

OPEN ACCESS

Preface

To cite this article: 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1402** 011001

View the [article online](#) for updates and enhancements.

You may also like

- [Calibration of the NEXT-White detector using \$^{83m}\text{Kr}\$ decays](#)
G. Martínez-Lema, J.A. Hernando Morata, B. Palmeiro et al.
- [Radiopurity assessment of the tracking readout for the NEXT double beta decay experiment](#)
S. Cebrían, J. Pérez, I. Bandac et al.
- [Design and characterization of the SiPM tracking system of NEXT-DEMO, a demonstrator prototype of the NEXT-100 experiment](#)
V Álvarez, M Ball, F I G Borges et al.



The Electrochemical Society
Advancing solid state & electrochemical science & technology

ECS UNITED

247th ECS Meeting
Montréal, Canada
May 18-22, 2025
Palais des Congrès de Montréal

Showcase your science!

**Abstracts due
December
6th**

PREFACE

This **NEXTBUILT 2024** Conference Proceedings comprise the selected papers contributing to the 2024 **International Conference on Challenges for the NEXT generation BUILT Environment**, held in Bologna on two years basis, with the ambition to become a reference event to share and discuss drivers of change, barriers and solutions for shaping the future built environment considering the impact of Climate Change. The Conference is one of the main outcomes of the NEXTBUILT Observatory, whose main scope is to collect, analyse, and report information, research, and studies dealing with the most urgent and hot topics influencing the transformation directions in contemporary cities with a forward-looking perspective. The initiative is supported and fed by the research activity run at the Department of Architecture of the **University of Bologna** as well as by the constant transformative plans led by the City of Bologna.

NEXTBUILT 2024 was **held in Bologna on May 9th and 10th 2024**, with the chance to join the conference online for those who were not able to attend in person, under the overarching theme of **“a reflection on the future of the built environment within a context of resource scarcity or heavily influenced by climate change impacts, assuming a strong future oriented approach”**.

The conference was accordingly organized around four main topics:

- **Energy use and affordability in the built environment**

Energy market global instability, progressive fossil fuel scarcity and related price fluctuations call for new approaches which combine technical and socio-economical interventions to possibly ensure fair and sustainable access to adequate energy services for all. Nonetheless, energy poverty rates are rising globally without effective and future-oriented solutions being promptly drafted to mitigate the impact of this issue. Besides, it strongly emerges the need to shift to cleaner energy sources while possibly reducing the demand intensity and impacts of the building sector. It is largely agreed within the scientific community that structural changes should be made to reduce the roots of energy challenges in the built environment, but how can policymakers, planners, and designers innovate the retrofiting market remains an open issue despite it is acknowledged to be the most urgent and promising field of action.

- **Water scarcity and cities response capacity to extreme events**

In recent years, many countries worldwide have suffered the effects of climate change, especially in relation to water. From devastating floods to severe droughts, water scarcity or abundance is increasingly affecting life in urban environments, involving over half of the world population according to IPCC projections. On the one hand, conventional water management solutions in cities have been proven inadequate to address intense rain events and water needs; on the other, progressive climate topicalization is posing a risk to ensuring adequate access to fresh water. Cities are actively seeking effective solutions to reduce the flood risk and save water for use (including, among others, water-efficient buildings and construction processes), but more integrated and interdisciplinary approaches are not well-established yet. More integrated and systemic solutions to let cities and buildings be reshaped to mitigate and/or adapt to increasingly severe water-related issues are needed.

- **New paradigms in buildings and components expected lifetime**

Heavy depletion of natural resources and the need to achieve carbon neutrality targets are strongly encouraging policymakers, researchers, and designers to change their perspectives on life-cycle impacts, durability and service life of buildings and components. However, the majority of current interventions in the building sector are still focused on lowering the operational energy demand while paying less attention to embodied energy and carbon as well as to the end-of-life stage. The increasingly fast evolution of needs and requirements is calling to strategically rethink the expected lifespan of buildings and to carefully consider the use of materials and design choices within a circular-based perspective, not only at the local level but also at a larger scale. This seeks for innovative measures, methodologies, procedures, and tools to facilitate and support a mind shift and a market transition.

- **Tools and means to go beyond the climate neutral transition**

Current policies, measures and tools to achieve sustainable development and carbon neutrality have largely proven inadequate and limited. Many of them can only deal with short-term visions and effects of planning procedures, design, and building processes. However, given the unpredictability of the future in the long run, effective and forward-thinking measures must be taken now. Can the carbon neutrality challenge, which is now assumed to be a target, be turned into a useful means to that end?



The main issue remains to plan, design, and build for future changes that will almost certainly imply progressive resource scarcity (physical and non-physical) along with other challenges yet to come.

The breadth and urgency of the topics allowed to collect several insightful and novel contributions spanning current trends and innovations, empirical findings and concrete applications in the fields of science, industry, policy, and governance. However, the main detected barriers to concrete progress deal with the lack of systemic approaches and long-term visions to go beyond the urgency of the present time. In the background, the need for more balanced and environmentally driven economic models remains a turning point yet to come.

The conference stimulated a vivid dialogue between the invited keynote speakers and the participants in both the plenary and parallel sessions. NEXTBUILT 2024 had the privilege to host:

- **Brenda Boardman**, from the Environmental Change Institute, University of Oxford, whose studies since the early 90s contributed to providing the definition of Energy Poverty still in use globally. Her key lecture titled *Energy prices, energy efficiency and equity* considered the competing needs of the poorest households and climate change, both today and into the future.
- **Louisa Bowles**, Partner and Head of Sustainability at Hawkins\Brown, who has led several multi-disciplinary projects and is an active contributor to many industry organisations working to improve environmental performance. Her key lecture titled *Circular economy, buildings as material banks* stimulated a reflection on a mind shift in the way we use and understand the service life of materials in contemporary architecture.
- **Paolo Negro**, Research officer at the Joint Research Centre of the European Commission, with a long experience in research activity and scientific policy advising, whose key lecture titled *A strategy for the holistic rehabilitation of buildings and the new European Bauhaus* outlined the main challenges at EU level with reference to multiple actions under the umbrella of the green deal.
- **Elisabete Teixeira**, from the University of Minho where she serves as a dedicated Researcher at ISISE (Institute for Sustainability and Innovation in Structural Engineering). Her key lecture titled *Synergizing nature-based solutions for water resilience and urban infrastructure protection* highlighted the importance of more coordinated actions and systemic approaches to put in place more effective mitigative strategies.

