sustainability

MDPI

Article

Advancing the Decarbonization of the Construction Sector: Lifecycle Quality and Performance Assurance of Nearly Zero-Energy Buildings

Emanuele Piaia [1], Beatrice Turillazzi [2,*], Roberto Di Giulio [1] and Rizal Sebastian [3]

[1] Department of Architecture, University of Ferrara, 44121 Ferrara, Italy; piamnl@unife.it (E.P.); dgr@unife.it (R.D.G.)
[2] Department of Architecture, University of Bologna, 40126 Bologna, Italy
[3] Faculty of Technology, Innovation and Society, The Hague University of Applied Sciences, 2521 EN Den Haag, The Netherlands; r.sebastian@hhs.nl
* Correspondence: beatrice.turillazzi@unibo.it; Tel.: +39-3479239229

Abstract: Dealing with and maintaining high-quality standards in the design and construction phases is challenging, especially for on-site construction. Issues like improper implementation of building components and poor communication can widen the gap between design specifications and actual conditions. To prevent this, particularly for energy-efficient buildings, it is vital to develop resilient, sustainable strategies. These should optimize resource use, minimize environmental impact, and enhance livability, contributing to carbon neutrality by 2050 and climate change mitigation. Traditional post-occupancy evaluations, which identify defects after construction, are impractical for addressing energy performance gaps. A new, real-time inspection approach is necessary throughout the construction process. This paper suggests an innovative guideline for prefabricated buildings, emphasizing digital 'self-instruction' and 'self-inspection'. These procedures ensure activities impacting quality adhere to specific instructions, drawings, and 3D models, incorporating the relevant acceptance criteria to verify completion. This methodology, promoting alignment with planned energy-efficient features, is supported by BIM-based software and Augmented Reality (AR) tools, embodying Industry 4.0 principles. BIM (Building Information Modeling) and AR bridge the gap between virtual design and actual construction, improving stakeholder communication and enabling real-time monitoring and adjustments. This integration fosters accuracy and efficiency, which are key for energy-efficient and nearly zero-energy buildings, marking a shift towards a more precise, collaborative, and environmentally sensible construction industry.

Keywords: building inspection; decarbonization; digitalization; energy-efficient buildings; environmental sustainability; nearly zero-energy buildings; prefabricated buildings; quality assurance

check for updates

Citation: Piaia, E.; Turillazzi, B.; Di Giulio, R.; Sebastian, R. Advancing the Decarbonization of the Construction Sector: Lifecycle Quality and Performance Assurance of Nearly Zero-Energy Buildings. *Sustainability* **2024**, *16*, 3687. https://doi.org/10.3390/su16093687

Academic Editor: Gerardo Maria Mauro

Received: 25 March 2024
Revised: 22 April 2024
Accepted: 26 April 2024
Published: 28 April 2024

1. Introduction

The European Union (EU) is acting upon the European Climate Law and the European Green Deal to make Europe's economy and society climate-neutral by 2050 with an intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Within this goal, the European Commission noted that buildings are the single largest energy consumer in Europe, using 40% of our energy, and creating 36% of our greenhouse gas emissions; and the construction sector is responsible for over 35% of the EU's total waste generation. Therefore, there is an urgent need for deep renovation of the worst performing building stock along with a pathway for transforming the building stock into zero-emission buildings by 2050.

The impact of such an action can only be achieved when the building quality and energy performance requirements are fulfilled during the deep renovation and new construction projects, at the commissioning and delivery of the existing or new buildings, and especially during the lifecycle operation and maintenance of the buildings.

In consideration of what has been introduced, dealing, and ensuring high quality standards during the design and construction stages can often be challenging for all involved actors and players, particularly in the case of on-site construction where often the improper implementation of building components and ineffective communication among the professionals in design, production, and construction phases may lead to a widening gap between the design specifications and the as-built conditions.

To address these challenges, especially in new construction and renovation of nearly zero-energy buildings (NZEB), it is necessary to develop strategies to meet the quality and performance standards (e.g., energy, indoor environmental quality, etc.) and to ensure the buildings' resilience against climate change [1].

These strategies should aim to enhance resource efficiency, minimize environmental footprint, and improve the overall livability and sustainability of the built environment. This approach would contribute significantly to achieving carbon neutrality by 2050 and mitigating the cause of climate change.

To overcome the limitations of the widely known post-occupancy evaluation (POE) approach particularly in terms of energy, wherein numerous defects and gaps become impractical to rectify when the building has been constructed, it is essential to introduce a new inspection methodology and monitoring—in real time—of the building performance. This new methodology should be conducted in real time and systematically implemented at each stage of the building process.

Based on the results achieved from the EU Horizon 2020 research project titled INSITER (Intuitive Self-Inspection Techniques) using Augmented Reality (AR) for construction, refurbishment, and maintenance of energy-efficient buildings made of prefabricated components [2] as well as the subsequent studies and practical experience gained by the research team, this paper introduces an innovative methodology which adopts digitalized procedures to reduce the gap between as-built and as-designed. This methodology is set to revolutionize the industry, offering a way to ensure that the constructed or renovated buildings align with the initially planned NZEB features.

In this methodology, cutting-edge BIM-based software tools, AR applications, and Digital Twins are pivotal for streamlining the procedures.

Embracing the principles of Industry 4.0, the proposed solutions harness the transformative potential of technology within the construction realm where BIM and AR technologies play a crucial role in bridging the virtual design environment (off-site) and the real production and construction environment (on-site).

At the European level, other parallel studies have been conducted on the topic of investigation. Examples of research projects are as follows: H2020 ACCEPT (Assistant for Quality Check during Construction Execution Processes for Energy-efficienT buildings) [3] and 'Built2Spec' (Built to Specifications: Self-Inspection, 3D Modeling, Management and Quality-Check Tools for the 21st Century Construction Worksite) [4].

ACCEPT suggested potential services and solutions to bridge the gap between the intended design and the actual performance of constructed buildings. The research implemented a shift in the fundamental workflow of a construction project, reshaping the distribution of information, decision-making processes, and accountability among the main involved actors (e.g., architects, clients, manufacturers, construction workers, and subcontractors). The ACCEPT system acts as a channel for ongoing information exchange among users, enabling architects to address site inquiries directly and promptly, even before tasks like covering completed works or removing scaffolding. It facilitates engineers and manufacturers to contribute to task sequencing on-site based on their specialized product knowledge. Additionally, subcontractors can identify detailing inconsistencies or unnoticed clashes that could only be anticipated through their craftsmanship expertise.

Built2Spec (B2S) unveiled a fresh array of technological advancements for self-inspection and quality assurance, empowering construction stakeholders to fulfill EU energy efficiency objectives, adhere to new build standards, and align with decarbonization goals. B2S introduced a cloud-based construction support platform, developed based on the latest integrated design and delivery framework for the building sector. This platform hosts applications aimed at enhancing worksite activities and ensuring quality compliance by providing contractors with access to shared design specifications and 3D models, installation guidelines, information on regulatory frameworks, and assistance from construction experts via smartphones and tablets.

BIM modeling enabled through instant 3D capture using smartphones, transmitted via the cloud to the refurbishment team's back office, facilitating precise and immediate evaluation of energy efficiency, quality checks, and a streamlined quotation process. Additionally, an innovative low-pressure air-tightness technique allows for testing occupied buildings conveniently. Smart sensor-embedded construction elements provide identification, assess structural performance, and monitor building environment parameters. Furthermore, a portable single device for Indoor Air Quality tests offers multi-gas capabilities, targeting the most harmful pollutants. Lastly, a novel lightweight portable sound source facilitates on-site acoustic tests to ensure compliance with regulations.

