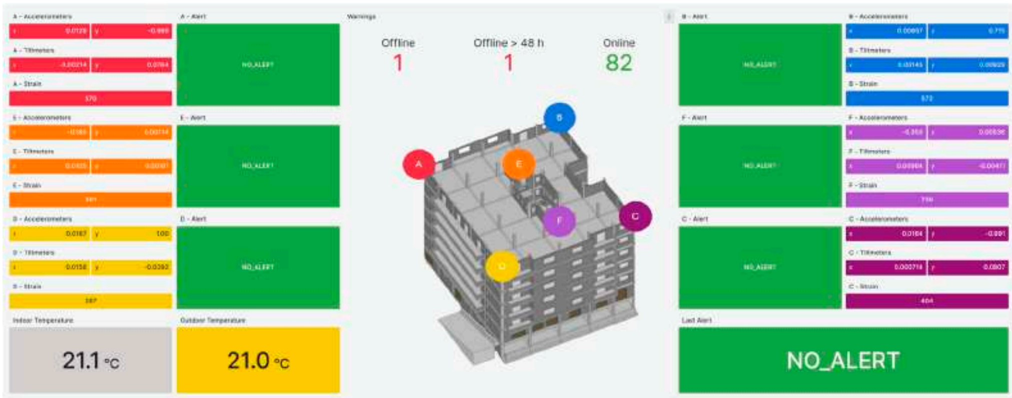


Figure 16. The dashboard of the collaborative platform.

DT4SEM infrastructure showcases the potential of DT in innovating and optimizing building management as well as controlling a building's safety and security conditions, offering real-time monitoring of the structural integrity of a building, guaranteeing automated alerts, providing fast intervention in the case of anomalies detected by one or more sensors, and scheduling maintenance.

Real-time data exchange between physical and virtual models also empowers stakeholders to make informed decisions, therefore fostering sustainability and safety, simulating different seismic scenarios, and analyzing the dynamic response of the building. Furthermore, the monitoring data can be compared with the results of simulation procedures by verifying their accuracy, also allowing their use as feedback data during the design phase.

As set out in the introduction, the proposal responds to the need for innovative governance of the built environment. Furthermore, DT4SEM deals with a mainstream application of seismic monitoring, considering existing residential buildings, not just particular circumstances or public buildings and monuments. The widespread application of the proposed infrastructure to residential buildings provides immediate data on the state of structures after a seismic event. This provides streamlining procedures to check the usability of buildings, timely intervention in the presence of high-risk conditions, and the general planning of necessary interventions based on priorities. They are all aspects that imply economic and social returns, the saving of resources, and opportunities for sustainable and coherent intervention.

5. Discussion

DT4SEM experimentation presented here confirms the digital twin as a potential paradigm shift for the built environment. Meanwhile, the preliminary results deriving from it specifically demonstrate the effectiveness of the DT approach for providing early warnings about structural issues. The virtual model visualizes and simulates different scenarios, facilitating informed decision-making for building management and optimizing maintenance schedules.

Future research on DT4SEM upgrades will focus on its broader adoption in the building sector for optimizing and controlling the carbon footprint of existing buildings and related decarbonization processes. The proposed seismic monitoring experimental application and feedback from data monitoring can significantly influence building design management and maintenance strategies.

The current new machine-friendly and interconnected spatiality promotes the evolution of smart buildings into cognitive buildings, equipping buildings—now intelligent constructions—with systems and devices that carry out activities, provide services, collect and return data, and exchange information from human to human, from human to machine, and between humans and machines. According to these new perspectives, technical challenges and fostering interdisciplinary collaborations can enhance the integration of data-driven approaches, such as the DT approach, through advanced technologies, sensors for comprehensive building monitoring, and predictive analytics algorithms. In particular:

