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ENHANCING ENERGY MANAGEMENT AND DECARBONIZATION IN COMPLEX BUILDINGS THROUGH DYNAMIC EVALUATION WITH DIGITAL TWINS: IMPACT ANALYSIS IN AN OFFICE BUILDING AND A RAILWAY STATION

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Abstract

Conventional static energy audits fail to capture the dynamic nature of building operation, generating persistent performance gaps and limiting the potential for CO₂ emission reductions throughout the building lifecycle. This paper presents a level-4 digital twin framework (Autodesk maturity scale) that integrates Building Information Modelling (BIM) models, Internet of Things (IoT)-based monitoring systems, and continuously recalibrated simulation models to enable dynamic, ongoing energy performance assessment and support decarbonization in complex buildings.

The methodology is structured around the deployment of the digital twin in two real use cases in Málaga, Spain: an office building and the María Zambrano intermodal railway station, representing distinct building typologies and different stages of digital twin implementation. In the office building, a baseline period prior to deployment and a subsequent demonstration period with full system access are compared: the results yield a measured annual CO₂ emission reduction of 4.17%, a simulation model accuracy of 2.16% annual performance gap, and a 66.93% reduction in renovation audit time. In the railway station, where deployment is ongoing, a preliminary analysis based on energy and lighting models developed during the characterisation phase estimates a CO₂ reduction potential of up to 30.39% in the office subsystem and approximately 71% in the platform lighting system.

The results demonstrate the capacity of level-4 digital twins to enhance energy management and support decarbonization across complex building typologies, enabling two complementary modes of dynamic evaluation: quantification of real impacts under operational conditions in assets already under intervention, and identification of maximum decarbonization potential in assets yet to undergo it.

Key Words: Digital twin, building energy performance, decarbonization, energy audit.

1 Introduction

The building sector accounts for approximately 40% of final energy consumption and 36% of greenhouse gas emissions in the European Union [1]. Within the European decarbonisation strategy towards climate neutrality by 2050, improving the energy efficiency of the existing building stock is a recognised priority under the Energy Performance of Buildings Directive (EPBD recast 2024) [2]. In this context, energy audits are a key instrument for diagnosing the condition of the building stock, quantifying improvement potential, and informing investment decisions in renovation.

However, the literature has identified four main barriers that limit the effectiveness of conventional energy audits. First, there is a persistent gap between simulation-based estimates and the actual energy performance of buildings in operation, which reduces the reliability of proposed energy conservation measures and generates mistrust among building owners [3]. Second, occupant behaviour is one of the most influential factors in energy consumption and, simultaneously, one of the most difficult to predict and manage; various studies estimate an energy saving potential associated with awareness and behavioural change of between 5% and 30% [4]. Third, conventional audits assess the building at a single point in time and do not account for changes arising from building ageing and shifts in occupancy patterns, rendering the model obsolete and undermining the reliability of the economic estimates associated with improvement measures [5]. Fourth, conventional energy audits are time- and resource-intensive processes, which limits their frequency and, consequently, the opportunities to identify and correct inefficiencies throughout the building lifecycle [5].

In response to these limitations, the digital twin has consolidated as an operational approach in several engineering sectors, integrating the BIM (Building Information Modelling) model of the asset with real-time monitored data to enable continuous and dynamic assessment of energy performance [6, 7]. However, according to the Autodesk maturity classification, the digital twins most widely deployed in the AEC sector still operate at levels 1 (descriptive) and 2 (informative), while higher levels, with capabilities for dynamic recalibration and scenario simulation, remain on the adoption horizon [8]. The transition towards level-4 digital twins, capable of recalibrating the energy model with real operational data and simulating what-if scenarios, therefore constitutes an unresolved need in the building sector.