The conference included eleven parallel sessions organised during the two days to expand the dialogue opportunities and to let all the participants from seventeen countries exchange ideas and proposals for facilitating synergies and future cooperation opportunities. A NEXT TALK inviting three architectural design firms, NET Engineering, Pier Currà Architettura, Open Project, was also held to bridge the gap between academic research and the professional market enlarging the horizon of research to very practical implications. As the necessary transition of our built and urban environments is becoming more urgent NEXT BUILT tried to attract the attention of the key involved stakeholders to stimulate collaboration and partnerships while laying the foundations for meaningfully shaping policy, practice, and capacity-building programs.

This Proceedings collect the main individual contributions organized according to the four main topics that underpin the conference's scientific program. Each submission underwent a two-round (abstract and full paper) double-blind peer-review process. The NEXTBUILT Scientific Committee and the Editors carefully handled the process to ensure only those meeting the necessary scientific standards were presented at the conference and included in these proceedings.

Editors

Jacopo Gaspari

Licia Felicioni

Lia Marchi

Ernesto Antonini

8 July 2024

NEXTBUILT 2024 Scientific Committee members and Reviewers (alphabetical order)**SCIENTIFIC COMMITTEE**

Laura Aelenei | Responsible for the Energy in Built Environment Research Area, Renewable Energy and Energy Efficiency Unit | LNEG – Lisbon, Portugal

Ernesto Antonini | Professor | Department of Architecture – University of Bologna, Italy

Noura Arab | Senior Lecturer | École nationale supérieure d'architecture de Normandie – Rouen, France

Jeremy Auerbach | Lecturer/Assistant Professor | University College Dublin, School of Geography – Dublin, Ireland

Valter Balducci | Professor | École nationale supérieure d'architecture de Normandie – Rouen, France

John Boardman | Emeritus Professor | Environmental Change Institute, Oxford, United Kingdom

Andrea Campioli | Professor | Department of Architecture, Built Environment and Construction Engineering (ABC) | Politecnico of Milano – Milano, Italy

Joaquim Comas Matas | Professor | University of Girona – Girona, Spain

Gareth Doherty | Professor | Harvard University Graduate School of Design – Harvard, United States

Geraint Ellis | Professor | School of Natural and Built Environment, Queen's University – Belfast, United Kingdom

Stephen Emmitt | Professor | Head of Department of Architecture and Civil Engineering – University of Bath, United Kingdom

Pietromaria Davoli | Professor | Department of Architecture – University of Ferrara – Ferrara, Italy

Kristian Fabbri | Lecturer/Assistant Professor | Department of Architecture – University of Bologna, Italy

Cristina Garzillo Leemhuis | Senior Coordinator | Culture and Cultural Heritage – Governance and Social Innovation – ICLEI European Secretariat – Freiburg, Germany

Jacopo Gaspari | Professor | Department of Architecture – University of Bologna, Italy

Marcio Gonçalves | R&D, Technical and Scientific Committee | ITECONS – Coimbra, Portugal

Petr Hajek | Professor | Faculty of Civil Engineering – Czech Technical University in Prague, Czechia

Kevin Hom | Professor – Fellow American Institute of Architects | Former Dean City University New York School of Technology and Design – New York, United States

Mohataz Hussain | Senior Lecturer | Department of the Natural and Built Environment, Sheffield Hallam University – Sheffield, United Kingdom

Nguyen Thai Huyen | Architect-urban planner | Vice director of Institute of International Training and Cooperation | Hanoi Architectural University – Hanoi, Vietnam

Aura Istrate | Lecturer/Assistant Professor in Urban Planning | University College Dublin, School of Architecture, Planning and Environmental Policy – Dublin, Ireland

Raphaël Labrunye | Architect | Director of ENSA Normandie – Rouen, France

Pamela Lama | Senior Program Manager | UNOPS United Nations Office for Project Services – Tirana, Albania

Ana Llopis Alvarez | Associate Professor | Department of Industrial Economics, Risk Management and Planning – University of Stavanger, Norway

Mario Losasso | Professor | Department of Architecture | University of Naples Federico II | SiTDA President – Naples, Italy

Antonín Lupíšek | Professor and Director of Research and Innovation | University Centre for Energy Efficient Buildings, Brno, Czech Republic

Antonello Monsù Scolaro | Professor | Department of Architecture, Design and Urban Planning, University of Sassari – Sassari, Italy

Valentina Orioli | Professor | Deputy Mayor for Mobility, infrastructures, liveability – Municipality of Bologna, Italy

Francesco Pilla | Professor | Smart & Sustainable Cities, Spatial Dynamics Lab, University College Dublin – Dublin, Ireland

Lucia Alexandra Popartan | Postdoctoral researcher | University of Girona – Girona, Spain

Filomena Russo | Climate Positive Environments Module Leader, Post Carbon Culture Module Leader | University of Westminster – London, United Kingdom

Ayşen Savaş | Professor | Department of Architecture – Middle East Technical University – Ankara, Turkey

Rosa Schiano-Phan | Principal Lecturer and Course Leader in Architecture and Environmental Design MSc | University of Westminster – London, United Kingdom

Rizal Sebastian | Professor | THUAS The Hague University of Applied Sciences – The Hague, the Netherlands

Cristian Silva | Lecturer | School of Natural and Built Environment (SNBE), Queen's University Belfast – Belfast, United Kingdom

Jan Tywoniak | Professor | Faculty of Civil Engineering – Czech Technical University in Prague, Czechia

Fabrizio Tucci | Professor | Department of Planning, Design Technology for Architecture – Sapienza University of Rome – Rome, Italy

Els van de Moortel | Postdoctoral researcher | KU Leuven, Department Architecture – Leuven, Belgium

Martin Volf | Senior researcher | University Centre for Energy Efficient Buildings – Bustehrad, Czech Republic

Julie Železná | Senior researcher | University Centre for Energy Efficient Buildings – Bustehrad, Czech Republic

NEXTBUILT 2024 Hosting Institution Board

Ernesto Antonini, Andrea Boeri, Jacopo Gaspari, Danila Longo, Beatrice Turillazzi

The editors are grateful to the members of the organizing staff for their contribution

Matteo Bertelli, Yu Chen, Zhengzheng Luo, A. Cristiana Palazzo, Yehui Peng

PAPER • OPEN ACCESS

New paradigms shift in buildings: experimental application of Digital Twin for safety and well-being

To cite this article: Maria Azzalin *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1402** 012046

View the [article online](#) for updates and enhancements.