- Data-driven approaches to ensure the safety and resilience of buildings. The monitoring data acquired by seismic sensors can be appropriately used in a post-earthquake detection phase by implementing the information and measures used by civil protection organizations and other emergency services. Detailed and historical documentation—pre- and post-earthquake—can improve the accuracy of damage assessments, supporting decision-making processes regarding priorities and the urgency of intervention. Finally, it can contribute to the improvement of procedures activated by all organizations involved via the possible implementation of information with new metrics or criteria referring to the data expressed by sensors [79–81].
- Advanced dynamic modeling and predictive simulations. The accuracy and understanding of building behavior during seismic events can be enhanced by incorporating historical data from seismic monitoring. This facilitates predictive simulations to assess seismic risk and identify critical areas requiring urgent interventions [82–84].
- Integration of innovative technologies for energy and seismic monitoring. Seismic monitoring can be integrated with other innovative technologies for building decarbonization, such as energy consumption sensors, automated control systems, and energy recovery/storage technologies. This integration improves building energy management, reduces greenhouse gas emissions, and optimizes energy use by simulating HVAC (heating, ventilation, and air-conditioning) systems and analyzing thermal flows [85–87].
- Energy efficiency management. Seismic monitoring can contribute to identifying dynamic building characteristics, including foundation and structural behavior patterns. By integrating seismic monitoring data, it is possible to evaluate how structural modifications impact building energy and environmental performance. These data can be used to optimize building design for enhanced energy efficiency. For instance, knowledge of building vibrations and oscillations can influence foundation design to reduce dissipated energy and optimize thermal performance, contributing to the reduction of the carbon footprint of buildings [88–90].
- Predictive maintenance and asset management. By integrating seismic monitoring data into the digital twin, it is possible to monitor structural aspects and predict

maintenance needs. This helps extend lifespan and reduces the resource consumption required for maintenance activities [91–94].

- Risk management and urban planning. Seismic monitoring provides crucial information for seismic risk management at an urban level. A better understanding of building seismic dynamics can influence urban planning policies and the design of earthquake-resistant infrastructure, contributing to more sustainable and resilient urban planning. This approach makes buildings nods of smart grids and smart cities capable of communicating with other buildings, safety systems, and end users [95–97].

Thus, the widespread use of digital twins results in a number of general benefits. Some of them already characterize the studies developed by the authors and the current experimentation of DT4SEM, and define contemporarily further research activities/domains/implementations as listed above.

Author Contributions: Conceptualization, M.L. and M.A.; methodology, M.L.; validation, M.L.; formal analysis, M.A.; investigation, M.A.; data curation, M.A.; writing—original draft preparation, M.L. and M.A.; writing—review and editing, M.A.; supervision, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in 2018 by POR Calabria Region funds, grant number 994926; in 2020 by the Italian Ministry of Economic Development, MISE, grant number 0002411; in 2021 by the Smart&Start Italia subsidy program of Invitalia Spa, grant number 7033269; in 2022 by the Italian Ministry of University and Research, MUR, DM 1062/2021, grant number C35F21001280009.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are unavailable due to privacy.

Acknowledgments: For the BIG srl spinoff, Tommaso Melchini and Antonino Gulletta participated in the research with an operational role.

Conflicts of Interest: The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results. The authors declare no conflicts of interest.