Analyzing the Italian context, there is a lack of innovative studies focusing on building inspection to assurance energy performance. However, given the increasingly stringent sector regulations regarding energy performance standards for buildings, Italy is witnessing a growing interest in Construction Quality Management (CQM) as the means to ensure the quality of constructed works.

The primary objectives of CQM are to minimize errors or defects identified during subsequent delivery stages and to proactively identify and address issues before they are noticed by the client. This phase is crucial as it ensures customer satisfaction and prevents rework, leading to time and cost savings. Within CQM, two key processes exist, i.e., quality assurance (QA) and quality control (QC). QA is particularly relevant to this discussion because, unlike QC, it encompasses the entire construction process, including planning, design, production, and installation/implementation.

CQM is supported during the procedural phase by Construction Quality Control (CQC). This control activity aims to ensure that the constructed work meets the required quality standards, thereby avoiding issues arising from poor material quality or processes over time. Effective quality control conducted on-site positively impacts the entire lifecycle of the asset. Quality control activities encompass ensuring that the design aligns with regulatory and functional requirements, meeting client specifications; verifying that materials conform to orders and design specifications upon arrival at the construction site; and guaranteeing that construction adheres to design specifications, manufacturer guidelines, and legal requirements.

Despite the potential benefits, it is evident from analyses involving comparisons with sector companies and design studios that there is limited adoption of innovative digital technologies offered by Industry 4.0.

As introduced in the following section of the paper, these technologies could significantly enhance and expedite quality control at all stages of the construction process.

Considering the high ambition, pressing timeline, and huge volume of the existing and new building stock to deal with cost-effective and scalable innovation for lifecycle quality and performance assurance, monitoring and optimization are highly demanded. Digitalization is believed to be an important factor.

Indeed, this paper presents applied research on this topic to improve the environmental impact of the construction sector with innovative inspection methodologies which adopt the advantages proposed by the Industry 4.0.

2. Research Goals and Methodology

Recent studies [5–8] highlight a disconcerting trend: buildings designed to be energy-efficient tend to consume 2 to 5 times more energy in the occupancy phase compared to the initially predicted energy consumption during their design phase.

This discrepancy is attributed to several factors, including construction errors, climate variations, substandard building materials, and suboptimal user behaviors. While these factors account for long-term energy performance differences, they do not fully explain the immediate surge in the post-construction or post-renovation energy consumption [9].

The energy performance of a building is closely linked to the quality of the executed construction or renovation. This also applies to buildings constructed using prefabricated components of which technical and energy performance has been calculated and tested before assembly. Evidently, defects and errors at on-site construction significantly reduce their high performance [10].

Construction errors are mainly caused by the following:

1. Difficulty in understanding the technical specifications of the project and assembly manuals by on-site workers.
2. Lack of practical and intuitive assembly instructions from the designers and/or manufacturers.
3. Miscommunication flaw among the various stakeholders throughout the process, exacerbated by the diversity of their skills, capabilities, roles, and responsibilities.
4. Assembly, installation, and inspection procedures based on the construction workers' and operators' experience and their skills to follow specific protocols.

The fourth industrial revolution introduced digital tools and information platforms that improved design precision and overcame some limitations [11,12].

To effectively achieve the objectives of NZEB, it is critical to address the aforementioned issues. Hence, innovative methods and procedures need to be proposed to eliminate errors during construction or renovation process to avoid the gaps in quality and energy performance between design and completion.

The research goal of this paper is to define a new building inspection approach for the construction and refurbishment of NZEB buildings by leveraging the opportunities presented by the fourth industrial revolution, especially by extending the application of Building Information Modeling (BIM) to the construction occupancy and maintenance phase through Mixed Reality, which interlinks the Real Environment (RE), AR, Augmented Virtuality (AV), and Virtual Environment (VE).

The research methodology adopted has eight steps:

1. Conduct site mapping and assessment using self-inspection software for renovation or construction projects.
2. Implement self-inspection in the selection and quality control of prefabricated components, integrating with BIM systems.
3. Utilize BIM for detailed planning of building components and installations, following IFC standards.
4. Apply BIM-based AR for self-instruction and inspection, enhancing construction workers' understanding and efficiency.
5. Validate building quality and performance virtually via BIM, addressing errors through self-inspection and collaboration for solutions.
6. Carry out self-inspection and instruction during site preparation, optimizing logistics and updating construction plans.
7. Perform ongoing self-evaluation during construction or renovation to ensure component accuracy and process efficiency.
8. Finalize self-inspection and instruction in pre-commissioning to identify common construction errors and their impacts.

The innovative inspection methodology presented in the following sections adopted the assumption of prefabricated elements and systems that they are factory-made and 'error-free', which means that they have already been tested in the laboratory so they should meet the performance requirements and conform to the quality standard.

3. Preliminary Analysis

Global energy consumption in buildings has increased annually by 1.1% since 2010, driven by rising demand in emerging economies, particularly China and India, with efficiency gains stabilizing or reducing consumption in the US, the EU, and Japan [13].

As assessed by the IEA's Tracking Clean Energy Progress (TCEP) Report [14], one of the sectors that is critical for clean energy transitions and the goal of the net zero by 2050 is the building sector. The building sector constitutes more than a third of worldwide energy usage and emissions due to the energy utilized for construction, heating, cooling, and lighting of residential and commercial buildings along with the energy consumption of appliances and equipment.

Regarding the goal for NZEB, the current progress is as follows:

- The progress of the lighting component is on track to meet the net zero scenario by 2050.
- The progress of the space cooling, heating, heat pumps, appliances, and equipment components needs to go faster as the continuation of the current trends without any acceleration would result in an achievement that is far behind the trajectory of the net zero scenario by 2050.
- The progress of the building envelope component is not on track, which indicates that the recent trends are either moving in the opposite direction or marked inadequate by 2030 to align with the net zero by 2050 goal.

To propose an advancement on the state of the art of the energy efficiency of the building envelope, this section is dedicated to defining the most common installation errors, inspection procedures, Key Performance Indicators (KPIs), and the corresponding measurement aspects.

The analyses were conducted following a series of analytical–experimental procedures, divided into four research steps:

1. A thorough review of the international literature on construction errors and building inspection was conducted.
2. Through direct collaboration with construction companies, current quality control procedures were examined, with a focus on the building envelope context.
3. Laboratory analyses were carried out on a representative model (mock-up) in order to initially assess the benefits of using the digital inspection tools developed as part of the research.
4. Application tests were conducted on real case studies in order to monitor the actually obtained results, including the one described in Section 5 of this paper.

3.1. Building Envelope: Classification and Inspection Procedures

It is clear that the role of the building envelope—which can be defined as the collection of parts of a building that form the primary thermal barrier between the interior and the exterior—is fundamental in determining the levels of comfort, natural lighting, and ventilation as well as the amount of energy required to heat or cool a building. Additionally, its design and construction greatly influence the comfort and productivity of the building occupants [15–17].

Although achieving energy neutrality is easier in new buildings, deep renovation and expansion of existing buildings can also attain a significant energy improvement, for instance, the energy consumption can be reduced up to 30–50% by insulating the external walls and roofing systems of the building [18].