You may also like

- [Space approaching assessment of SVOM satellite to other space objects](#)
Dong Li, Hu Jiang, Xiaofeng Zhang et al.
- [Amidoximated Bacterial Cellulose Film for Pb²⁺ Adsorption in Aqueous Environment](#)
O Oktaviani, A R Syahputra, A L Yunus et al.
- [Development of commercial fountain clocks in NIM](#)
Kun Liu, Fasong Zheng, Weiliang Chen et al.



ECS The Electrochemical Society
Advancing solid state & electrochemical science & technology

ECS UNITED

247th ECS Meeting
Montréal, Canada
May 18-22, 2025
Palais des Congrès de Montréal

Showcase your science!

Abstracts due December 6th

New paradigms shift in buildings: experimental application of Digital Twin for safety and well-being

Maria Azzalin^{1*}, Massimo Lauria², Antonino Gulletta, Tommaso Melchini

¹ *Mediterranean University of Reggio Calabria, Department of Architecture and Territory, Via dell'Università 25, 81124, Reggio Calabria, Italy*

² *Mediterranean University of Reggio Calabria, Department of Civil, Energy, Environmental and Material Engineering, Via dell'Università 25, 81124, Reggio Calabria, Italy*

*Corresponding author: maria.azzalin@unirc.it

Abstract. Enhancing durability and service life of buildings and components is pivotal for sustainable development. It constitutes an opportunity to reduce energy consumption, carbon emissions and life cycle impact of buildings in a climate neutral perspective. Issues strongly introduced and set as priorities by EU policies that highlight the urgent need to tackle them also through deeply heritage renovation and digital transformation in the building sector. Digitalization is a cornerstone of this transformation, instrumental in facilitating and enabling it sustainably. The Key Enabling Technologies (KETs) are directly associated with new technological potential and emerging technologies. Digital Twin (DT) approach appears alongside these. Its experimentation and widespread application are gaining prominence in innovating Life Cycle Management (LCM) and sustainability practices of buildings.

In this scenario the paper explores the role and potentialities of DT approach presenting the experimental application of the DT4SEM. A digital infrastructure that, by integrating Internet of Things (IoT), synchronizes a physical building with its virtual counterpart. The two realities (physical and virtual) remain interconnected through the mutual exchange of data, both in real-time and asynchronously enabling proactive monitoring and analysis of seismic behaviour. The experimental setup involves simultaneously Big Data analytics, simulation tools and deploying sensors within the sample building. Data is then fed into the virtual DT model, allowing for continuous comparison and analysis to detect anomalies and predict potential risks. This approach facilitates enhanced decision-making, performance optimization and sustainability improvements across the building's lifecycle: a new vision for built environment management that evolves from a process resulting in a sequence of operative phases into a complex digital infrastructure. The design of the DT4SEM and the current application for seismic monitoring in buildings, results from a collaborative effort involving the academic spinoff BIG srl, the startup Sysdev, the company Berna Engineering srl, and ACCA Software spa.

Keywords: Digital Twin, seismic monitoring, decarbonization, energy efficiency

1. Introduction

After years of indifference to the environment, low productivity and limited technological innovations, the Construction sector is now undergoing an in-depth revision and innovation process of its statutes and operativeness.

This process must necessarily be combined with the broader challenges of Agenda 2030.

Sustainable development cannot ignore more conscious, innovative and inclusive governance actions for the social and economic development of cities and communities. Renovation and management of the



built environment become the expression of a new transformation perspective capable of involving the environment as a whole on different scales: environment, landscape, territory, cities and buildings. Further, life cycle strategies assume the role of key actions achieving the decarbonisation of the building stock into the timeframes of both the 2030 and 2050 scenarios for carbon and climate neutrality [1-4].

Thus, the interaction of climate neutrality with digital assets also emerges as a key issue, specifically supported by the application of Information Communication Technologies (ICT) with related enabling and emerging technologies – such as Building Information Modeling (BIM), Internet of Things (IoT) and Digital Twin – to improve decision-making processes of the built environment in a sustainable governance perspective.

Nevertheless, the strategies for decarbonization of buildings and their implementation in sustainable processes and operational practices still need systemic and scalable innovations, to bridge the current gap between traditional modalities and the digital frontier [5].

According to Energy Performance of Buildings Directive, 85% of EU buildings were built before 2000, and amongst those, 75% have poor energy performance [6].

Therefore, a complex and articulated system of possible new challenges takes shape. Enhancing durability and service life of buildings and components, optimizing energetical performance, reducing energy consumption and emissions, they all constitute an opportunity to reduce life-cycle impact from which economic, environmental and extra social costs derive [7].

With reference to this scenario and increasing attention to environmental vulnerability resulting from natural disasters or extreme weather events, including seismic, the paper introduces an ongoing experimental application of Digital Twin – DT4SEM - to monitor seismic and energetical building behaviour.

2. Background

At the European level introducing key enabling technologies (KETs) marks the beginning of the digital transformation of industrial and productive sectors [8].

KETs combine and establish a strong integration between research and industry affirming through their digital matrix the dual purpose of supporting innovation and operativity, promoting improved digital solutions for processes, products and services.

Many years after their introduction, European digital policies still affirm and strengthen the same principles: digitalization, automation and interconnection of production processes [9–11].

By moving away from the simple digitization phase, KETs and emerging technologies are now driving a new and ongoing phase of the digital transformation of industrial sectors [12].

Nowadays, in the context of the Fourth Industrial Revolution [13], starting from Digital Agenda, the European policies mark the transition from Industry 4.0 to Industry 5.0, opening new development scenarios [14–17].

The EU report “Industry 5.0 introduces a new “stage” in the historical sequence of Industrial Revolutions. It affirms the need to accelerate the transformation already underway - digital and ecological - to restore the environment and the economy, focusing on three principles: centrality of man - self-sustainability - flexibility and resilience [18].

A Collaborative Industry and Super Smart Society affirmed by intelligent cooperation between machines and humans, to accompany the transition from digital industry to digital society.

For the construction sector it means increasing attention towards the issues of durability and life cycle management, energy efficiency and the recovery of existing buildings [19–21].

The European Green Deal [22] supports specific aforesaid issues such as:

- *Circular Economy Action Plan* promoting the principles of circularity throughout the life cycle of buildings to increase the efficiency of materials, reduce climate impact and improve the durability and adaptability of buildings in the life cycle [23].
- *A Europe fit for the digital age* encouraging digital transformation to combat climate change and achieve the green transition [9].

- *A Renovation Wave for Europe - Greening our buildings, creating jobs, improving lives* formalizing the goal of doubling the upgrade of existing building stock to achieve greater energy efficiency contributing to the process of decarbonization by 2030 [24].