References

1. *COM/2009/512*; Preparing for Our Future: Developing a Common Strategy for Key Enabling Technologies in the European Union. EU-COM: Maastricht, The Netherlands, 2009.
2. Schwab, K. *The Fourth Industrial Revolution*; Portfolio Penguin: London, UK, 2016.
3. *COM/2021/118*; Digital Compass: The European Way for the Digital Decade. EU-COM: Maastricht, The Netherlands, 2021.
4. *COM/2010/245*; A Digital Agenda for Europe. EU-COM: Maastricht, The Netherlands, 2010.
5. EU. *A Europe Fit for the Digital Age*; EU-COM: Maastricht, The Netherlands, 2020.
6. EU. *Shaping Europe's Digital Future*; EU-COM: Maastricht, The Netherlands, 2020.
7. *COM/2020/102*; A New Industrial Strategy for Europe. EU-COM: Maastricht, The Netherlands, 2020.
8. PwC-PricewaterhouseCoopers. *Global Industry 4.0 Survey. Industry 4.0: Building the Digital Enterprise*; PwC-PricewaterhouseCoopers: Amsterdam, The Nederlands, 2016.
9. Omrany, H.; Al-Obaidi, K.M.; Husain, A.; Ghaffarianhoseini, A. Digital twins in the construction industry—A comprehensive review of current implementations, enabling technologies, and future directions. *Sustainability* **2023**, *15*, 10908. [CrossRef]
10. EU. *Industry 5.0: Towards More Sustainable, Resilient and Human-Centric Industry*; EU: Maastricht, The Netherlands, 2021.
11. Geraldo, G.; Bisset-Alvarez, E.; Pinto, M.D.S. Digital Humanities and the Sustainable Development Goals: A reflection for Information Science. *Transinformação* **2023**, *35*, e227210. [CrossRef]
12. Zhao, N.; Zhang, H.; Yang, X.; Yan, J.; You, F. Emerging information and communication technologies for smart energy systems and renewable transition. *Adv. Appl. Energy* **2023**, *9*, 100125. [CrossRef]
13. Samuelson, O.; Stehn, L. Digital transformation in construction—A review. *J. Inf. Technol. Constr.* **2023**, *28*, 385–404. [CrossRef]
14. Kineber, A.F.; Singh, A.K.; Fazeli, A.; Mohandes, S.R.; Cheung, C.; Arashpour, M.; Ejohwomu, O.; Zayed, T. Modelling the relationship between digital twins implementation barriers and sustainability pillars—Insights from building and construction sector. *Sustain. Cities Soc.* **2023**, *99*, 104930. [CrossRef]
15. Xu, S.; Wang, J.; Liu, Y.; Yu, F. Application of emerging technologies to improve construction performance. *Buildings* **2023**, *13*, 1147. [CrossRef]