This paper analyses the impact of level-4 digital twin-based dynamic energy assessment on energy management and decarbonisation across two building typologies: an office building with annexed laboratories in Málaga and the Málaga Maria Zambrano intermodal railway station. The analysis is conducted within the framework of two research projects: AICREDITS [9] (CDTI, IDI-20210497), focused on enhancing energy audits through artificial intelligence, and Rail4EARTH [10] (Horizon Europe, GA 101101917), part of Flagship Project 4 of Europe's Rail Joint Undertaking. Both pilots share a common methodology structured around the deployment of a sensor network, the development of a level-4 digital twin, its implementation in each pilot, and the evaluation of its impact on energy management and decarbonisation.

The paper is structured in five sections: Section 2 presents the methodology, covering the description of both case studies, information and monitoring requirements, digital twin development and implementation, and the validation plan; Section 3 presents the analysis and results of the office building case study; Section 4 presents the analysis and preliminary results of the railway station case study; and Section 5 sets out the conclusions, comparative analysis between typologies, and future lines of work.

2 Methodology

This work proposes a dynamic assessment framework based on level-4 digital twins which, in contrast to conventional static energy audits, enables a continuous and updated evaluation of the asset's energy performance, aimed at reducing energy consumption and CO₂ emissions. The framework is structured around four methodological blocks: (i) description of the case studies, (ii) information and monitoring requirements for each pilot, (iii) development and implementation of the digital twin, and (iv) validation plan.

2.1 Use cases

The methodology is implemented in two real use cases located in Málaga (Spain), representing two asset typologies with distinct technical and operational characteristics.

2.1.1 Use case 1: Office building

The AICREDITS project pilot is an office building, located in Málaga and built in 2007 (Figure 1). The building has one basement level used for parking and four above-ground floors with mixed uses: the ground floor houses material testing laboratories as well as a reception area and offices, while the first, second, and third floors are entirely dedicated to offices. The total built area amounts to 6,402 m², of which approximately 5,000 m² are air-conditioned, with a typical occupancy of around 120 people distributed across the four floors. The building's only energy source is electricity. The HVAC system is composed of five Air Handling Units (AHUs) located on the roof that supply outdoor air to all floors through a duct system, connected to a CARRIER 30RH120 heat pump (117 kW heating / 108 kW cooling, installed in 2007) and a CARRIER 30RA160 reciprocating compressor chiller (157 kW cooling, nominal Coefficient of Performance (COP) 3.2, installed in 2021). The perimeter zones additionally have fan coils with local user control, which introduces a source of variability in the building's energy behaviour with a direct impact on efficiency.

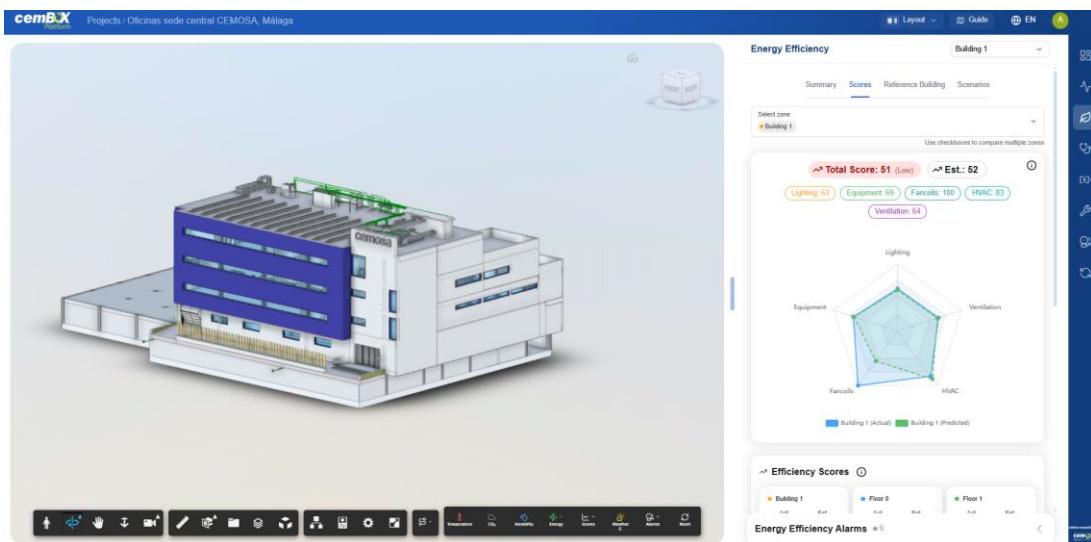


Figure 1. Use case 1: AICREDITS office building pilot.