In line with these political and strategic goals, some other operational principles and indicators have been established, such as:

- *Energy Performance of Buildings Directive* promoting policies to achieve high energy efficiency and decarbonised building stock by 2050; introducing a methodology and a related Indicator to measure the smart readiness of existing buildings, i.e., their ability to be included in the digital reconversion process of buildings [6].

These are general goals that have already been affirmed, but rarely placed so explicitly close to each other both from a political and operative point of view.

Meanwhile, enabling and emerging technologies introduce new opportunities to manage the whole life cycle of buildings. This starts from the design to the construction and operation phases, involving multidisciplinary and transdisciplinary approaches. The management of great amount of information is required pertaining to performance and operation data in buildings, as well as behavioural and experiential aspects related to end users, their well-being and their level of satisfaction [25,26]

The Digital Twin approach constitutes the key aspect of this new perspective [27].

Coined by Michael Grieves in 2011, the term Digital Twin simultaneously defines the digital and virtual reality of a physical object [28]. Since its introduction by Grieves, a few years before, the Digital Twin has configured a dynamic operational tool linking the real and virtual realms throughout a system's lifecycle: from design and production to use and disposal [29].

Following Grieves's vision, applied research across various scientific fields is increasingly validating the significance of the Digital Twin concept and affirming its importance [30].

In 2019, a survey on the adoption of innovative technologies has identified digital twins among the top five emerging trends driving technological innovation for the coming decades [31]. Market trends also confirm its exponential growth and potential [32].

Nowadays in the construction sector, the Digital Twin enables intelligent construction advancing from Smart Buildings to Cognitive Buildings: "Phygital" constructions that leverage, synergically, data and information modeling throughout the building's lifecycle [33,34].

It guarantees - with Building Information Modeling (BIM), Geographic Information Systems (GIS), Internet of Things (IoT), smart connection and sensor systems such as Home Automation and Building Automation Control Systems (BACS), Augmented and Virtual Reality (AR/VR), data analytics, blockchain, Artificial Intelligence and machine learning solutions - a unique and synergic convergence of capacities to generate, manage, and exchange information throughout the entire lifecycle of buildings, monitor real-time building performances and simulate or predict behaviour during the time. This close integration optimizes building management by organizing and systematizing complex information networks also integrating real-time monitoring data [35-38].

According to this background, experimental applications of Digital Twin methodologies aim to implement structured decision-making processes for reducing the environmental impact of buildings and infrastructure, plan maintenance strategies, enhancing end-user comfort and satisfaction. They enable simultaneous management of available and acquired information from operational conditions surveys, real-time monitoring and updating of sensor-collected data, anomaly and risk detection and performance simulations using machine learning and artificial intelligence [39-41].

Thus, the challenge, as defined by the European Commission in the strategic foresight report 2022 "Matching ecological and digital transition in the new geopolitical context" is to use Digital Twins to revolutionize urban planning, monitoring, and management. This could lead to reduced urban emissions, increased resource efficiency and quality of life, better utilization of building space and improved building resilience against hazardous events [42].

3. An experimental application of Digital Twin for safety and well-being in buildings

The previous paragraph underlines increase attention to the built environment vulnerability, resulting from natural disasters and extreme weather and seismic events.

Moreover, the Digital Twin effort in combining real entities and computational models, assumes high potential to improve, in a sustainable and climate-neutral perspective, design, monitoring, control and management of buildings.

In this scenario, the authors, as a group of researchers also operating at BIG srl, an Academic spinoff of the Mediterranean University of Reggio Calabria, three of which are among its founding partners, involving the startup Sysdev, the company Berna Engineering srl, and ACCA Software spa, implemented and prototyped a new experimental application of the digital infrastructure, the Management Model, promoting an innovative vision for the management of seismic safety and well-being in buildings [43,44].

BIG srl operates in the field of technological innovation exploiting the potential of Information Communication Technology (ICT), in line with the operational trend of Industry 4.0. To implement its mission, it assumes the interactions between technological capital (infrastructure and technology), human capital (researchers, companies, professionals, end users, etc.), administration (institutions, universities, managers, etc.) and real estate (public and/or private heritage). Its goal is to promote the introduction of smart processes for the experimentation, implementation and dissemination of innovative systems for the governance of real estate assets (www.bigspinoff.it).

3.1. *The architecture of the Digital Twin for monitoring seismic behaviour in buildings*

The Digital Twin for monitoring seismic behaviour in buildings uses the potential of advanced technologies, already available but not yet widely systemised in the service of the construction sector.

DT4SEM achieves synchronization between the sample building and its virtual model.

Throughout the entire life cycle, the two realities (physical and virtual) will remain connected through the mutual exchange of data and information, both in real-time and asynchronously.

Its architecture consists of:

- The “as built” BIM digital model. It is the graphic and informative model of the sample building, complete with information and technical specifications relating to the assets it contains. According to the ISO 19650 standard, the “as built” dimension corresponds to the digital representation of the construction systems to which the scheduling of Operation and Maintenance phase is associated.
- A smart connection hardware and system sensors. They monitor the performance through real-time acquisition and recording of data.
- The Internet of Things. It connects sensors, software and ICT technologies across the network. It creates an information infrastructure that activates significant potential data flows relating to the physical dimensions and performance of single parts of buildings.
- A collaborative platform. It is an open, accessible Platform As A Service (PAAS), usable online by various operators (owners, managers, administrators, technicians and professionals, end users), allowing the management of openBIM models in a single Common Data Environment (CDE). By integrating viewers, virtual and augmented reality, the usage of the digital model for data visualization and subsequent simulations and checks is possible.
- A Cloud computing and storage. It makes mass memories available for archiving and contextual management of BIM models.

3.2. *The sample building and its digital model*

The sample building is in Reggio Calabria, Viale della Libertà 28.

It is a six-storey building on which the company Berna Engineering srl has carried out deep restoration since late 2022 (Figure 1).

The load-bearing structure is made up of reinforced concrete pillars and beams.



Figure 1. The sample building before and during renovation.

The first step to create the as-built digital model was the systematization of the available information which, disaggregated, was organized in relation to the different formats (paper documentation, dwg, pdf, doc files, etc.) and different types (administrative, technical, management). The structuring and organization of data was aimed towards accurate management and transmission of information.

Furthermore, the possibility of using reverse engineering approaches - “scan to BIM” - allows the control and integration of information derived from the design documentation made available by the client. Imaging techniques and a laser scanner were used for the survey (Figure 2).