The first step to reach the expected quality of the building envelope involves planning a systematic set of surveys, inspections, collections, and analysis of parameters related to specific energy consumption, linked to the operational conditions of the building and its systems as well as to the technical and economic assessment of energy flows. For methodological simplicity, the building envelope is divided into various subsystems, each with its own characteristics.

Following the construction phase, four elements of the building envelope with a substantial impact on energy use are identified and classified as follows:

- Lower horizontal closures: foundations and ground floors, including the ground attachment and junctions with the facade. Ground floor elements and foundations are considered a specific subsystem due to their constant contact with the ground and the corresponding risk of performance loss.
- Opaque vertical closures: perimeter walls, including window openings. The vertical elements primarily present problems of connection with the building's structural frame and between different modules.
- Transparent vertical closures: fixtures and glazed facades (continuous facades). These components have similar problems to opaque facades regarding air tightness and overall performance (acoustically and thermally). They also pose peculiar issues concerning the glazing and seals.
- Upper closures: roofing. These elements can be flat or sloped. Flat roofs are vulnerable to water accumulation, while sloped roofs must manage runoff water. Roofs are crucial in terms of energy saving, especially regarding heat loss and water tightness (waterproofing). The performance analysis of the roof elements takes into account also their connections to the vertical elements of the facade.

To develop effective inspection procedures for building envelope components, it is necessary to consider two key aspects that influence the behavior of a building's skin:

1. The consistency of technical dimensional tolerances;
2. The state of joints and connections, in particular the interface between different elements that primarily influence the actual performance of the installed building components.

Tolerances can vary depending on materials and products. Adherence to dimensional tolerances ensures mechanical strength, functionality, and compatibility of each element with the rest of the structure and other non-structural components. Certain standards or guidelines (e.g., UNI EN 13369: 2018 Common rules for precast concrete—Annex J) [19] define geometric constraints, surface imperfections, measurement methods, and acceptable deviations of a prefabricated element's surface, but many products lack evidence of their compliance to an applicable standard. Therefore, defining the right procedures is particularly important on-site, where regular inspections are necessary to ensure compliance with the specified requirements.

Regarding connections, various forms of linkages can be identified, particularly the connections between components that constitute the envelope itself (internal connections) and between the outer skin and the building's load-bearing structure or other parts of the building, such as the basement and the roofing system (considered as external connections). The forms and methods of joining vary according to the materials and products used, the structural type of the building, and the number of functional layers comprising the envelope system.

All elements have geometric differences, but dimensional tolerances must fall within a certain limit. Not only are the dimensional tolerances of the element important, but also those of the openings where the element is placed. Joints where tolerances are not acceptable due to a greater geometric difference than allowed, which cannot be resolved on-site, must be rejected and sent back to the factory. This requires the development of communication protocols with the manufacturing company and possibly the cancellation of the delivery of other components for which similar errors are anticipated. Certain joints known as 3D joints are the most critical parts where potential errors can occur with significant impact on the building's energy performance, especially when they behave as voids. This problem must be resolved on-site. At the same time, 2D connections are also important when analyzing critical components. In this regard, a 'joint approach' has been developed to study the building components and reduce the complexity of the problem.

Prefabricated components can be made of wood, steel/aluminum, concrete, polymers, and a variety of composites created from the combination of the aforementioned materials. Being prefabricated systems, regardless of the materials used, the performance and quality of the system must comply with industry standards. For systems that satisfy the performance standard and have already been tested in the laboratory, the proposed methodology and tools are sufficiently generic and applicable independently from the materials that compose the systems.

Prefabricated elements delivered to the construction or renovation site are considered error-free. However, sample tests must be conducted on-site to assure the quality. Elements arriving at a construction site can be damaged during transport and must be inspected on-site to check for defects. The communication protocols related to this self-inspection are based on performance indicators, for which a four-phase approach is introduced:

1. Prefabricated as designed: this involves internal quality control at the factory.
2. Delivered as prefabricated: Phase Zero of self-inspection upon arrival at the site, before assembly. It involves only the identification of the element and a sample inspection.
3. Mounted as delivered: assuming that no storage on-site is planned but immediate assembly, this phase involves measurement in case of dimensional evaluation of the foundations as a preliminary action.
4. Performing as pre-calculated: this phase focuses on the construction of the building and all measuring devices capable of identifying possible errors, assessing their significance, and deciding their admissibility.

3.2. Building Envelope Construction Defects

The analysis of potential construction defects and the related methodological approach are complex by the extreme diversity of building materials, weather, standards, and local building design and construction practices. However, the assessment of the most common anomalies in building envelope construction can be generally traced based on literature review and long-term practice (Table 1). A summary of the construction errors is as follows:

- Off-site production not conforming to the project.
- On-site production not conforming to the project.
- Poor production of components.
- Mounting of building components with damages.
- Improper mounting of building components.
- Incorrect placement of components or non-compliant installation.
- Misinterpretation or improper use of documentation (e.g., technical drawings).
- Failure to install or assemble components other than the executive design.
- Geometric discrepancies of building components.
- Installation of unsuitable material.
- Fixtures not correctly sealed on-site.
- Irregular site inspection by the project manager.

Table 1. Critical and recurring anomalies.

Most Common Anomalies	Main Impacts (Qualitative Assessment)
Geometric discrepancies	Unexpected discrepancies, water/vapor infiltrations with related interstitial condensation
Lack of insulation	Low U-value, thermal bridges
Lack of air tightness	Thermal bridges, water/vapor infiltrations
Unexpected increase of heat through transparent surfaces	Sensitivity to solar radiation, surface condensation, glare

3.3. Key Performance Indicators

To assure the expected building quality through consistent inspection procedures, Key Performance Indicators (KPIs) have been defined to measure the performance of the entire building, such as air tightness, acoustic insulation, building quality, and energy efficiency.

There are two sets of KPIs with a particular relevance for building envelope:

1. Energy efficiency (EE);
2. Indoor environmental quality (IEQ).

Energy efficiency (EE) is the ratio between performance, services, goods, or energy, and the input of energy (Directive 2012/27/EU) [20]. For buildings, it means using energy efficiently to ensure healthy and comfortable buildings. Therefore, the KPIs related to energy efficiency focus on the following:

- Heat transmission of the building envelope;
- Efficiency of heat/cold generation;
- Efficiency of heat/cold distribution.

Indoor environmental quality (IEQ), essentially described as the condition inside the building, typically includes air quality, access to daylight, view, pleasant acoustic conditions, and occupant control over lighting and thermal comfort [21]. In the set of KPIs on IEQ, the considered parameters are as follows:

- Thermal comfort;
- Visual comfort;
- Acoustics;
- Air quality.

It should also be noted that two aspects are particularly relevant for the energy performance of all building components:

1. Geometry—in this context, understood to be flatness, settlement, sliding, shrinkage, or thermal movement—is the main property to consider and verify on-site.
2. Air tightness—in this context, understood to be limited air passage through the building envelope—is essential for ensuring energy efficiency in new constructions and deep renovations and must be verified by conducting standardized tests. Air tightness alone can reduce heating requirements by 20–30%. Hermetically sealed structures, provided they have adequate ventilation control, can ensure a healthy indoor microclimate. Energy audits, like the mandatory energy performance certificates in the European Union, should include regular and validated tests on air leaks (for example, at least every 10 years).