2.1.2 Use case 2: María Zambrano railway station

The Málaga-María Zambrano Railway Station is the main railway hub of the city of Málaga, inaugurated in 2006 (Figure 2). With a total surface area of 160,000 m², of which 80,000 m²

correspond strictly to railway use, the station operates as an intermodal hub integrating train, bus, and metro connections, with 8 tracks served by 5 platforms. Within the framework of the FA4-Rail4EARTH project, the scope of the digital twin is structured around two specific operational subsystems: first, the platform area, focused on the optimization of the lighting system conditioned by train schedules and the requirements of the UNE-EN 12464-2 standard; and second, the multipurpose building (Block 3), which houses the ADIF offices and is the subject of HVAC performance improvement.



Figure 2. Use case 2: Málaga María Zambrano railway station

2.2 Requirements

The development of the digital twin in each case study requires three categories of input: static data from the asset's BIM model and the collection of information (geometry, envelope, HVAC systems, occupancy patterns, and technical documentation), dynamic data from the monitoring system (disaggregated energy consumption, indoor comfort and air quality conditions, and outdoor meteorological variables), and energy simulation models (a calibrated model continuously updated with monitored data and a reference model representing optimal operational conditions).

In the office building, the pre-existing BIM model was updated following an on-site characterisation visit. The monitoring infrastructure comprises 43 measurement points covering all major systems, with data transmitted via MQTT to a SAP HANA database. In the railway station, the BIM model was supplemented with platform geometry and luminaire layout as the basis for the DIALux lighting model. The available monitoring infrastructure at the time of analysis comprised 31 measurement points from the ADIF Smart Station system; a planned expansion to 92 points, incorporating illuminance sensors and a rooftop weather station, was not yet operational. In both case studies, energy models are implemented in EnergyPlus.

2.3 Development and implementation of the digital twin

2.3.1 Architecture

The digital twin is implemented on a four-layer information architecture: static data from the BIM model, real-time dynamic data from the monitoring system, data processing for the

continuous calculation of energy performance indicators, and automatically recalibrated simulation models. These layers are integrated through a set of Python-based computational microservices, covering climate file generation, energy simulation, automatic calibration, and KPI derivation, that constitute the computational backbone enabling the dynamic evaluation framework described in Section 2.4. The system is exposed to end users through an interactive web interface built on the asset's BIM model, providing geolocated access to monitored data, performance indicators, and scenario results. A detailed description of the system architecture and its modular implementation is provided in Deliverable D13.1 of the FA4 project and Deliverable E5.3 of the AICREDITS project.

2.3.2 Monitoring module

The monitoring module provides the continuous observational layer that feeds the validation framework described in Section 2.4. During the baseline period it records the asset's unassisted operational behaviour; during the demonstration period it captures the effect of management decisions informed by the digital twin, enabling the before-after comparison on which the impact assessment is based.

The module centralises real-time and historical access to three data dimensions: disaggregated energy consumption by circuit and use type, indoor comfort and air quality conditions (temperature, relative humidity, and CO₂ concentration by zone), and outdoor meteorological variables. All data are presented geolocated on the three-dimensional BIM model through heat maps that colour the model surfaces according to the deviation from the optimal value of each variable, enabling remote inspection of the asset and immediate identification of zones with anomalous conditions (Figure 3). The user can filter by zone, compare sensors in parallel, and navigate time series at different temporal resolutions.