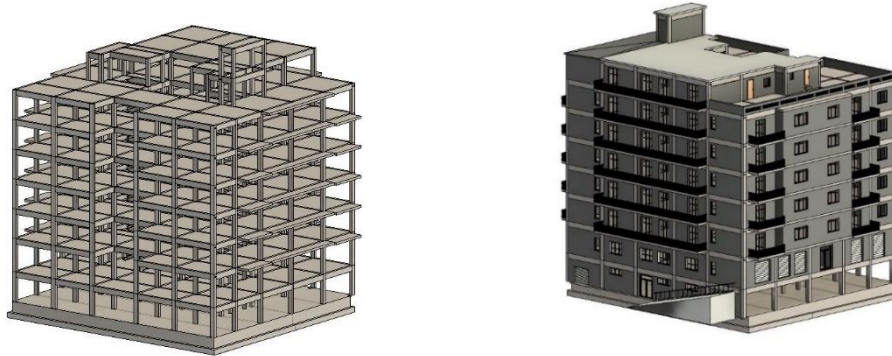


Figure 2. The survey phase with laser scanner.

The produced point cloud was assembled and cleaned for export to the modeling phase (Figure 3).

At the same time, attention was paid to the issue of openBIM using the IFC standard (UNI EN ISO 16739) for the import/export process of information models, as well as for the transmission and display of data during the in-use phase (Figure 4).

The level of information requirement (LOIN) for the start of the information management process (UNI 17412) and the definition of the development level (LOD) for the modeling phase were decisive in defining the information and geometric accuracy (UNI 11337-4).



Figures 3 and 4. The structural and architectural us built of the sample building.

3.3. The Deployment Plan of multi-sensor node and gateway

Once the architectural and structural as-built of the building had been created, a “Deployment Plan” was processed to analyse the structure and to define the most effective position of multi-sensor nodes. They record seismic events and measure displacements, inclinations, accelerations during a seismic event, and external temperatures.

Each is identifiable through 3D BIM coordinates as shown in the figures below (Figure 5, 6).

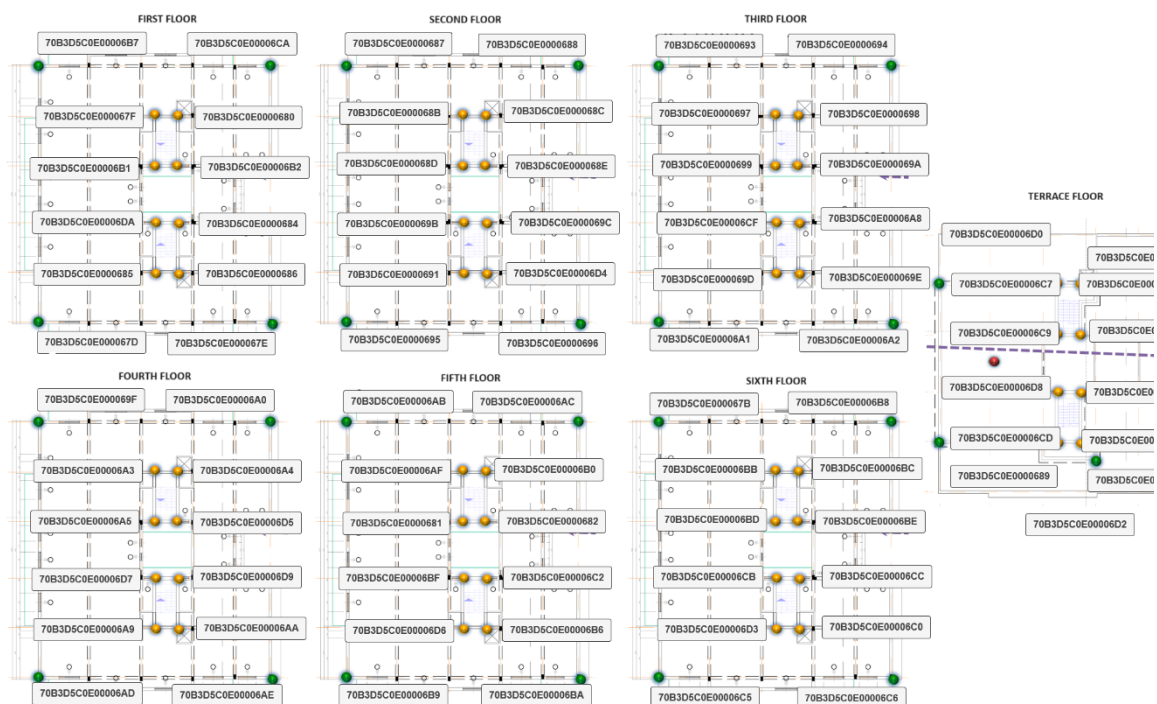


Figure 5. The Deployment Plan of multi-sensor node and gateway. Floor plans.

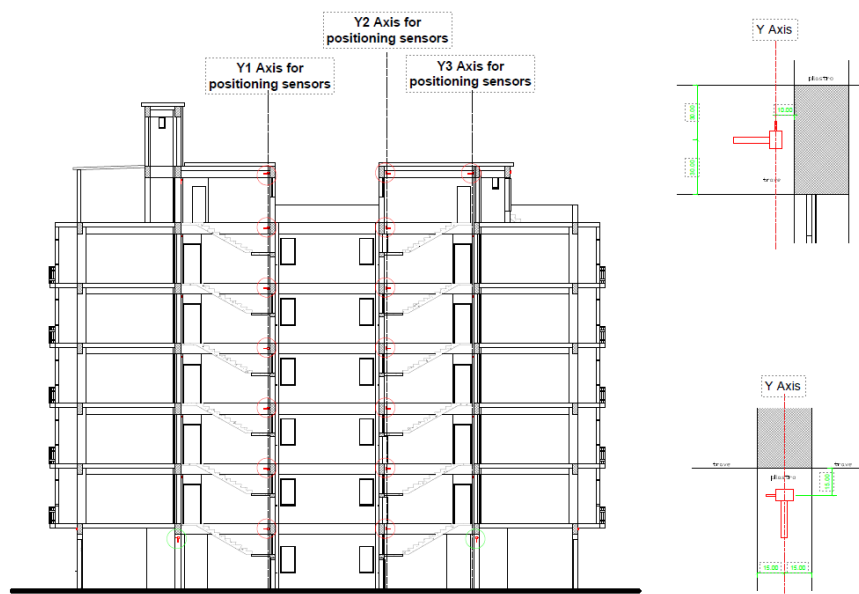


Figure 6. The Deployment Plan. Section of the sample building and details.