16. Caprari, G.; Castelli, G.; Montuori, M.; Camardelli, M.; Malvezzi, R. Digital Twin for Urban Planning in the Green Deal Era—A State of the Art and Future Perspectives. *Sustainability* **2022**, *14*, 6263. [CrossRef]
17. Olanipekun, A.O.; Sutrisna, M. Facilitating Digital Transformation in Construction—A Systematic Review of the Current State of the Art. *Front. Built Environ.* **2021**, *7*, 660758. [CrossRef]
18. Succar, B.; Poirier, E. Lifecycle Information Transformation and Exchange for Delivering and Managing Digital and Physical Assets. *Autom. Constr.* **2020**, *112*, 103090. [CrossRef]
19. Leng, J.; Wang, D.; Shen, W.; Li, X.; Liu, Q.; Chen, X. Digital twins-based smart manufacturing system design in Industry 4.0: A review. *J. Manuf. Syst.* **2021**, *60*, 119–137. [CrossRef]
20. *ISO 15686—7:2017(en)*; Buildings and Constructed Assets—Service Life Planning—Part 7: Performance Evaluation for Feedback of Service Life Data from Practice. ISO: Geneva, Switzerland, 2017.
21. Wu, H.; Ji, P.; Ma, H.; Xing, L. A Comprehensive Review of Digital Twin from the Perspective of Total Process: Data, Models, Networks and Applications. *Sensors* **2023**, *23*, 8306. [CrossRef] [PubMed]
22. Lauria, M.; Azzalin, M. Digital Twin Approach in Buildings: Future Challenges via a Critical Literature Review. *Buildings* **2024**, *14*, 376. [CrossRef]
23. Carpo, M. *The Digital Turn in Architecture 1992–2012*; Wiley: Chichester, UK, 2013.
24. Carpo, M. *The Second Digital Turn in Architecture. Design Beyond Intelligence*; MIT Press: Cambridge, MA, USA, 2017.
25. UN—General Assembly. *Transforming Our World—The 2030 Agenda for Sustainable Development*; Document A/RES/70/1; UN—General Assembly: New York, NY, USA, 2015.
26. IPCC—Intergovernmental Panel on Climate Change. *Global Warming of 1.5 °C—An IPCC Special Report*; IPCC: Geneva, Switzerland, 2018.
27. IPCC—Intergovernmental Panel on Climate Change. *Climate Change 2023—Synthesis Report—Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2023.
28. EU. *Stepping up Europe's 2030 Climate Ambition Investing in a Climate-Neutral Future for the Benefit of Our People*; Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions—562 Final; EU: Maastricht, The Netherlands, 2020.
29. *COM/2020/103*; An SME Strategy for a Sustainable and Digital Europe. EU-COM: Maastricht, The Netherlands, 2020.
30. EU. *The European Green Deal*; Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions—Document 52019DC0640, 640 Final; EU: Maastricht, The Netherlands, 2019.
31. *COM/2020/662*; A Renovation Wave for Europe. Greening Our Buildings, Creating Jobs, Improving Lives. EU-COM: Maastricht, The Netherlands, 2020.
32. Menegon, J.; da Silva Filho, L.C.P. The Impact of Industry 4.0 Concepts and Technologies on Different Phases of Construction Project Lifecycle: A Literature Review. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2023**, *47*, 1293–1319. [CrossRef]
33. Wang, K.; Guo, F. Towards Sustainable Development through the Perspective of Construction 4.0: Systematic Literature Review and Bibliometric Analysis. *Buildings* **2022**, *12*, 1708. [CrossRef]
34. Fokaides, P.A.; Apanaviciene, R.; Cerneckiene, J.; Jurelionis, A.; Klumbyte, E.; Kriauciunaite-Neklejonoviene, V.; Pupeikis, D.; Rekus, D.; Sadauskiene, J.; Seduikyte, L.; et al. Research challenges and advancements in the field of sustainable energy technologies in the built environment. *Sustainability* **2020**, *12*, 8417. [CrossRef]
35. Dale, K.I.; Pope, E.C.D.; Hopkinson, A.R.; McCaie, T.; Lowe, J.A. Environment Aware Digital Twins—Incorporating Weather and Climate Information to Support Risk-Based Decision-Making. *Artif. Intell. Earth Syst.* **2023**, *2*, 1–6. [CrossRef]
36. Grieves, M. *Product Lifecycle Management: Driving the Next Generation of Lean Thinking*; McGraw-Hill: New York, NY, USA, 2006.
37. Grieves, M. *Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management*; Space Coast Press: Merritt Island, FL, USA, 2011.
38. Grieves, M. Virtually Intelligent Product Systems: Digital and Physical Twins. In *Complex Systems Engineering: Theory and Practice*; Flumerfelt, S., Ed.; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2019.
39. Gartner Inc. *Gartner Survey Reveals Digital Twin Are Entering Mainstream Use*; Gartner: Stamford, CT, USA, 2019.
40. Research and Market. *Digital Twin Market Size, Share & Trends Analysis. Report by End-Use (Manufacturing, Agriculture), by Solution (Component, Process, System), by Region, and Segment Forecasts, 2023–2030*; Research and Market: Dublin, Ireland, 2022.
41. Piras, G.; Agostinelli, S.; Muzi, F. Digital Twin Framework for Built Environment—A review of Key Enablers. *Energies* **2024**, *17*, 436. [CrossRef]
42. *COM/2022/289*; Strategic Foresight Report Twinning the Green and Digital Transitions in the New Geopolitical Context. European Parliament and Council of the European Union, Final Document 52022DC0289; EU-COM: Maastricht, The Netherlands, 2022.
43. EU. *Study on the Development of an European Union Framework for Digital Building Logbooks*; Final Report; EU: Maastricht, The Netherlands, 2021.
44. Mêda, P.; Hjelseth, E.; Calvetti, D.; de Sousa, H. Data Templates and Digital Building Logbooks boosting Digital Twin in Construction. In Proceedings of the Conference CIB W78 2021, Luxembourg, 11–15 October 2021.
45. Boschert, S.; Rosen, R. *Digital Twin—The Simulation Aspect. Mechatronic Futures Challenges and Solutions for Mechatronic Systems and their Designers*; Hehenberger, P., Bradley, D., Eds.; Springer Nature: Berlin/Heidelberg, Germany, 2016.

