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Use of Advanced Digital Methodologies for the Analysis of Complex Systems: HBIM for the Development of Cognitive/Energy-Responsive Digital Twins

Eleonora VENDETTI[1], Francesco Livio ROSSINI[2]*, and Giuseppe PIRAS[1]

[1] Department of Electrical and Energy Engineering, Sapienza University of Rome, Italy
[2] Department of Planning, Design, and Technology of Architecture, Sapienza University of Rome, Italy

ABSTRACT

This study proposes an integrated framework for developing Cognitive Digital Twins (CDT) to transform heritage buildings into proactive nodes within smart grid infrastructures. By the integrated implementation of HBIM, IoT sensors, Machine Learning and Lean methodologies could be possible to balance energy efficiency with heritage building's preservation. To achieve this, the framework follows a three-phase pathway: foundational data acquisition through standardized HBIM protocols; semantic algorithm synthesis using Neural Networks and Federated Learning for predictive forecasting; and validation through pilot deployments. The scope of the paper is the analysis of the system's cognitive capacity like perception, reasoning, and learning, for enabling autonomous adaptation to environmental and occupancy variations of the reference parameters. This could enhance a deep Lean behaviour, where the CDT is the approach that established a clear communication among process actors, reducing wastes related to the lack of interoperability of data and information, and definitively is able to provide information to proactive maintenance phases. This approach aligns heritage conservation with the 2030 Agenda, positioning protected buildings as technologically advanced components of resilient, sustainable smart cities.

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Corresponding Author
Francesco Livio Rossini
francesco.rossini@uniroma1.it

Department of Planning, Design, and Technology of Architecture, Sapienza University of Rome, Italy

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KEYWORDS

Heritage BIM (HBIM), Facility Management (FM), Cognitive Buildings (CB), Cognitive Digital Twin (CDT).

Introduction

In recent years, also in light of the fragmented geopolitical context, the EU has implemented strategic measures within the broader European Green Deal framework aimed at renovating both public and private buildings, with particular focus on energy performance aspects (Lucchi & Agliata, 2023). Within the construction industry, one of the main actions to undertake for the energy-digital transition is the progressive introduction of Smart Grids and Smart Buildings as strategic digital applications essential for achieving community decarbonization targets (Asadi et al., 2025). The challenge is significantly amplified by the existing built stocks, where almost 75% of it remains energy inefficient, yet approximately 85% is projected to remain in use through 2050, as underscored by the Energy Performance of Buildings Directive (EPBD 2024/1275). This reality is further complicated by the prevalence of heritage and historic buildings, which require maintenance that balances energy retrofitting with preservation of architectural and artistic integrity to sustain functionality. Consequently, given that the International Energy Agency (IEA) identifies the integration of Artificial Intelligence (AI) systems in energy management as critical for developing increasingly intelligent, interconnected, reliable, and sustainable energy networks, the development of robust digital modeling frameworks becomes indispensable.

Therefore, a multidisciplinary approach is essential, leveraging established systems engineering practices in the construction sector to extend AI capabilities to this substantial portion of the building stock which simultaneously faces significant challenges in achieving compliance with energy efficiency regulations and performance standards (de Oliveira et al., 2026).

The proposed framework aims to develop a cloud-based digitalization framework regarding the investigation of Lean-based process optimization methodologies aimed at enhancing maintenance management and operational performance on existing buildings. The framework is grounded in a critical pathway that establishes a standardized HBIM specification, developed through methodologies for the development of a Heritage Digital Twin (HDT).

The integration of DT technologies with HBIM represents an emerging frontier in heritage asset management. Recent literature demonstrates diverse methodological approaches and application contexts, ranging from energy efficiency optimization to preventive conservation strategies.

HBIM translates historic heritage uniqueness into digital models via reverse engineering, serving as semantic and geometric foundation for DT. Semantic base refers to object-oriented parametric modeling where each object encodes its physical characteristics with strictly rules-defined relationships. The modeling process creates parametric virtual geometry based on standard libraries of architectural elements associated with alphanumeric information establishing a semantic modeling structure founded on object family ontologies, following actual construction logic and predefined digitization rules.

In this scenario, the DT acts as a digital asset to simulate non-invasive efficiency improvement scenarios. Through HBIM and the use of IoT sensors, it is possible to continuously monitor microclimate parameters and energy flows, enabling dynamic management that reduces waste without altering architectural characteristics through more invasive interventions.