From the process analysis, two main phases have been identified in which the choice of building components is critical for energy performance (Table 2) and where it is necessary to measure the KPIs, namely, construction/assembly processes and performance analysis/evaluation:

- Construction/assembly processes are considered as the most critical phase for allowing the targeted energy performance to be achieved. Any defect in this phase can lead to anomalies, if not pathologies, that would hinder the quality and/or durability of the building's performance. Several solutions can be envisioned, such as prefabrication of standard units to facilitate on-site assembly, on-site assembly processes with more careful and thorough performance control, deployment of sensors to monitor intermediate performance stages, continuous improvement processes as a part of a quality process, and worker training on the impacts of incorrect component installation on final energy performances.
- Assessing the performance of the existing buildings enables users, the owners, and the investors to monitor and manage energy consumption and user behavior, to identify the possible misuse of building systems caused by unawareness or lack of knowledge by the users, and to identify potential building disturbances and/or pathologies. Moreover, a condition-based maintenance approach can add value for performance

and guarantee contracts. This phase is crucial not only for maintenance, but also, above all, for a multi-criteria approach in the renovation of existing buildings.

Table 2. Summary of building components and their impact on energy performance. Resolving these anomalies can have significant impacts on energy performance.

Component/Interface	Impact on Energy Performance
Walls—Roofing—Basement	High levels of insulation—optimized through Life Cycle Costs (LCC) evaluation—in walls, roofs, and floors reduce heat loss, especially in cold climates. Highly reflective surfaces are advantageous in hot climates, including roofs and walls that are white and/or painted with cool colors, reducing glare
Glass Facades	High-performance windows and facades with low thermal transmittance for the entire system (including frames and seals) and climate-appropriate Solar Heat Gain Coefficients (SHGC) are the most advantageous solution
Interface (Joints and Connections)	Minimizing thermal bridges with high thermal conductivity fastening and structural elements (while managing moisture problems within the components and integrated building materials) ensures limited air infiltration percentages. Adequately sealed structures must guarantee controlled ventilation with air exchange

3.4. Inspection Tools and Indicators

As mentioned earlier, the performance of the building envelope to be inspected and monitored is multifaceted.

KPIs are usually verified based on the data of energy consumption or building performance in multiple operations at various energy consumption levels. Numerous techniques exist for detecting and assessing significant parameters, but first a reference threshold should be established, comparable parameters should be identified, and achievable goals should be set. For this reason, the proposed methodology sets up specific protocols to measure the factors that affect energy performance. These factors are grouped into three main categories:

1. Geometric discrepancy/moisture;
2. Positioning/sensitivity;
3. Thermography/diagnostics.

Accordingly, the protocols are grouped as follows:

- Protocols for thermal tests;
- Protocols for acoustic testing;
- Protocols for testing geometric discrepancy;
- Protocols for moisture testing;
- Protocols for the testing of the localization system.

The analytical methods for carrying out the measurements and applications are outlined in the table below, highlighting the techniques and tools to be used (Table 3).

Table 3. Framework of measurement parameters, instruments, and detection elements.

Parameters	Sensors or Measuring Instruments	Objectives or Indicators
Thermal Contrast [K]	Thermal Camera	Structural Integrity
Dimensional Difference [m]	Geometric Discrepancy	Geometric Discrepancy
U-Value [W/m^2K]	Thermal Camera, Thermal Flow Transducer	Thermal Transmittance
HD [W/K]	Thermal Camera	Thermal Bridge
Thermal Bridge [L]	3D Laser Scanner 3D	Moisture

4. Innovative Inspection Methodology Based on Self-Instruction and Self-Inspection Procedures

Taking into account the analyses conducted and the results obtained, especially for investigating the building envelope, an innovative building inspection methodology has been developed. The methodology embraces a novel concept of self-instruction and self-inspection procedures throughout the entire building's lifecycle, addressing each of its constructive parts. This approach aims to guarantee the anticipated building quality and energy performance.

The recommended procedures can be employed by construction workers, component suppliers, subcontractors, and all actors involved in the building's lifecycle. A set of hardware and software tools support these procedures during all phases of the building's lifecycle, from conception to realization and occupancy. The procedure is also supported and valorized by Mixed Reality technologies to improve the construction workers' or operators' activities by enabling them to visualize virtual design models during the actual construction or renovation phase, and thus overcoming incorrect interpretations of the design information.

The methodology consists of eight steps:

- Step 1: Utilizing the self-inspection software, building occupants, owners, technical consultants, and inspectors conduct a comprehensive inventory of the current technical state of the site and/or the existing building. This includes an as-is condition assessment and real estate valuing in case of renovation.
- Step 2: Self-inspection in the procurement, production, and delivery of prefabricated building components, which includes pre-qualification selection via quality management based on the criteria for contractors and suppliers that have competencies in industrialized design, engineering, and energy-performance labeling. This step encompasses integrating manufacturers' 3D product databases with BIM systems and performing in-factory/pre-delivery product inspections.
- Step 3: BIM modeling of the building (new or existing), comprising comprehensive modeling of building components and MEP (mechanical, electrical, and plumbing)/HVAC (heating, ventilation, and air conditioning) systems that are crucial for building quality and energy performance. BIM is created according to the open and interoperable international standard IFC (Industry Foundation Classes).
- Step 4: Producing and delivering BIM-based AR for self-instruction and self-inspection, by incorporating BIM and VR into AR and translating BIM/VR information from the process into self-instruction for construction workers. The Mixed Reality model will be made available on the mobile devices of the construction workers. Data from the hardware tools for inspections will be interfaced with BIM and the inspection software.
- Step 5: Virtual validation of quality and performance by checking BIM models and clash detection, as well as process enhancement through VR simulation. In case of errors, self-inspection protocols will be implemented to scrutinize clash details, assess clash severity, track faulty components back to their manufacturers/suppliers, request these entities to conduct a review and suggest a remedial solution, and ultimately prevent damage or engage in collaborative recovery efforts involving multiple stakeholders.
- Step 6: Self-inspection and self-instruction during the preparation of the construction site and logistics. This step includes checking the construction site and update of site's BIM model based on the actual conditions, optimizing the time and cost schedules by analyzing the risks of delay and budget-overrun, and updating the self-instruction guidelines for construction workers.
- Step 7: Performing self-inspection and self-instruction during construction, renovation, or maintenance process. This phase includes the control of the accuracy and condition of the delivered prefabricated components, the implementation of self-instructions on the mobile devices of the construction workers, the comprehensive evaluation of the process at certain intervals, carried out by the site supervisor, and the involvement of

the workers belonging to contractors and subcontractors. These preliminary quality and performance outcomes are measured quantitatively and analyzed as input for collaborative decision making with the building occupants.

- Step 8: Self-inspection and self-instruction during pre-commissioning, commissioning, and project delivery. A preliminary and crucial step for the elaboration of the proposed methodology is the analysis of the most common construction errors and the identification of the building components that are most affected by these errors in consideration to the fact that both the defect and the type of element will significantly affect the building's quality and energy performance, as well as its construction costs and timelines.

The proposed methodology is versatile and applicable to various scenarios, including new construction, maintenance, and renovation projects.

5. Case Study

In order to provide an example of the applicability of the presented inspection methodology in a real construction project, this paper analyses the deep retrofit, redesign, and re-conversion of an unused university building, part of the campus of the University of Twente, in Enschede, in the east of the Netherlands (Figure 1). The existing building, built in 1965, was refurbished and converted into student lodging (75%) and a hotel (25%).