46. Visartsakul, B.; Damrianant, J. A review of building information modeling and simulation as virtual representations under the digital twin concept. *Eng. J.* **2023**, *27*, 11–27. [CrossRef]
47. Yang, B.; Lv, Z.; Wang, F. Digital Twins for Intelligent Green Buildings. *Buildings* **2022**, *12*, 856. [CrossRef]
48. Mukhacheva, A.V.; Ugryumova, M.N.; Morozova, I.S.; Mukhachyev, M.Y. Digital Twins of the Urban Ecosystem to Ensure the Quality of Life of the Population. In Proceedings of the International Scientific and Practical Conference Strategy of Development of Regional Ecosystems "Education-Science-Industry" (ISPCR 2021), Online, 7–8 December 2021; Atlantis Press: Amsterdam, The Netherlands, 2022; pp. 331–338.
49. Laamarti, F.; Badawi, H.F.; Ding, Y.; Arafsha, F.; Hafidh, B.; Saddik, A.E. An ISO/IEEE 11073 Standardized Digital Twin Framework for Health and Well-Being in Smart Cities. *IEEE Access* **2020**, *8*, 105950–105961. [CrossRef]
50. Rao, A.S.; Radanovic, M.; Liu, Y.; Hu, S.; Fang, Y.; Khoshelham, K.; Palaniswami, M.; Ngo, T. Real-time monitoring of construction sites: Sensors, methods, and applications. *Autom. Constr.* **2022**, *136*, 104099. [CrossRef]
51. Alanne, K.; Sierla, S. An overview of machine learning applications for smart buildings. *Sustain. Cities Soc.* **2022**, *76*, 103445. [CrossRef]
52. Cespedes Cubides, A.S.; Jradi, M. A review of building digital twins to improve energy efficiency in the building operational stage. *Energy Inform.* **2024**, *7*, 11. [CrossRef]
53. *ISO 19650-1:2024*; Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling. Part 1: Concepts and Principles. ISO: Geneva, Switzerland, 2024.
54. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]
55. Nguyen, T.D.; Adhikari, S. The role of BIM in Integrating Digital Twin in Building Construction: A Literature Review. *Sustainability* **2023**, *15*, 10462. [CrossRef]
56. Wang, W.; Guo, H.; Li, X.; Tang, S.; Li, Y.; Xie, L.; Lv, Z. BIM Information Integration Based VR Modeling in Digital Twins in Industry 5.0. *J. Ind. Inf. Integr.* **2022**, *28*, 100351. [CrossRef]
57. Delgado, J.M.D.; Butler, L.J.; Brilakis, I.; Elshafie, M.Z.; Middleton, C.R. Structural performance monitoring using a dynamic data-driven BIM environment. *J. Comput. Civ. Eng.* **2018**, *32*, 04018009. [CrossRef]
58. Jacoby, M.; Usländer, T. Digital Twin and Internet of Things—Current Standards Landscape. *Appl. Sci.* **2019**, *10*, 6519. [CrossRef]
59. Baghalzadeh Shishehgarkhaneh, M.; Keivani, A.; Moehler, R.C.; Jelodari, N.; Roshdi Laleh, S. Internet of Things (IoT), Building Information Modeling (BIM), and Digital Twin (DT) in Construction Industry: A Review, Bibliometric, and Network Analysis. *Buildings* **2022**, *12*, 1503. [CrossRef]