According to Ni et al. (2021), a distributed cloud infrastructure optimizes the energy performance of historic structures through integrated IoT sensors and ML algorithms. The framework acquires heterogeneous environmental data streams such as interior climate conditions, metered energy flows, visitor flows and meteorological variables, synchronized within cloud systems. ML models generate energy consumption forecasts and autonomous optimization, balancing thermal efficiency, structural preservation, and occupant comfort. Once standard model parameters are defined, increasingly intelligent and proactive functionality tests can be conducted through the construction of computer ontologies and semantic networks, leading to the concrete implementation of a Cognitive Digital Twin (CDT). Lu et al. (2020) define the CDT as a DT «with augmented semantic capabilities for identifying the dynamics of virtual model evolution, promoting the understanding of interrelationships between virtual models and enhancing the decision-making based on DT»

Within the energy management domain, the CDT enables comprehensive heritage representation through BIM methodology, encompassing energy infrastructure design, including renewable generation systems, thermal storage solutions, and adaptive technologies for sustainable heritage preservation. Furthermore, ML models monitor, analyze, and optimize energy consumption patterns at both individual heritage unit and aggregate community levels, enabling predictive interventions that balance energy efficiency with heritage conservation objectives (Zheng et al., 2022).

Table 1. Heritage digital twin research: Key applications and outcomes.

References	Keywords	Goals	CDT advancement	Results
(Lucchi, 2023)	«DT; AI; BIM; HBIM; Cloud computing; Internet of things; Laser scanner; Metaverse»	Review DT Applications in Built Heritage	Non-operational; DT limited to predictive capabilities	Analysis of DT maturity levels and AI/ML integration for heritage building management
(Cecere et al., 2024)	«Internet of Things; HBIM; Predictive Maintenance»	Interoperability among data and software	Operational DT limited to monitoring and predictive maintenance	Real-time Building Environmental Monitoring System
(Zhang et al., 2023)	«Heritage building preservation; Multi-indicator IAQ; Adaptive HVAC control; DT; Energy efficiency»	Digital Twin HVAC Control for Heritage Building IAQ	Operational DT limited to predictive/ adaptive capabilities	CFD-Based Adaptive HVAC Control for Heritage Preservation
(Sugiyama et al., 2025)	«Heritage DT; Built heritage; DT; Classification; Methodology; Evaluation»	Formulate project indicators for Heritage DT addressing built heritage constraints	CDT outlined as future research direction	HDT platform developed for integrated heritage monitoring data visualization
(Guo et al., 2025)	«Architectural heritage; Preventive conservation; DT modeling; HBIM; LSTM»	Perform fast qualitative and quantitative analysis oriented towards conservation and management projects.	Operational DT limited to predictive capabilities	Develop predictive DT for heritage structural conservation

Methodology

The proposed framework concerns the development of an integrated system for the management and control of a smart grid infrastructure deployed within the historic built environment, where heritage buildings are stated as critical distributed nodes within the IA improved net.

The system architecture comprises two primary components: the building domain and the cloud infrastructure. In the building domain, sensing and actuation devices deployed across the perception tier collect building environmental data, occupancy information, and facility operation metrics. Edge computing nodes aggregate sensor readings and transmit them to cloud infrastructure, while simultaneously receiving control directives from cloud services. The data transmission layer enables bidirectional exchange between building and cloud systems. Within the cloud infrastructure, a data storage layer persists heterogeneous information streams using relational and non-relational databases, including stored DT models. An analytics processing layer applies ML methodologies and computational models to enable various optimization objectives.

The application layer delivers user interfaces for data visualization, predictive maintenance, and energy consumption analytics.

In this context, the DT constitutes a dynamic database integrating operational phase data and real-time condition assessment of building structures and systems, enabling decision-making frameworks that balance economic sustainability with heritage preservation and functional accessibility. This paradigm repositions the historic building as an efficient node within the smart grid infrastructure, simultaneously achieving cost reduction and emissions mitigation aligned with the EU's strategic direction, while safeguarding architectural integrity and operational functionality.

Concurrent with cyber-physical system integration, the framework systematically specifies distributed renewable energy (DRE) infrastructure, including photovoltaic (PV) generation systems, battery storage capacity, and integrated power electronics. An IoT-based power monitoring system integrates high-gain converter architectures, enabling real-time tracking of renewable generation, consumption, and grid exchange flows. Parametric specification of renewable energy systems within HBIM establishes the technical foundation for prosumer functionality, enabling historic buildings to transition from passive consumers to active distributed energy resources (DER) within the smart grid. Data collection methodology expands to capture renewable generation metrics, storage state-of-charge, and grid injection and consumption dynamics, supporting subsequent optimization algorithms.

A distinctive innovation of the proposed research resides in the system's cognitive capacity, understood as the ability to perceive, interpret, and adaptively respond to contextual conditions through ML mechanisms (Herrero & Dasari, 2025). Leveraging advanced statistical AI techniques, the framework enables real-time environmental perception and dynamic parameter optimization, accommodating the inherent functional versatility of heritage buildings.