Figure 1. State of the building before (March 2009) and after (August 2022) deep renovation (Copyright 2018, H2020-INSITER Project Consortium Partnership).

This demonstration case holds significant replication potential, driven by the imperative to enhance the energy efficiency of a substantial existing building stock in Europe. Additionally, the relevance extends to the current scenario where numerous university campus buildings dating back to the 1960s are being replaced by more contemporary structures. European universities face challenges in identifying transformation opportunities for these aging buildings, seeking solutions that not only prioritize energy efficiency but also contribute new functional value to the institutions.

The condition prior to intervention was subpar: utility systems (MEP) had reached the end of their lifespan, and the building facade was outdated in terms of energy efficiency. Only the concrete basement, rib floor plates, and the main structural concrete construction were deemed suitable for reuse.

The design decisions for the building retrofit were exclusively oriented towards the adoption of prefabricated plug-and-play solutions. The following prefabricated retrofitting solutions have been applied in the building:

- Installation of new building envelope;
- Modular units of kitchens and bathrooms;
- New MEP/HVAC systems.

Construction, comprising dismantling and land reclamation, began in April 2017 and was completed by the end of 2018 (Figures 2 and 3).

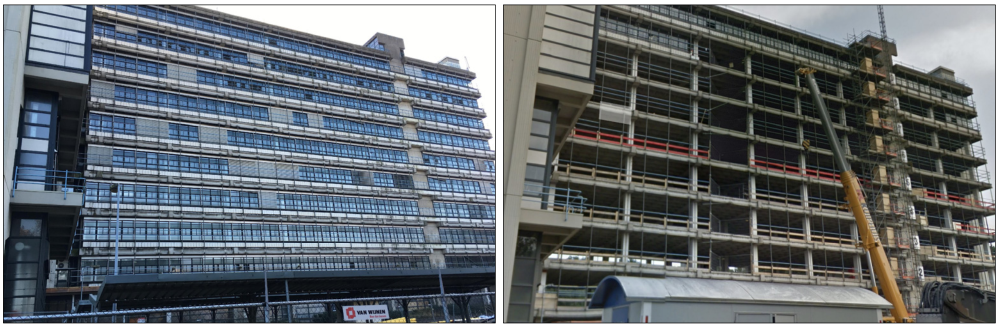

Figure 2. State of the building during the deep renovation reveals the dismantling of the existing elements of the facade, alongside the preservation of the reinforced concrete structure (Copyright 2018, H2020-INSITER Project Consortium Partnership).

Figure 3. Student apartment renovation: new prefabricated building facade and bathroom unit (Copyright 2018, H2020-INSITER Project Consortium Partnership).

Based on the eight steps of the introduced inspection methodologies, the field demonstration activities focused on the following:

1. Inspection of deviations or defects in the positioning of new facade panels and windows (building facade). The facade panels and windows installed on site were compared with the BIM model and any inaccuracies and flaws were identified by means of a geometric survey with 3D laser scanning, thermal scanning, and acoustic measurement at critical joints of the facade system.
2. AR on-site simulation of the assembly/installation part of the new MEP-HVAC system. The objective of the demo was to provide an effective design and installation process, reducing possible errors to a minimum by utilizing INSITER tools.

5.1. Inspection Demonstration on Building Facade

The primary aim of the initial demonstration was to confirm the integration of prefabricated facade components with the existing building structure to mitigate energy loss. This information was crucial for both the contractor and on-site workers (the facade installation team), enabling them to detect potential thermal bridges, address any shortcomings, and implement preventive measures to avoid similar issues in the future.

The inspection demonstration activities on the building envelope have been performed following these steps:

- Step 1: Pre-renovation condition assessment and checking structural adequacy of substructure for installation of new panels and windows on the existing building.
- Step 2: After self-inspection of building components in procurement and production, the prefabricated panels were delivered to the building site, and they were stored on-site for new inspection by scanning RFID (Radio Frequency Identification) or QR code (Quick Response code) and the retrieval of component's ID in BIM. During the transportation phase, the primary individuals involved were the construction workers/installers and production/manufacturing workers. Their responsibilities included ensuring the accurate delivery of components to the site and proper storage of these components.
- Step 3: BIM modeling, including the detailed modeling of the building components and MEP/HVAC installations that are crucial for ensuring the quality and energy efficiency of the building. Deployment of BIM models for on-site use. Loading the partial BIM model onto a tablet (iPad), showing the specific parts of the facade including the panels.
- Step 4: Creation and implementation of a BIM-based AR system for self-instruction and self-inspection in construction. All information will be available to construction workers and accessible on workers' mobile devices to reduce potential construction errors (Figure 4).

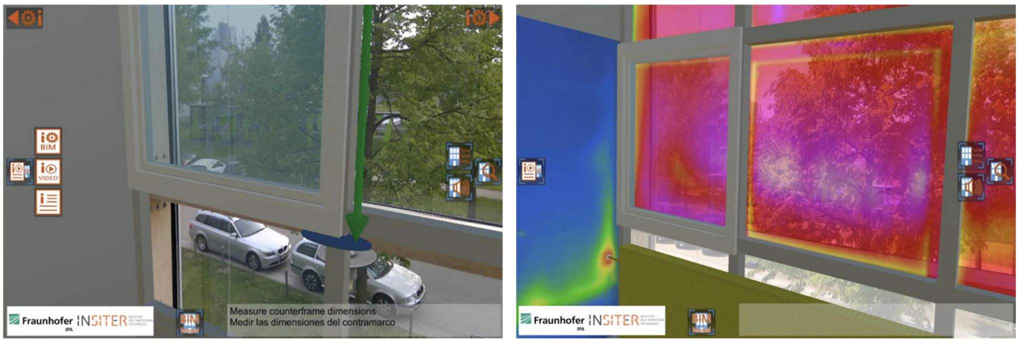

Figure 4. INSITER BIM-based Self-Instruction AR app displaying thermal measurement images to assess thermal deviations and their causes by using the digital BIM model and the on-site conditions (Copyright 2018, H2020-INSITER Project Consortium Partnership).

- Step 5: Virtual validation through BIM model control and clash detection was carried out.
- Step 6: The prefabricated components, produced off-site, were assembled on-site using self-instruction procedures accessible through mobile devices. A continuous on-site visual comparison with the BIM model was performed to ensure the quality of the work aligned with the project plan and met the anticipated requirements consistently (Figure 5).
- Step 7: After the completion of the installation of the new panels, the self-inspection of the building facade through thermal and laser scanning was carried out. The measured values (i.e., the sizes of the gaps) were checked to assess if they were acceptable (within the tolerance limit), to avoid thermal bridges, airtightness, and leakages, and thermal scanning was performed to identify thermal bridges. With a thermographic camera, infrared scanning was performed for quality control, resulting in thermal imaging that indicated whether there were thermal/energy losses in the new facade. The INSITER procedure for assessing the impact of thermal bridges on the thermal transmittance of the building envelope relied on infrared camera measurements. This approach was implemented in a room within the University of Twente building, featuring one external wall and three internal walls. The inspection aimed to confirm the presence of a thermal gradient of approximately 10 °C between the interior and exterior. Typically, a well-insulated facade ensures this thermal gradient; otherwise, the room needs to be conditioned to identify thermal bridges (Figure 6).

Figure 5. Confronting real conditions with the BIM model (Copyright 2018, H2020-INSITER Project Consortium Partnership).