60. Böhm, F.; Dietz, M.; Preindl, T.; Pernul, G. Augmented Reality and the Digital Twin—State of the art and perspectives for Cybersecurity. *J. Cybersecur. Priv.* **2021**, *1*, 519–538. [CrossRef]
61. Sacks, R.; Brilakis, I.; Pikas, E.; Xie, H.S.; Girolami, M. Construction with Digital Twin information systems. *Data-Centric Eng.* **2020**, *1*, e14. [CrossRef]
62. Qi, Q.; Tao, F.; Hu, T.; Anwer, N.; Liu, A.; Wei, Y.; Wang, L.; Nee, A.Y.C. Enabling technologies and tools for digital twin. *J. Manuf. Syst.* **2019**, *58*, 3–21. [CrossRef]
63. Lu, Q.; Xie, X.; Parlikad, A.K.; Schooling, J.M.; Konstantinou, E. Moving from building information models to digital twins for operation and maintenance. *Proc. Inst. Civ. Eng. Smart Infrastruct. Constr.* **2020**, *174*, 46–56. [CrossRef]
64. 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]
65. Motamedi, A.; Hammad, A.; Asen, Y. Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management. *Autom. Constr.* **2014**, *43*, 73–83. [CrossRef]
66. Errandonea, I.; Beltrán, S.; Arrizabalaga, S. Digital Twin for maintenance: A literature review. *Comput. Ind.* **2020**, *123*, 103316. [CrossRef]
67. Xu, J.; Shu, X.; Qiao, P.; Li, S.; Xu, J. Developing a digital twin model for monitoring building structural health by combining a building information model and a real-scene 3D model. *Measurement* **2023**, *217*, 112955. [CrossRef]
68. Mishra, M.; Lourenço, B.P.; Ramana, G.V. Structural health monitoring of civil engineering structures by using the internet of things: A review. *J. Build. Eng.* **2022**, *48*, 103954. [CrossRef]
69. Funari, M.F.; Hajjat, A.E.; Masciotta, M.G.; Oliveira, D.V.; Lourenço, P.B. A Parametric Scan-to-FEM Framework for the Digital Twin Generation of Historic Masonry Structures. *Sustainability* **2020**, *13*, 11088. [CrossRef]
70. Sampaio, A.Z.; Gomes, A.M. BIM interoperability analyses in structure design. *Civ. Eng.* **2021**, *2*, 174–192. [CrossRef]
71. Lauria, M.; Azzalin, M.; Gulletta, A.; Saturno, F. BIM-Based Procedures for Testing Digital Building Envelope Models. In *ETHICS: Endorse Technologies for Heritage Innovation*; Battisti, A., Baiani, S., Eds.; Springer Nature: Berlin/Heidelberg, Germany, 2024; ISBN 978-3-031-50120-3.
72. Delgado, J.M.D.; Oyedele, L. Digital Twin for the built environment: Learning from conceptual and process models in manufacturing. *Adv. Eng. Inform.* **2021**, *49*, 101332. [CrossRef]
73. Zhang, Z.; Wei, Z.; Court, S.; Yang, L.; Wang, S.; Thirunavukarasu, A.; Zhao, Y. A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry. *Buildings* **2024**, *14*, 1113. [CrossRef]