Figure 3. Monitoring module interface

2.3.3 Efficiency module

The efficiency module constitutes the analytical core of the dynamic evaluation framework. Its function is to continuously quantify the gap between the asset's actual operational performance and its optimal operational state, providing the evidence base for the impact assessment described in Section 2.4.

This quantification relies on the systematic comparison of two simulation models: a calibrated model, automatically updated every 15 days with real monitored data to represent the building's current operational behaviour, and a reference model, representing the same building operated under optimal conditions. The automatic recalibration cycle is a critical methodological requirement: only a model continuously adjusted to real operational data provides sufficient reliability to attribute observed changes in energy consumption to management decisions rather than to modelling assumptions. This distinction is empirically validated in Section 3.2.1, where the annually calibrated model achieves a performance gap of 2.16% against measured consumption, compared to 7.83% for a conventional non-recalibrated model.

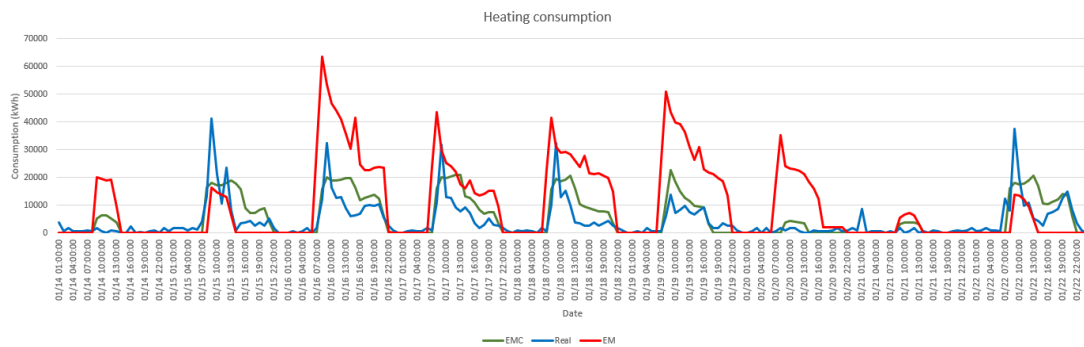


Figure 4. Comparison between a calibrated energy model (EMC) and an uncalibrated energy model (EM) for heating consumption

From the comparison of both models, the module derives continuous efficiency indicators for each consumption type —equipment, lighting, HVAC, and total— expressed as a score

$$Score = \frac{C_{reference}(kWh)}{C_{calibrated}(kWh)} \times 100 \quad (1)$$

Where $C_{reference}$ is the consumption of the reference model and $C_{calibrated}$ is that of the calibrated energy model. The score is interpreted as follows: values between 100% and 90% indicate high energy efficiency; between 90% and 80%, medium efficiency; between 80% and 70%, acceptable efficiency; and below 70%, low efficiency.

2.3.4 Alarm module

The alarm module continuously monitors the data from the monitoring system through a microservice that evaluates, every 5 minutes, a set of predefined rules on the latest available readings. The alarms are classified into two families: efficiency alarms, which detect inefficient operating conditions such as consumption outside occupancy hours, inappropriate setpoints, comfort conditions out of range or lighting active without justification; and monitoring alarms, which ensure data quality and integrity such as absence of readings or physically impossible values. The alarms are visualized geolocated on the BIM model, classified by priority and resolution status, allowing immediate identification of the equipment or zone that generated the alert.

2.4 Validation plan

Conventional static energy audits provide a single-point snapshot of a building's performance, making it impossible to distinguish between seasonal variability, occupancy fluctuations, and the actual effect of management interventions. The validation framework proposed in this work addresses this limitation through a controlled experimental design structured around two sequential periods —baseline and demonstration— which enables the attribution of observed changes in energy consumption and CO₂ emissions to the operation of the digital twin, while controlling for external confounding factors such as climate and occupancy.

2.4.1 Baseline & demonstration period

The baseline period establishes the reference state of the asset's energy behaviour prior to the activation of the digital twin functionalities. During this phase, data are collected continuously through the monitoring system, but neither facility managers nor building users have access to the platform's performance indicators, alarms, or scenario tools. These controlled conditions ensure that the baseline characterises the building's unassisted operational behaviour, providing a clean reference for subsequent comparison.