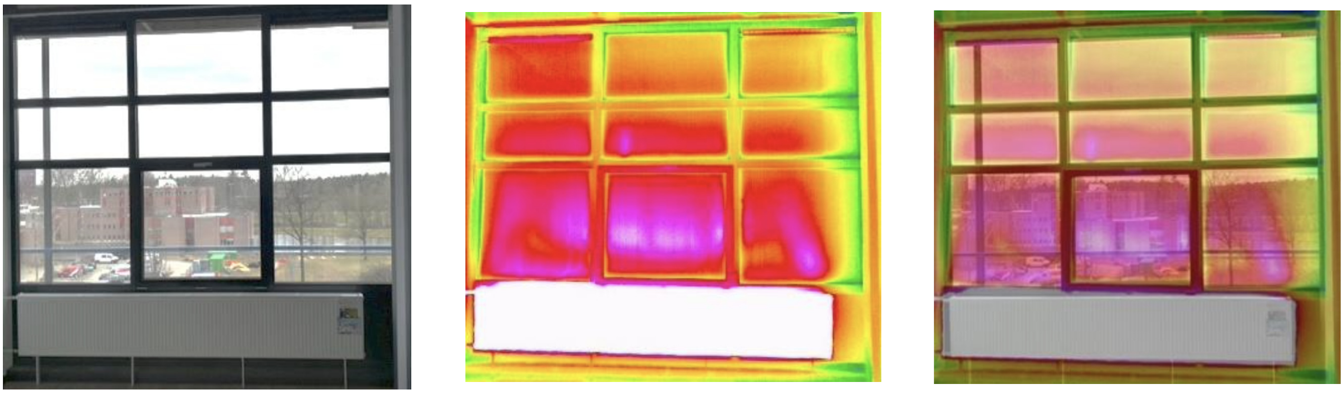

Figure 6. Inspection by thermal scanning image during the construction work. From the left: real picture of closed window; undistorted IR image of closed window; and overlapping closed window (Copyright 2018, H2020-INSITER Project Consortium Partnership).

5.2. Inspection Demonstration on MEP-HVAC

MEP-HVAC systems installed in existing buildings pose challenges for retrofitting due to the dispersed nature of their components throughout different spaces, including indoor and outdoor elements in various floors and ceilings. However, when opting for deep retrofits of buildings, strategic decisions regarding MEP-HVAC systems can substantially contribute to overall energy savings. The goal of the demonstration was to implement an effective design and installation process, utilizing INSITER tools. In this particular case study, emphasis was placed on verifying the precision of BIM-modeled MEP components and retrofit elements to reduce the likelihood of errors during the retrofitting procedure.

The inspection demonstration activities on new MEP system have been performed following these steps of the proposed methodology:

- Step 1: Pre-renovation condition assessment specifying building characteristics and checking the technical condition including building type, orientation, area, envelope, usage, etc., as well as national building regulations, mandatory technical requirements for HVAC systems and requirements for indoor environmental quality (IEQ).
- Step 2: Checking the particular MEP components delivered on the building site. Scanning RFID or QR of the MEP components and retrieval of component's ID in BIM. This stage requires retrieving a list of materials from the BIM and collecting the (prefabricated) components that have to be installed.
- Step 3: BIM modeling of the existing building, including detailed modeling of the building components and MEP/HVAC installations that are critical for the indoor environmental quality and energy performance. Deployment of BIM models for on-

site use. Loading the partial BIM model onto a tablet, showing the specific parts of MEP-HVAC.

- Step 4: Creating and implementing BIM-based AR for self-instruction and self-inspection involves integrating BIM and VR into AR, translating BIM/VR processes into self-instructions for construction workers. The Mixed Reality model will be accessible on the mobile devices of construction workers, and data from hardware tools will interface with BIM and inspection software for effective inspections (Figure 7).

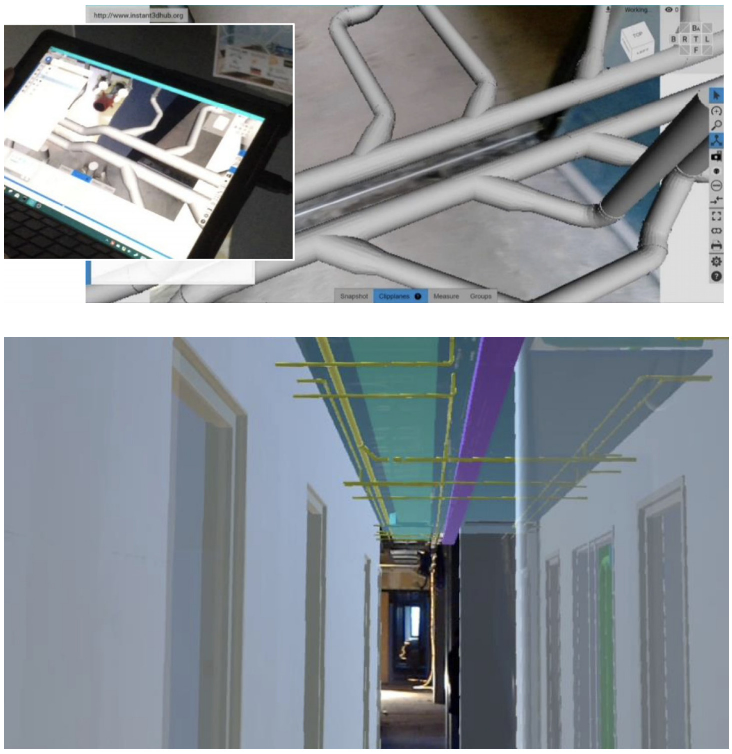

Figure 7. BIM AR and MR Vision App. MEP and HVAC systems' self-instruction for construction workers (Copyright 2018, H2020-INSITER Project Consortium Partnership).

- Step 5: The clash detection process involves defining parameters, preparing the BIM model, and conducting clash detection by scrutinizing all MEP trades. Employing the 3D clash detection method aims to expedite the design coordination process and ensure a thoroughly coordinated design.
- Step 6: Using AR to check the possible installation of the designed MEP components. In detail, checking the design scenarios, problematic situations, necessary interventions for the structure, and use of materials. Preparing the building structure for the installation of the MEP components (e.g., checking the design scenario with the BIM model for drilling holes if necessary).
- Step 7: Installation/replacement of the MEP systems in the building. Using BIM model to check accuracy. The installation has been followed by the placement of the sanitary and kitchen modules according to a manual from the manufacturer. The installation procedure has been checked with the BIM model for any discrepancies. After the installation started the self-inspection activity trough deployment of AR tool at the location where the MEP components are installed adopting this procedure: loading the BIM on a portable device (tablet); setting the positioning and orientation points for AR; visual inspection of the installation work using AR; and project AR overlay over the installed components/ducting to verify correct installation, course, and location (Figure 8).