According to the concept of “point cloud” and the related intrinsic principle of redundancy, the best positioning of the multi-sensor nodes to be applied on the salient structural elements, was defined. The multi-sensor nodes are the “atomic” elements of the system, similar to a digital survey “point cloud”, with the difference that they are dynamic points. In fact, they constantly update the structural digital model. The redundancy of multi-sensor nodes does not constitute their duplication but an increase in the resolution of the information.

Thus, the gateways and multi-sensor nodes have been positioned and configured to ensure optimal coverage of the building. In this way it will be possible to carry out monitoring and analysis both at structural element scale and at that of the building as one.

The latter overcomes the analysis referring to the single element or the single zone. Thanks to the coordinated processing of multiple measurements, it allows in-depth evaluations to be carried out on the entire building with the opportunity to compare its real behaviour with theoretical simulation models.

Between November 2023 and February 2024, the startup Sysdev (www.sysdev.eu) installed 2 gateways and 85 multi-sensor nodes based on the LoRaWAN protocol (Figure 7).





Figure 7. The multi sensor nodes installed.

A gateway was installed on the ground floor and one on the terrace.

The new generation gateways (network access points) communicate with the multi-sensor nodes and with the software platform via 3G/4G physical ETHERNET network (Figure 8).



Figure 8. The gateway installed.

At the end of the installation, in-depth tests were conducted to verify the correct functioning of the system. Subsequently, the software platform was configured for the analysis of the data acquired by the installed multi-sensor nodes.

The calibration procedure of the multi-sensor nodes and the setting was carried out in February 2024 at the end of the deep renovation underway on the building, to avoid the continuous recording of non-standard information caused by construction site activities.

3.4. *The collaborative platform to exchange data through network infrastructures*

The definition of DT4SEM is completed through the virtual recombination of the information detected by the deployment of the multi-sensor nodes in a collaborative platform; a Platform As A Service (PAAS) usable online by various operators (owners, managers, administrators, technicians and professionals, end users). The multi-sensor nodes and the collaborative platform exchange data through a network infrastructure.

In the experimentation described the platform for data processing, storage and visualization is the “usBIM.IoT”, produced by ACCA Software spa, and specially customized for the specific experimentation. (www.acca.it/bim-iot-platform)

In its current configuration it allows:

- Viewing of the openBIM three-dimensional digital model through specifically dedicated guided and/or customized navigation paths, functional to the localization and indication of active “reports”.
- Viewing and organizing sensor data on the model in real time with a dedicated dashboard.
- Implementing the supervision and remote control of IoT devices directly from the openBIM model, which becomes a dynamic system that reacts in real time to the events generated by the multisensor nodes.
- Accessing data and related processing directly from the browser.
- Activating appropriate warning signals if the threshold values of the quantities measured by the multi-sensor nodes are exceeded.
- Reconstructing the structural performance of the building over time, ensuring the historical storage of any data collected.
- Implementing the integrated management of machine learning algorithms for statistical and predictive analysis, as well as reporting deviations and anomalies in the structural state of the building.
- Checking and changing the operating parameters of the individual monitored structural nodes.
- Activating specific queries from end users and dynamic chat between different operators with advanced team working functions, online meetings and conference call.

To date, verification and setting tests have all given positive results, guaranteeing the total scalability of the system, capable of supporting any expansion of both the number of sensors deployed and the number of users. DT4SEM is tested and ready to go into operation as soon as two 75" monitors are installed in the entrance hall of the two stairwells. These will inform technicians and end users in real time about the operating status of sensors and gateways; they will display the data values detected by the sensors and the operating temperature; they will indicate the last alert issued relating to the recording of a seismic event.

4. **Implications and Discussion**

The DT4SEM presents an original experimental proposal of research dealing with the potentiality of DT in enhancing the durability and service life of buildings and components combining monitoring of the building's seismic behaviour with decarbonization issues and control of carbon emission of the existing building stock.

Thus, a new potential paradigm shift for the built environment through Digital Twin in building appears. Hereafter some aspects from the study are listed.

Optimization of decarbonization strategies. Digital twins can be utilized to simulate building decarbonization scenarios, considering factors such as energy efficiency, resource utilization, and emissions reduction. By integrating seismic monitoring data, it is possible to evaluate how structural modifications impact building energy and environmental performance [45-47].

Integration of innovative technologies. 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 resource use by simulating HVAC (Heating, Ventilation, and Air Conditioning) systems and analyzing thermal flows [48-50].

Energy efficiency management. Digital twins consolidate multiple data sources, including building energy consumption data. Adding information from seismic monitoring helps identify correlations between structural behaviour and energy performance, supporting targeted decarbonization interventions to optimize building energy efficiency. Moreover, seismic monitoring can contribute to identifying dynamic building characteristics, including foundation and structural behaviour patterns. This 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 reduce buildings' carbon footprint [51-53].

Advanced dynamic modeling and predictive simulations. Digital twins enable the creation of detailed building models that encompass structural and dynamic behaviour. By incorporating historical data from seismic monitoring into digital twins, the accuracy and understanding of building behaviour during seismic events can be enhanced. This facilitates predictive simulations to assess seismic risk and identify critical areas requiring urgent interventions. These simulations support seismic retrofitting designs that also address decarbonization aspects through material and/or intervention technology choices, optimizing decarbonization strategies, preventing structural damage, and improving building seismic resilience [54-56].

Predictive maintenance and asset management. Digital twins enable predictive maintenance by identifying anomalies and potential failures in buildings in real-time. By integrating seismic monitoring data into digital twins, it is possible to monitor structural aspects and predict maintenance needs. This helps extend lifespan and reduces the resource consumption required for maintenance activities [57-58].

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. Digital Twin thus makes buildings smart and cognitive, nodes of Smart Grids and Smart Cities, capable of communicating with other buildings, with safety systems and end users [59-61].

5. Conclusion

Digital Twin approach represents a paradigm shift in building lifecycle management, enabling proactive monitoring and optimization of structural integrity. The paper contributes to the discourse on Digital Twin technology in building sustainability, in advancing sustainability goals and improving the overall performance and resilience in the built environment.

The ongoing experiment of DT4SEM infrastructure showcases the potential of DT in innovating building management and monitoring seismic building behavior. Real-time data exchange between physical and virtual models empowers stakeholders to make informed decisions, fostering sustainability and safety. Preliminary results demonstrate the effectiveness of the DT approach in providing early warnings of structural issues and optimizing maintenance schedules. The synchronized virtual model visualizes and simulates different scenarios, facilitating informed decision-making for building management.