The demonstration period begins after full deployment of the digital twin and the enablement of access for all managers and users. To control for seasonal effects, the demonstration period is defined over the same calendar window as the baseline period, ensuring that differences in energy performance between the two phases are not attributable to climatic variation.

In the office building (AICREDITS), the baseline period extended from February 2022 to February 2023, covering all four seasons and a full annual cycle of occupancy variability. The demonstration period began in March 2023 following the full activation of the platform for all building users and managers.

In the railway station (FA4–Rail4EARTH), the baseline period covers August to November 2025, using consumption data from sensors already operational at the station since August 2025. This period will be extended through March 2026 as the planned expansion of the sensor network is completed, allowing the incorporation of additional consumption, indoor air quality, and illuminance measurements. The demonstration period is defined over the equivalent seasonal window of August to November 2026, ensuring direct comparability with the reference period. At the time of writing, the digital twin is in its deployment phase and the demonstration period has not yet commenced; the results presented in Section 4 therefore correspond to a preliminary potential assessment based on the available monitoring data and calibrated models.

2.4.2 Quantitative impact assessment

The quantitative evaluation allows assessing the impact of the digital twin on the asset by comparing a set of indicators measured during the baseline and demonstration periods, covering aspects such as CO₂ emission reductions, improvements in the energy audit process, changes in occupant behaviour, indoor environmental quality compliance, and maintenance performance. The central indicator of this work is the CO₂ emission reduction, calculated as:

$$CO_{2,red}(\%) = \frac{CO_{2,extrapolated} - CO_{2,demo}}{CO_{2,extrapolated}} \times 100 \quad (2)$$

where $CO_{2,extrapolated}$ is the CO₂ emissions extrapolated from the baseline period consumption to the demonstration period timeframe, and $CO_{2,demo}$ is the CO₂ emissions measured

during the demonstration period. Both terms are expressed in kgCO₂ and calculated by applying the official emission factors published annually by the Spanish Ministry for Ecological Transition.

3 Use case 1: Office building

The pilot characteristics, the deployed monitoring system, and the digital twin implementation process are described in Section 2. The baseline period extended from February 2022 to February 2023, and the demonstration period began in March 2023 with the full activation of the platform for all building users and managers. This section presents the analysis process and the results of the quantitative impact assessment.

3.1 Analysis process

The evaluation of the impact of the digital twin on the office building is structured around two areas. The first evaluates the improvement of the energy audit process, quantifying the reduction in time required to carry out renovation audits compared to the conventional approach. The second evaluates the operational and environmental performance of the building by comparing the following indicators between the baseline and demonstration periods: CO₂ emission reduction, improvement in user energy behaviour, hours of simultaneous compliance with comfort and indoor air quality criteria, and reduction in critical failures.

3.2 Results

3.2.1 Accuracy of the calibrated model

Prior to the impact assessment, the accuracy of the calibrated model was validated by comparing simulated and measured consumption over the full baseline period. The calibrated energy model (CEM) achieved an annual performance gap of 2.16%, remaining below 10% for all months except May, which corresponds to a period with sensor data interruptions. In contrast, the conventional non-calibrated model presents an annual error of 7.83%, with monthly deviations exceeding 20–30% in several cases. These results confirm a key methodological premise: only a continuously calibrated model based on real operational data provides a sufficiently reliable baseline for assessing energy performance and quantifying the impact of management actions.

3.2.2 CO₂ emission reduction

Applying the official emission factors from the Spanish Ministry for Ecological Transition (0.223 kgCO₂/kWh for 2022 and 0.201 kgCO₂/kWh for 2023), the comparison between the extrapolated baseline consumption and the measured consumption during the demonstration period shows an annual CO₂ emission reduction of 4.17%, corresponding to a decrease from 102,832 kgCO₂ to 98,548 kgCO₂. The reduction is more pronounced during winter months, particularly November (17.31%) and December (19.81%), when the digital twin's alarm system and real-time performance indicators had a stronger influence on operational decision-making.