The system is based on AI models trained through appropriate ML algorithms to monitor historic buildings, forecast energy consumption, and autonomously control energy-consuming equipment to achieve balanced integration of energy efficiency, building conservation, and occupant comfort. These algorithms operate on dedicated parametric object libraries, which constitute the foundational methodological pillar underpinning HBIM evolution (Salah et al., 2025). The synergistic integration of AI with the informational models of protected heritage buildings enables dual-scale intelligent building management: at the micro-scale, optimizing indoor environmental quality and occupant comfort within individual spaces; and at the macro-scale, facilitating comprehensive facility monitoring across the entire building complex.

Through iterative ML processes, the system autonomously detects granular energy demands, accounting for distinctive thermal characteristics of heritage construction and optimizing dynamic energy balancing. The AI framework continuously monitors indoor environmental conditions via streaming sensor data. It implements autonomous dynamic control of lighting and ventilation, regulating non-critical loads to mitigate peak consumption and stabilize demand profiles. Building-specific energy baselines inform photovoltaic sizing and storage capacity allocation. Multi-scale energy management integrating individual building storage with community-level resources enhances self-sufficiency and grid resilience.

The CDT integrates six foundational cognitive capabilities. Perception processes sensor data into actionable asset representations. Attention filters critical operational signals such as occupancy, energy demand, thermal dynamics, prioritizing efficiency objectives. Memory retains building lifecycle history and energy performance data, informing adaptive retrofit strategies. Reasoning synthesizes real-time conditions with heritage conservation constraints. Problem-solving optimizes energy balancing and spatial utilization. Learning transforms operational experience into refined HBIM models and maintenance protocols (Faruque et al., 2021). The system operates with predictive anticipation: when energy constraints, occupancy variations, or spatial uncertainties arise, it initiates proactive interventions to optimize building performance and operational resilience.

The system implementation framework is organized into three distinct operational phases:

Foundational Data Acquisition and Cyber-Physical Integration

The initial operational phase establishes the foundational digital and cyber-physical architecture through advanced HBIM methodology and parametric infrastructure specification. This phase encompasses the comprehensive modeling of the building asset through standardized HBIM protocols, integrated with systematic parametrization of energy infrastructure, including renewable generation systems, storage capacity, and load distribution networks and informatics architecture for real-time data management. Concurrent with this modeling effort, a systematic data collection methodology is established, defining what data to collect across primary categories such as: indoor environment, HVAC and lighting operation status, energy consumption metering building characteristics, outdoor weather conditions, and operational parameters such as energy prices and activity schedules, and how to acquire these data through sensors, BMS queries, weather stations, and facility documentation. An integrated informational model synthesizing geometric, semantic, and functional building data with cyber-physical system representations, enables seamless digital management of heterogeneous sensor data streams provided by Internet-of-Things (IoT). This structure establishes the foundation upon which subsequent automation and decision-support capabilities operate Multi-Agent (Zhang et al., 2022).