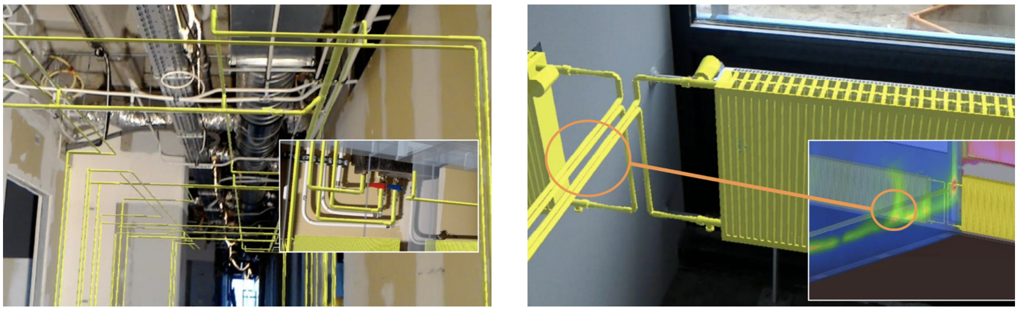

Figure 8. INSITER HoloLens BIM-based Mixed Reality App screenshots for self-inspection. The on-site demonstration centered on the heating system, with a focus on visualizing instrumentation measurement data related to thermal variations and heat dispersion of heating pipes (Copyright 2018, H2020-INSITER Project Consortium Partnership).

6. Results and Discussion

The adoption of innovative inspection methodologies, coupled with the installation of new prefabricated solutions for the building's envelope and HVAC (heating, ventilation, and air conditioning) systems, along with the utilization of embodied energy, resulted in energy savings of up to 70% compared to the pre-renovation state. Additionally, the use of prefabricated solutions, encompassing facade panels and modular units for kitchens and sanitary facilities, facilitated a 50% reduction in the renovation timeline. This success is also demonstrated by the final energy label post-deep renovation of A, a significant improvement from the G label the building had prior to the renovation.

The case study reported in this paper comprehensively demonstrates the achievement of the objectives of the proposed methodology such as error reduction, cost reduction, and construction time.

Considering the improvement in energy saving and the prediction in energy costs, a few remarks on the economic aspects are, however, necessary. Although a cost analysis comparing the initial investment in digital tools with the long-term savings from reduced errors and improved efficiency was not conducted as a part of this research, the existing literature [11,22] highlights the economic benefits of new technologies in the construction sector, particularly in the context of NZEB. Construction companies that absorb these initial costs can gain significant advantages:

- Reducing the cost of new technologies: studies [23,24] have shown that the cost of digital technologies, especially BIM and AR, has decreased in recent years due to technological evolution and mass adoption, facilitating their wider adoption.
- Added value: the implementation of advanced technologies can significantly increase operational efficiency, reduce construction time, and improve the overall quality of projects. This can not only reduce construction costs but also increase the competitiveness of construction companies in the market.
- Reuse of technologies on multiple sites: once acquired, digital technologies can be reused on numerous projects, spreading initial costs over multiple sites and increasing the return on investment over time.

Another important consideration is the current standards and the need to enhance the standardization of self-monitoring procedures and training programs for construction workers in the use of new components, technological and digital tools—an aspect that has been extensively addressed in research (D6.1 training modules and pilot training courses) [25] and resulted in the following actions:

- Standardized Training Modules: INSITER developed training modules to enhance awareness and proficiency in using new digital tools and self-inspection methods, aiming to standardize how workers integrate these technologies into their workflows.
- AR and BIM integration: the project standardized their use for on-site self-instruction, providing consistent, real-time guidance to standardize training and operations across projects.

- Community of Practice: INSITER fostered a community to promote standardized learning and the exchange of best practices throughout the EU, enhancing the uniformity of training programs (in collaboration with PROF/TRAC, BUStoB, and BUILDUP.eu) [26–28].
- Certification Programs: the initiative prepared skill-oriented professional training and certification programs to standardize training across EU countries, equipping workers with the skills needed to effectively use new technologies and comply with current standards.

7. Conclusions and Perspectives

Important new measures that strengthen the interest in decarbonization have recently been approved by the European Parliament through the contents of the revised Directive Energy Performance of Buildings renamed 'Green Homes Directive' [29]. This Directive marks a decisive moment for energy efficiency and environmental sustainability of buildings in the European Union.

Aiming to align with the commitments of the Paris Agreement and the European Green Deal, this Directive aims to reduce emissions from the building sector by 60 per cent by 2030 and to achieve climate neutrality by 2050.

In summary, the new Directive mandates the following for all member states:

- All new private buildings must achieve zero emissions by 2030, with the deadline set at 2028 for public buildings.
- Residential buildings are required to reduce their average energy consumption by 16% by 2030 and by 20–22% by 2035.
- Non-residential buildings must reduce their average energy consumption by 16% by 2030 and by 26% by 2033.

Analyzing the current building stock, the target of a 55% reduction is to be attained by renovating 43% of the poorest-performing buildings.

According to studies by Fillea CGIL [30], in Italy, the provisions outlined in the Directive will interests the renovation of between 5.5 and 7.6 million residential buildings in the near future. In fact, by 2050, residential buildings currently classified in the lowest-performing classes F and G will need to undergo a substantial energy transition through renovation strategies.

Given the introduced measures, achieving concrete substantial progress towards climate neutrality requires more than just ensuring the proper design of buildings. It is crucial to verify that constructed buildings effectively meet the specified performance standards in terms of energy efficiency and zero impact. Consequently, innovative methodologies and procedures for ensuring energy performance will become valuable tools in the battle against climate change.

Actually, in the dynamic panorama of global industrial evolution, the construction sector emerges as a fundamental battleground in the fight against climate change.

Industry 4.0 has inaugurated an unprecedented era of transformation, where digitalization is not just an addition but a central pillar in the search for sustainability. In a world where precision and efficiency are of paramount importance, digitalization and innovative inspection procedures become crucial for unlocking the full potential of NZEB.

Indeed, in the last ten years, the digitalization of the construction sector has produced a further acceleration in the reliability of procedures and tools that allow for the reduction in errors, the optimization of timing, and the reduction in costs.

Within the framework of the ongoing digital transition process, the inspection methodologies presented in this paper can contribute to the further development of procedures and tools for quality management and, in particular, for the performance of energy efficiency over the building lifecycle to reduce the environmental impact towards climate neutrality. Such potential could increase on the integration of Information and Communication Technologies (ICTs) and Artificial Intelligence (AI) in the planning and management procedures as well as in design and maintenance activities of the existing building stock.

As demonstrated, the integration of digitalized process as well as digital tool technologies does not only enhance the communication among stakeholders but also serves as a dynamic tool for real-time monitoring and optimization throughout the building's lifecycle. This ensures that the result of a new construction or a renovation aligns with the initially envisioned energy-neutral design.

In a particular historical moment of the sector where the interest in the valorization and deep renovation of the existing building stock is fundamental to attend the aims of the New European Green Deal and Renovation Wave program toward the decarbonization of the construction segment, the building inspection became of obvious importance.

Periodic inspections have long been recognized as one of the main methods for evaluating the component and building performance but also material conservation, particularly for building maintenance.

In fact, on the existing building stock, the results of inspections and the data from monitoring systems are an essential tool for choosing the best interventions to be carried out evaluating the deadlines for their execution, defining the specifications on products and technologies to be used, indicating the specializations and skills required of the operators who will have to execute them.

During the last year, it has been extensively demonstrated that the computational power of AI is revolutionizing traditional practices, making them more efficient and intelligent.

Into the construction domain, the recent merger of AI technologies, mainly machine learning and deep learning systems, has catalyzed a paradigm shift. This integration opens the way to new procedures in planning, managing new constructions and restorations, as well as simplifying maintenance operations.

In summary, the ongoing advances driven by digitalization and its allied technologies introduced in this paper offer a range of sophisticated solutions to reduce the construction errors by self-instruction solutions and to evaluate building performance and conditions by self-inspection.