Future research will focus on scaling up DT applications for broader adoption in the building sector; this requires addressing technical challenges and fostering interdisciplinary collaborations enhancing integration with advanced technologies and data-driven approaches, additional sensors for comprehensive building monitoring and optimizing predictive analytics algorithms.

Collaboration among experts in seismic monitoring, digital twins, and building decarbonization is crucial for developing integrated solutions that address current sustainability challenges in the construction sector. Experimental applications of seismic monitoring can significantly influence building design and management strategies aimed at reducing carbon emissions and promoting sustainability.

Author Contributions: Conceptualization, ML and MA; methodology, ML and MA.; investigation TM and AG; writing-original draft preparation ML and MA; writing-review and editing ML and MA; supervision ML. All authors have read and agreed to the published version of the manuscript.

References

- [1] European Commission, 2020, *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 – Stepping up Europe’s 2030 climate ambition Investing in a climate-neutral future for the benefit of our people*, 562 final.
- [2] United Nation, General Assembly, 2015, *Transforming our World – The 2030 Agenda for Sustainable Development*, document A/RES/70/1.
- [3] COM/2020/103, 2020, *An SME Strategy for a Sustainable and Digital Europe*, EU-COM: Maastricht, The Netherlands.
- [4] Intergovernmental Panel on Climate Change, IPCC, 2023, *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*.
- [5] Olanipekun, A.O. and Sutrisna, M., 2021, Facilitating Digital Transformation in Construction - A Systematic Review of the Current State of the Art, *Frontiers in Built Environment*, vol. 7, article 660758.
- [6] European Parliament and Council of the European Union, 2023, *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast)*, document 32023L1791, PE/15/2023/INIT.
- [7] Ma, Z., Awan, M. B., Lu, M., Li, S., Aziz, M. S., Zhou, X., Du, H., Sha, X. and Li, Y., 2023, An overview of emerging and sustainable technologies for increased energy efficiency and carbon emission mitigation in Buildings, in *Buildings*, vol. 13, issue 10, article 2658, pp. 1-26
- [8] COM/2009/512, 2009, *Preparing for Our Future: Developing a Common Strategy for Key Enabling Technologies in the European Union*, EU-COM, Maastricht, The Netherlands.
- [9] European Union, 2020, *A Europe Fit for the Digital Age*, EU-COM, Maastricht, The Netherlands.
- [10] European Union, 2020, *Shaping Europe’s Digital Future*, EU-COM, Maastricht, The Netherlands.
- [11] COM/2021/118, 2021, *Digital Compass: The European Way for the Digital Decade*, EU-COM, Maastricht, The Netherlands.
- [12] Xu, S., Wang, J., Liu, Y. and Yu, F., 2023, Application of emerging technologies to improve construction performance, in *Buildings*, vol. 13, issue 5, article 1147, pp. 1-4.
- [13] Schwab K., 2016, *The Fourth Industrial Revolution*, Portfolio Penguin, UK
- [14] COM/2010/245, 2010, *A Digital Agenda for Europe*, EU-COM, Maastricht, The Netherlands.
- [15] PricewaterhouseCoopers - PwC, 2016, *Global Industry 4.0 Survey. Industry 4.0: Building the Digital Enterprise*, PwC-PricewaterhouseCoopers: Amsterdam, The Netherlands.
- [16] COM/2020/102, 2020, *A New Industrial Strategy for Europe*, EU-COM, Maastricht, The Netherlands.
- [17] Oesterreich, T. D., and Teuteberg, F., 2016, Understanding the Implications of Digitisation and Automation in the Context of Industry 4.0: A Triangulation Approach and Elements of a Research Agenda for the Construction Industry, *Comput. Industry* 83, pp. 121–139
- [18] European Union, 2021, *Industry 5.0 - Towards More Sustainable, Resilient and Human-Centric Industry*, European Union, Maastricht, The Netherlands.
- [19] Menegon, J. and da Silva Filho, L.C.P., 2023, 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.* 47, pp. 1293–1319.

- [20] El jaouhari, A., Arif, J., Samadhiya, A. and Kumar, A., 2023, Net zero supply chain performance and industry 4.0 technologies – Past review and present introspective analysis for future research directions, in *Heliyon*, vol. 9, issue 11, article 21525, pp. 1-29.
- [21] Wang, K. and Guo, F., 2022, Towards Sustainable Development through the Perspective of Construction 4.0 - Systematic Literature Review and Bibliometric Analysis, in *Buildings*, vol. 12, article 1708.
- [22] European Commission, 2019, *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 – The European Green Deal*, document 52019DC0640, 640 final.
- [23] European Commission, 2020, Circular Economy Action Plan, Maastricht, The Netherlands.
- [24] European Commission, 2020, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – A Renovation Wave for Europe – Greening our buildings, creating jobs, improving lives*, document 52020DC0662, 662 final.
- [25] Samuelson, O., and Stehn, L., 2023, Digital transformation in construction – A review *Journal of Information Technology in Construction*, 28, 385-404.
- [26] Succar, B., and Poirier, E., 2020, Lifecycle Information Transformation and Exchange for Delivering and Managing Digital and Physical Assets. *Automation in construction*, Vol. 112, article 103090.
- [27] Lauria, M. and Azzalin, M., 2024, Digital Twin approach in Buildings – Future challenges via a critical literature review, in *Buildings*, vol. 14, issue 2, article 376, pp. 1-18.
- [28] Grieves, M., 2006, *Product Lifecycle Management: Driving the Next Generation of Lean Thinking*, McGraw-Hill, New York, UK, USA.
- [29] Grieves, M., 2011, *Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management*, Space Coast Press, Merritt Island, FL, USA.
- [30] Piras, G., Agostinelli, S. and Muzi, F., 2024, Digital Twin Framework for Built Environment – A review of Key Enablers, in *Energies*, vol. 17, issue 2, article 436, pp. 1-27.
- [31] Gartner Inc., 2019, *Gartner Survey Reveals Digital Twin Are Entering Mainstream Use*, Gartner, Stamford, CT, USA.
- [32] Research and Market, 2022, *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*.
- [33] Lauria, M., and Azzalin, M., 2023, Intelligent Construction via Digital Twin Approach, in XVI DBMC 2023, China, K.F. Li and D.P. Fang (Eds) DBMC, DOI: 10.23967/c.dbmc.2023.085
- [34] Deng, M., Menassa, C.C., Kamat, V.R., 2021, From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry, *J. Inf. Technol. Constr.*, vol. 26, pp. 58–83.
- [35] Yang, B. and Lv, Z.; Wang, F., 2022, Digital Twins for Intelligent Green Buildings. *Buildings*, vol. 12, article 856.
- [36] Nguyen, T. D. and Adhikari, S., 2022, The role of BIM in integrating Digital Twin in Building Construction – A literature review, in *Sustainability*, vol. 15, issue 13, article 10462, pp. 1-26.
- [37] Böhm, F., Dietz, M., Preindl, T. and Pernul, G., 2021, Augmented Reality and the Digital Twin – State of the art and perspectives for Cybersecurity, in *Journal of Cybersecurity and Privacy*, vol. 1, issue 3, article 26, pp. 519-538.
- [38] Visartsakul, B. and Damrianant, J., 2023, A review of building information modeling and simulation as virtual representations under the digital twin concept, *Eng. J.*, vol. 27, pp. 11–27.
- [39] Rao, A.S., Radanovic, M., Liu, Y., Hu, S., Fang, Y., Khoshelham, K., Palaniswami, M. and Ngo, T., 2022, Real-time monitoring of construction sites: Sensors, methods, and applications, *Autom. Constr.*, vol. 136, article 104099.