3.2.3 Impact on the energy audit process

The availability of continuous monitoring data and a calibrated energy model reduced the time required to perform a renovation energy audit by 66.93% compared to the conventional approach. This reduction is mainly due to the elimination of manual data collection and the availability of a validated model as a starting point for analysis. Additionally, the methodology increased the

annual audit capacity of the technical team by 77.77%, demonstrating a significant improvement in scalability.

3.2.4 Operational and behavioural improvements

Beyond energy and process-related indicators, the implementation of the digital twin also led to measurable improvements in building operation. The number of hours with inefficient energy use decreased by 25%, while the percentage of hours within comfort and indoor air quality ranges increased from 91.3% to 94.4%. In parallel, the number of critical failures was reduced by 25% due to the implementation of automated alarms and preventive maintenance strategies.

3.2.5 Summary of key indicators

Table 1 summarises the main impact indicators of the study, focusing on those directly related to the objectives of this paper: model accuracy, decarbonisation, operational efficiency, and improvement of the energy audit process.

Table 1. Summary of key impact indicators: office building case study

Indicator	Value	Comment
Renovation Audit time reduction	66.93%	Reduction due to availability of monitored data and calibrated energy model
Increase in annual audit capacity	77.77%	Higher productivity enabled by continuous data availability and reduced manual workload
Energy model performance gap (annual)	2.16%	Significant improvement compared to 7.83% for the conventional model
Comfort and indoor air quality compliance	94.4%	Increase from 91.3% in the baseline period, exceeding project target
Reduction in inefficient user behaviour	25%	Decrease from 2,188 to 1,036 hours of inefficient operation
CO ₂ emission reduction	4.17%	Decrease from 102,832 kgCO ₂ to 98,548 kgCO ₂
Reduction in critical failures	25%	Improvement due to preventive maintenance supported by digital twin alarms

4 Use case 2 – María Zambrano railway station

The pilot characteristics, the available monitoring infrastructure, and the particularities of the digital twin development status are described in Section 2. Unlike Use Case 1, the results presented in this section do not correspond to a baseline–demonstration comparison, but to a preliminary analysis of the CO₂ reduction potential, based on the available data from the existing monitoring system and on the energy models developed during the characterisation phase.

4.1 Analysis process

The preliminary analysis process is developed separately for the two subsystems within the scope of the digital twin: the office building and the platform lighting system.

For the office building, the consumption data available from the ADIF Smart Station infrastructure were used to calibrate the energy model through the digital twin's calibration service, identifying the energy conservation measures with the greatest reduction potential.

For the platform lighting system, a lighting study was carried out using DIALux software to verify compliance with UNE-EN 12464-2 requirements under different combinations of active circuits. The study systematically evaluated the circuit combinations required for each platform occupancy scenario determined by the train schedule, identifying both the baseline case and the minimum configuration ensuring regulatory illuminance levels, thereby defining the intelligent control strategy that maximises energy savings without compromising operational safety.

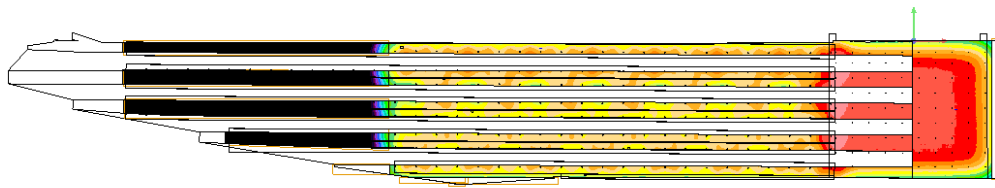


Figure 5. DIALux illuminance simulation model of the María Zambrano station platforms, showing luminous flux distribution under full circuit activation

4.2 Preliminary results

4.2.1 Office building

The reference model represents the building operated under optimal conditions, incorporating four key improvements over the calibrated model: full replacement of the lighting system with LED technology (5 W/m²), operation of rooftop units at nominal catalogue performance, regulatory temperature setpoints (22–24 °C), and elimination of uncontrolled infiltrations. These assumptions were derived from the analysis of discrepancies between monitored data and the calibrated model, which revealed significant inefficiencies in HVAC operation and lighting performance.