These advancements are indispensable for the inspection and assessment of buildings, with the final goal of preserving their efficiency and performance. Ensuring compliance with energy efficiency standards over time is not only a matter of regulatory compliance but also is crucial for minimizing the environmental footprint of buildings, thereby contributing significantly to the mitigation of the impacts of climate change.

Self-instruction and self-inspection procedures, combined with advanced digitalization technologies (BIM, Digital Twins, AR, etc.), create a synergy that will propel the construction industry into a new era of precision, collaboration, and environmental awareness as the foundation for a climate-neutral future.

Author Contributions: Conceptualization, E.P. and B.T.; methodology, E.P.; formal analysis, B.T.; investigation, E.P., B.T. and R.S.; resources, R.S.; data curation, R.D.G.; writing—original draft preparation, E.P. and B.T.; writing—review and editing, E.P., B.T. and R.S.; supervision, R.D.G. All authors have read and agreed to the published version of the manuscript.

Funding: The INSITER project has received funding from the European Union's Horizon 2020 Research and Innovation Program under Grant Agreement No. 636063.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are available in: https://cordis.europa.eu/project/id/636063/results/it (accessed on 20 April 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683 (accessed on 6 March 2024).
2. Available online: https://cordis.europa.eu/project/id/636063 (accessed on 2 February 2024).
3. Available online: https://cordis.europa.eu/project/id/636895 (accessed on 20 April 2024).

4. Available online: https://cordis.europa.eu/project/id/637221 (accessed on 20 April 2024).
5. Ioannou, A.; Itard, L.C.M. Energy performance and comfort in residential buildings: Sensitivity for building parameters and occupancy. *Energy Build.* **2015**, *92*, 216–233. [CrossRef]
6. Martinaitis, V.; Edmundas, E.K.; Motuzienė, V.; Vilutienė, T. Importance of occupancy information when simulating energy de-mand of energy efficient house: A case study. *Energy Build.* **2015**, *101*, 64–75. [CrossRef]
7. Carpino, C.; Loukou, E.; Heiselberg, P.; Arcuri, N. Energy performance gap of a nearly Zero Energy Building (nZEB) in Denmark: The influence of occupancy modelling. *Build. Res. Inf.* **2020**, *48*, 899–921. [CrossRef]
8. Eon, C.; Breadsell, J.K.; Byrne, J.; Morrison, G.M. The Discrepancy between As-Built and As-Designed in Energy Efficient Buildings: A Rapid Review. *Sustainability* **2020**, *12*, 6372. [CrossRef]
9. Mahdavi, A.; Berger, C.; Amin, H.; Ampatzi, E.; Andersen, R.K.; Azar, E.; Barthelmes, V.M.; Favero, M.; Hahn, J.; Khovalyg, D.; et al. The Role of Occupants in Buildings' Energy Performance Gap: Myth or Reality? *Sustainability* **2021**, *13*, 3146. [CrossRef]
10. Alencastro, J.; Fuertes, A.; de Wilde, P. The relationship between quality defects and the thermal performance of buildings. *Renew. Sustain. Energy Rev.* **2018**, *81 Pt 1*, 883–894. [CrossRef]
11. Wang, M.; Wang, C.C.; Sepasgozar, S.; Zlatanova, S. A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0. *Buildings* **2020**, *10*, 204. [CrossRef]
12. You, Z.; Feng, L. Integration of Industry 4.0 Related Technologies in Construction Industry: A Framework of Cyber-Physical System. *IEEE Access* **2020**, *8*, 122908–122922. [CrossRef]
13. IEA. *Energy Efficiency 2023*; License: CC BY 4.0; IEA: Paris, France, 2023; Available online: https://www.iea.org/reports/energy-efficiency-2023 (accessed on 20 April 2024).
14. IEA. *Tracking Clean Energy Progress 2023*; License: CC BY 4.0; IEA: Paris, France, 2023; Available online: https://www.iea.org/reports/tracking-clean-energy-progress-2023 (accessed on 20 April 2024).
15. Gan, V.J.L.; Lo, I.M.C.; Ma, J.; Tse, K.T.; Cheng, J.C.P.; Chan, C.M. Simulation optimisation towards energy efficient green buildings: Current status and future trends. *J. Clean. Prod.* **2020**, *254*, 120012. [CrossRef]
16. Lotfabadi, P.; Hançer, P. A comparative study of traditional and contemporary building envelope construction techniques in terms of thermal comfort and energy efficiency in hot and humid climates. *Sustainability* **2019**, *11*, 3582. [CrossRef]
17. Far, C.; Far, H. Improving energy efficiency of existing residential buildings using effective thermal retrofit of building envelope. *Indoor Built Environ.* **2019**, *28*, 744–760. [CrossRef]
18. Boriani, A.; Cariani, W.; Romani, R. Agenzia Nazionale Efficienza Energetica—ENEA, Febbraio 2020, Guida Pratica alla Ristrutturazione e Riqualificazione Energetica Degli Edifici per Amministratori di Condominio. I BONUS nel Settore Edilizio con le Novità della Legge di Bilancio 2020 (Legge 27 Dicembre 2019, n. 160, G.U. n. 304 del 30 Dicembre 2019). p. 14. Available online: https://www.pubblicazioni.enea.it/download.html?task=download.send&id=18:guida-pratica-alla-ristrutturazione-e-riqualificazione-energetica-degli-edifici-per-amministratori-di-condominio&catid=3 (accessed on 20 April 2024).
19. Available online: https://store.uni.com/en-13369-2018 (accessed on 20 April 2024).
20. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC. Available online: https://data.europa.eu/eli/dir/2012/27/oj (accessed on 20 April 2024).
21. Kubba, S. *Handbook of Green Building Design and Construction. LEED, BREEAM, and Green Globes*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2017; ISBN 978-0-12-810433-0.
22. Pan, N.-H.; Isnaeni, N.N. Integration of Augmented Reality and Building Information Modeling for Enhanced Construction Inspection—A Case Study. *Buildings* **2024**, *14*, 612. [CrossRef]
23. Pascucci, F.; Savelli, E.; Gistri, G. How digital technologies reshape marketing: Evidence from a qualitative nvestigation. *Ital. J. Mark.* **2023**, *2023*, 27–58. [CrossRef]
24. Noghabaei, M.; Heydarian, A.; Balali, V.; Han, K. Trend Analysis on Adoption of Virtual and Augmented Reality in the Architecture, Engineering, and Construction Industry. *Data* **2020**, *5*, 26. [CrossRef]
25. D6.1 Training Modules and Pilot Training Courses. Available online: https://www.insiter-project.eu/en/Documents/Deliverables/INSITER%20D6.1Training%20modules%20and%20pilot%20training%20courses%20.pdf (accessed on 20 April 2024).
26. Available online: https://cordis.europa.eu/project/id/649473 (accessed on 20 April 2024).
27. Available online: https://cordis.europa.eu/project/id/649737/it (accessed on 20 April 2024).
28. Available online: https://build-up.ec.europa.eu/en/home (accessed on 20 April 2024).
29. Revised Directive on the Energy Performance of Buildings, Council of the European Parliament. Available online: https://data.consilium.europa.eu/doc/document/PE-102-2023-INIT/en/pdf (accessed on 20 April 2024).
30. FILLEA-CGIL, Testo Unico Degli Incentivi. 2023. Available online: https://www.filleacgil.net/images/cannata/EVENTI/27luglio2023/PropostaFilleaIntegrale.pdf (accessed on 20 April 2024).