- [40] Cespedes Cubides, A.S. and Jradi, M., 2024, A review of building digital twins to improve energy efficiency in the building operational stage, in *Energy Informatics*, vol. 7, article 11, pp. 1-31.
- [41] Lauria, M. and Azzalin, M., 2022, Digital twin approach for Maintenance Management, in: Eugenio Arbizzani et al. (Eds), *Technological Imagination in the Green and Digital Transition* [s.l.], The Urban Book Series, Springer Nature.
- [42] Zhao, Y., Wang, N., Liu, Z. and Mu, E., 2022, Construction Theory for a Building Intelligent Operation and Maintenance System Based on Digital Twins and Machine Learning, in *Buildings*, vol. 12, article 87.
- [43] Lu, Q., Xie, X., Parlikad, A.K., Schooling, J.M. and Konstantinou, E., 2020, Moving from building information models to digital twins for operation and maintenance, *Proc. Inst. Civ. Eng. Smart Infrastruct. Constr.*, 174, pp. 46–56.
- [44] COM/2022/289 2022, *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.
- [45] Ma, Z., Awan, M. B., Lu, M., Li, S., Aziz, M. S., Zhou, X., Du, H., Sha, X. and Li, Y. (2023), “An overview of emerging and sustainable technologies for increased energy efficiency and carbon emission mitigation in Buildings”, in *Buildings*, vol. 13, issue 10, article 2658, pp. 1-26.
- [46] Rodrigo, M. N., Perera, S., Senaratne, S. and Jin, X. (2020), “Potential application of blockchain technology for embodied carbon estimating in construction supply chains”, in *Buildings*, vol. 10, issue 8, article 140, pp. 1-13.
- [47] Zhang, Z., Wei, Z., Court, S., Yang, L., Wang, S., Thirunavukarasu, A., & Zhao, Y. (2024). A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry. *Buildings*, 14(4), 1113, pp. 1-23.
- [48] Hassebo, A. and Tealab, M. (2023), “Global Models of Smart Cities and potential IoT applications – A Review”, in *IoT*, vol. 4, issue 3, article 17, pp. 366-411.
- [49] Apanaviciene, R., Shahrabani, M.M.N. Key Factors Affecting Smart Building Integration into Smart City: Technological Aspects (2023) *Smart Cities*, 6 (4), pp. 1832-1857.
- [50] Schweigkofler, A.; Brahल्ली, O.; Akro, S.; Siegele, D.; Penna, P.; Marcher, C.; Matt, D. (2022, April). Digital Twin as energy management tool through IoT and BIM data integration. In CLIMA 2022 conference, April 2022.
- [51] Heperkan, H.A., Önal, B.S., Uyar, T.S. Renewable Energy Integration and Zero Energy Buildings (2022) *Lecture Notes in Energy*, 87, pp. 105-148.
- [52] Desogus, G., Frau, C., Quaquero, E. and Rubiu, G. (2023), “From Building Information Model to Digital Twin – A Framework for Building Thermal Comfort Monitoring, Visualizing, and Assessment”, in *Buildings*, vol. 13, issue 8, article 1971, pp. 1-22.
- [53] Bortolini, R., Rodrigues, R., Alavi, H., Vecchia, L.F.D., Forcada, N. Digital Twins’ Applications for Building Energy Efficiency: A Review (2022) *Energies*, 15 (19), art. no. 7002.
- [54] Pan, Y., Zhu, M., Lv, Y., Yang, Y., Liang, Y., Yin, R., Yang, Y., Jia, X., Wang, X., Zeng, F., Huang, S., Hou, D., Xu, L., Yin, R. and Yuan, X. (2023), “Building energy simulation and its application for building performance optimization – A review of methods, tools, and case studies”, in *Advances in Applied Energy*, vol. 10, article 100135, pp. 1-24.
- [55] Ali, U., Bano, S., Shamsi, M. H., Sood, D., Hoare, C., Zuo, W., Hewitt, N. and O’Donnell J. (2024), “Urban building energy performance prediction and retrofit analysis using data-driven machine learning approach”, in *Energy and Buildings*, vol. 303, pp. 1-16.
- [56] 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.
- [57] Saloux, E., Zhang, K., Candanedo, J.A.A Critical Perspective on Current Research Trends in Building Operation: Pressing Challenges and Promising Opportunities (2023) *Buildings*, 13 (10), art. no. 2566.

- [58] 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.
- [59] He, X., Lin, M., Chen, T.-L., Liu, B., Tseng, P.-C., Cao, W., Chiang, P.-C. Implementation plan for low-carbon resilient city towards sustainable development goals: Challenges and perspectives (2020) *Aerosol and Air Quality Research*, 20 (3), pp. 444-464.
- [60] Ramaswami, A., Pandey, B., Li, Q., Das, K., Nagpure, A. Toward Zero-Carbon Urban Transitions with Health, Climate Resilience, and Equity Co-Benefits: Assessing Nexus Linkages (2023) *Annual Review of Environment and Resources*, 48, pp. 81-121.
- [61] Caprari, G., Castelli, G., Montuori, M., Camardelli, M. and Malvezzi, R. (2022), “Digital Twin for Urban Planning in the Green Deal Era – A State of the Art and Future Perspectives”, in *Sustainability*, vol. 14, article 6263, pp. 1-16.