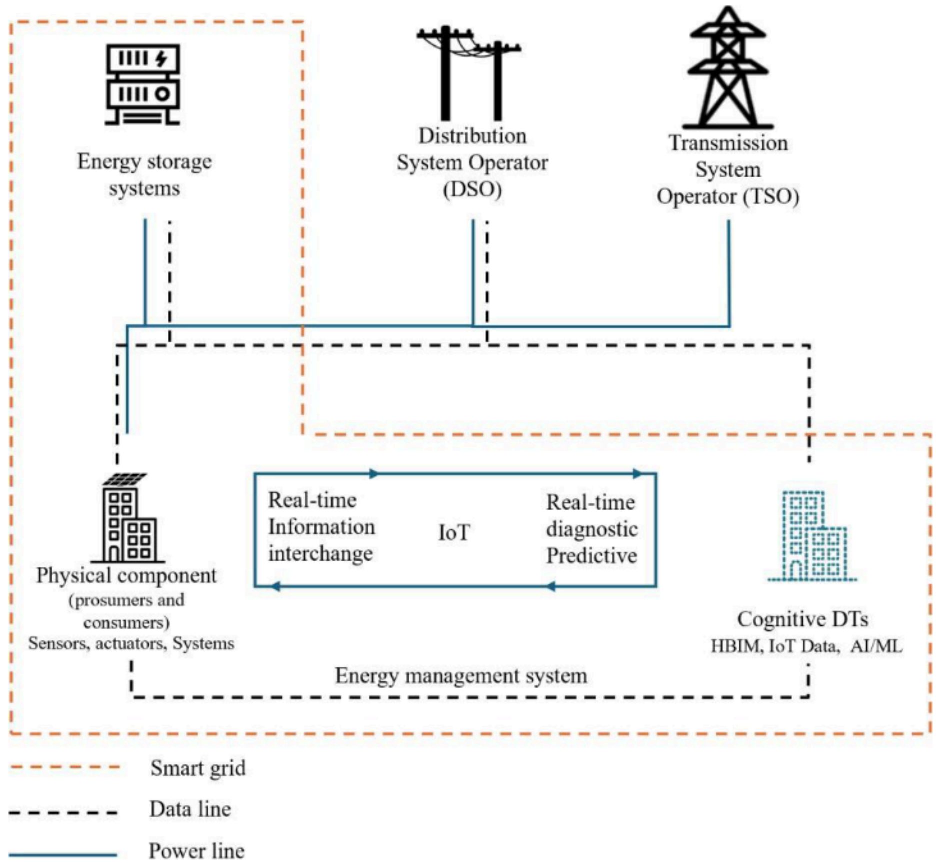

Figure 1. CDT framework for heritage building smart grid integration.

Data Analysis and Semantic Algorithm Synthesis

The second operational phase advances from static modeling to dynamic operational intelligence through continuous behavioural monitoring and semantic knowledge formalization. This phase systematically observes and analyzes building-occupancy patterns, energy consumption responses, and service-delivery dynamics across diverse functional scenarios, encompassing HVAC performance, lighting optimization, and electrical load management. Concurrently, the framework develops domain-specific HBIM object libraries and associated ontological constructs, creating semantically-enriched parametric components that formalize the relationships between heritage building characteristics, energy system behaviour, and occupancy-driven performance. This semantic network architecture, grounded in building-specific operational data, enables the deployment of intelligent automation algorithms by establishing explicit logical relationships and inference pathways that support autonomous decision-making.

To maximize AI effectiveness in energy management automation, this phase integrates advanced ML methodologies through the analysis data process, including Neural Networks and Support Vector Machines for predictive energy forecasting, complemented by Federated Learning and Q-learning techniques for demand-responsive scheduling and energy trading optimization. These algorithms operate on feature-engineered datasets derived from multi-source data mining and big data analytics, enhancing pattern recognition and predictive accuracy. The semantic ontologies developed in this phase serve as the computational substrate enabling hybrid and multi-stage algorithmic models to synthesize real-time operational data with historical performance knowledge.

Results and Discussion

The findings of this study confirm the viability and strategic relevance of integrating Heritage BIM with Cognitive Digital Twin technologies as a coherent response to the dual challenge of energy transition and heritage conservation. A central outcome of the framework is the operationalization of the prosumer paradigm within heritage contexts. By parametrically specifying distributed renewable energy resources, including photovoltaic generation, battery storage, and power electronics, directly within the HBIM model, the system enables quantitative assessment of energy self-sufficiency and grid contribution capacity without requiring invasive physical surveys. The cognitive layer introduced by the six-capability CDT architecture, perception, attention, memory, reasoning, problem-solving, and learning, constitutes a qualitative advancement beyond conventional building energy management systems. Unlike rule-based automation, the ML-driven cognitive engine autonomously adapts to occupancy variations, climatic shifts, and heritage-specific thermal behaviour through iterative reinforcement learning and federated model aggregation. The semantic HBIM ontology developed in the second phase represents an additional methodological contribution. By establishing explicit logical relationships between heritage building characteristics, energy system behaviour, and occupancy-driven performance, the ontological framework provides a computable semantic substrate that supports automated inference and interoperability across heterogeneous data streams. Notwithstanding these contributions, several limitations must be acknowledged. The framework presented is primarily theoretical and methodological; empirical validation across diverse heritage typologies, climatic zones, and regulatory contexts remains to be conducted. The performance metrics projected for photovoltaic sizing, storage dimensioning, and demand reduction are conditional on the quality and completeness of sensor data streams, which in heritage buildings can be subject to installation constraints and electromagnetic interference. Furthermore, the assumption of continuous ML model refinement implies sustained data governance and system maintenance capacities that may not be universally available in heritage facility management organizations. Future work should therefore address the development of robust data quality protocols, lightweight edge inference architectures suitable for heritage deployment, and regulatory interface guidelines reconciling IoT installation requirements with conservation authority mandates.

Conclusion

This study has presented an integrated methodological framework for the development of Cognitive Digital Twins applied to heritage buildings, with the objective of enabling their transition from passive energy consumers to active prosumers within smart grid infrastructures. The principal theoretical contribution of the research lies in the formalization of cognitive capacity as an operational design criterion for heritage digital twins. This position of cognition not merely as an energy management objective but as a new typological category within the smart city taxonomy, characterized by the capacity for continuous self-optimization without compromise to architectural integrity. The Lean-informed process architecture reduces informational waste across stakeholder interfaces, improving coordination between conservation authorities, energy planners, and building operators. These capabilities directly support compliance with the EPBD.

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