74. Lauria, M.; Azzalin, M. Azzalin, M. A Maintenance Management Model. Upgrading and Experimentation. In *Current Topics and Trends on Durability of Building Materials and Components, Proceedings of the XV Edition of the International Conference on Durability of Building Materials and Components (DBMC 2020) International Center for Numerical Methods in Engineering, Barcelona, Spain, 20–23 October 2020*; Serrat, C., Ramon Casas, J., Gibert, V., Eds.; International Center for Numerical Methods in Engineering (CIMNE): Barcelona, Spain, 2020.
75. Lauria, M.; Azzalin, M. Intelligent Construction via Digital Twin Approach. In Proceedings of the XVI Edition of the International Conference on Durability of Building Materials and Components (DBMC 2023), Beijing, China, 10–13 October 2023; Li, K.F., Fang, D.P., Eds.; DBMC: Quang Ngai City, Vietnam, 2023. [CrossRef]
76. *UNI 17412-1:2021*; Building Information Modelling—Livello di Fabbisogno Informativo—Parte 1: Concetti e Principi. UNI: Milan, Italy, 2021.
77. *UNI 11337-4:2017*; Edilizia e Opere di Ingegneria Civile—Gestione Digitale dei Processi Informativi delle Costruzioni—Parte 4: Evoluzione e Sviluppo Informativo di Modelli, Elaborati e Oggetti. UNI: Milan, Italy, 2017.
78. *UNI EN ISO 16739-1:2024*; Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries—Part 1: Data Schema. UNI: Milan, Italy, 2024.
79. Mata, O.; Méndez, J.I.; Ponce, P.; Peffer, T.; Meier, A.; Molina, A. Energy Savings in Buildings Based on Image Depth Sensors for Human Activity Recognition. *Energies* **2023**, *16*, 1078. [CrossRef]
80. Rodríguez-Quiñonez, J.C.; Valdez-Rodríguez, J.A.; Castro-Toscano, M.J.; Flores-Fuentes, W.; Sergiyenko, O. Inertial Methodology for the Monitoring of Structures in Motion Caused by Seismic Vibrations. *Infrastructures* **2024**, *9*, 116. [CrossRef]
81. Hassani, S.; Dackermann, U.; Mousavi, M.; Li, J. A systematic review of data fusion techniques for optimized structural health monitoring. *Inf. Fusion* **2024**, *103*, 102136. [CrossRef]
82. Hu, Y.; Wang, W.; Li, L.; Wang, F. Applying Machine Learning to Earthquake Engineering: A Scientometric Analysis of World Research. *Buildings* **2024**, *14*, 1393. [CrossRef]
83. Jarah, N.B.; Alasadi, A.H.H.; Hashim, K.M. Earthquake prediction technique: A comparative study. *IAES Int. J. Artif. Intell. (IJ-AI)* **2023**, *2252*, 1027.
84. Mangalathu, S.; Sun, H.; Nweke, C.C.; Yi, Z.; Burton, H.V. Classifying earthquake damage to buildings using machine learning. *Earthq. Spectra* **2020**, *36*, 183–208. [CrossRef]
85. Foti, D.; Ruggiero, F.; Sabbà, M.F.; Lerna, M. A Dissipating Frames for Seismic Retrofitting and Building Energy-Efficiency. *Infrastructures* **2020**, *5*, 74. [CrossRef]
86. Penazzato, L.; Illampas, R.; Oliveira, D.V. The Challenge of Integrating Seismic and Energy Retrofitting of Buildings: An Opportunity for Sustainable Materials? *Sustainability* **2024**, *16*, 3465. [CrossRef]
87. Zhuang, D.; Gan, V.J.; Tekler, Z.D.; Chong, A.; Tian, S.; Shi, X. Data-driven predictive control for smart HVAC system in IoT-integrated buildings with time-series forecasting and reinforcement learning. Appl. *Energy* **2023**, *338*, 120936.
88. Arezki, S.; Kamel, L.; Amar, K. Effects of temperature changes on the behavior of a cable truss system. *J. Constr. Steel Res.* **2017**, *129*, 111–118.
89. Shi, G.; Liu, Z.; Meng, X.; Wang, Z. Intelligent Health Monitoring of Cable Network Structures Based on Fusion of Twin Simulation and Sensory Data. *Symmetry* **2023**, *15*, 425. [CrossRef]
90. Menna, C.; Vitiello, U.; Mauro, G.M.; Asprone, D.; Bianco, N.; Prota, A. Integration of Seismic Risk into Energy Retrofit Optimization Procedures: A Possible Approach Based on Life Cycle Evaluation. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Prague, Czech Republic, 2–4 July 2019.
91. Saloux, E.; Zhang, K.; Candanedo, J.A. A Critical Perspective on Current Research Trends in Building Operation: Pressing Challenges and Promising Opportunities. *Buildings* **2023**, *13*, 2566. [CrossRef]
92. Zhao, Y.; Wang, N.; Liu, Z.; Mu, E. Construction Theory for a Building Intelligent Operation and Maintenance System Based on Digital Twins and Machine Learning. *Buildings* **2022**, *12*, 87. [CrossRef]
93. Mahmoodian, M.; Shahrivar, F.; Setunge, S.; Mazaheri, S. Development of Digital Twin for Intelligent Maintenance of Civil Infrastructure. *Sustainability* **2022**, *14*, 8664. [CrossRef]
94. Coupry, C.; Noblecourt, S.; Richard, P.; Baudry, D.; Bigaud, D. BIM-Based Digital Twin and XR Devices to Improve Maintenance Procedures in Smart Buildings: A Literature Review. *Appl. Sci.* **2021**, *11*, 6810. [CrossRef]
95. Hassebo, A.; Tealab, M. Global Models of Smart Cities and potential IoT applications—A Review. *IoT* **2023**, *4*, 366–411. [CrossRef]
96. Ariyachandra, M.R.M.F.; Wedawatta, G. Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts. *Sustainability* **2023**, *15*, 11910. [CrossRef]
97. Apanaviciene, R.; Shahrabani, M.M.N. Key Factors Affecting Smart Building Integration into Smart City: Technological Aspects. *Smart Cities* **2023**, *6*, 1832–1857. [CrossRef]