The application of these measures yields an estimated annual CO₂ reduction potential of 30.39%, accompanied by a 36.05% reduction in energy consumption and a 26.29% reduction in energy costs. The impact is particularly pronounced during summer months, when cooling demand amplifies HVAC inefficiencies.

4.2.2 Platform area

The analysis of the platform lighting system revealed severe degradation of the existing infrastructure. The calibration of the lighting model, based on real consumption data, showed that between 50% and 77% of luminaires were not operational across different tracks at the time of analysis.

The baseline scenario assumes that all lighting circuits are activated during fixed time periods, independently of platform occupancy, which leads to inefficient energy use. In contrast, the reference scenario incorporates two key improvements enabled by the digital twin: (i) full restoration of the lighting system and (ii) implementation of an intelligent control strategy based on real-time platform occupancy and compliance with UNE-EN 12464-2 lighting requirements.

The optimisation strategy was developed through a DIALux simulation model combined with train schedule data, allowing the identification of the minimum set of lighting circuits required to ensure regulatory illuminance levels for each occupancy scenario. This approach ensures that safety requirements are maintained while minimising energy consumption.

The results show that the implementation of occupancy-based lighting control reduces daily energy consumption from 456.75 kWh to 131.81 kWh in representative scenarios, corresponding to savings between 65% and 82% depending on the month.

In terms of environmental impact, the estimated CO₂ emission reduction ranges between 62% and 81%, with an average value of approximately 71%, while energy cost savings reach up to 80%.

5 Conclusions

The results presented in this paper demonstrate that level-4 digital twins constitute an effective framework for transitioning from static, point-in-time energy audits to continuous, data-driven assessment of building energy performance. The proposed approach, integrating BIM models, Internet of Things (IoT)-based monitoring systems, and automatically recalibrated simulation models, has been validated across two real case studies of distinct typology and operational complexity.

In the office building, the deployment of the digital twin yielded simultaneous improvements across multiple dimensions of building performance. The calibrated energy model achieved an annual performance gap of 2.16%, with monthly deviations remaining within acceptable bounds, compared to errors exceeding 20–30% in the conventional non-calibrated model. Under real operational conditions, the system delivered a measured CO₂ emission reduction of 4.17% between the baseline and demonstration periods, alongside a 66.93% reduction in renovation audit time and measurable improvements in occupant comfort compliance and preventive maintenance.

The railway station case study extends the applicability of the methodology to complex transport infrastructures. The preliminary analysis, based on the comparison between calibrated and reference models, estimates a CO₂ reduction potential of up to 30.39% in the office building subsystem of the railway station and approximately 71% in the platform lighting system through occupancy-based intelligent control.

The contrast between these results reflects the dual analytical capability of the proposed framework. In the office building, a real impact is quantified under actual operational conditions, inevitably constrained by user behaviour and the inherent inertia of the building. In the railway station, the maximum improvement potential is estimated under optimal conditions, based on the gap between the calibrated and reference models. This duality is not a limitation but rather a

defining feature of the framework, which accommodates two complementary modes of evidence-based energy management: quantifying demonstrated impacts in assets already under intervention, and identifying decarbonisation potential in assets yet to undergo it.

Future work within the FA4-Rail4EARTH project, scheduled for completion in March 2027, will focus on the full deployment of the digital twin at the station and the execution of the baseline and demonstration periods to validate the impact under real operational conditions. Further research will address the incorporation of energy flexibility strategies and the extension of the methodology to other infrastructure typologies.

6 References

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