BEM-based multidisciplinary design supported by artificial intelligence for the creation of cognitive and sustainable smart hospitals

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Abstract. Healthcare facilities are characterized by a high level of construction and management complexity. Digital transformation and the green transition (Twin Transition) require integrated, multidisciplinary design based on BIM (Building Information Modeling) and BEM (Building Energy Modeling). This study proposes a conceptual framework in which engineering design is integrated with the architecture of spaces and environments, focusing on the comfort of patients and healthcare staff. The study considers design from a holistic perspective that prioritizes efficiency, sustainability, and the humanization of care processes through multidisciplinary, systemic design based on BIM/BEM. This proactively integrates multiple design and management aspects: from the BMS (Building Management System) for monitoring all structural, performance, and environmental parameters, to continuous interaction with the hospital lifecycle through the use of AI (Artificial Intelligence) to optimize resource use in relation to the external environment, according to a One Health approach. The conceptual framework integrates engineering and architectural disciplines with ICT (information and communication technologies), AI, and VRA (virtual augmented reality), addressing the psychological, cognitive, social, and risk management aspects that influence the comfort, ergonomics, and functional adaptation of the structure to hospital users and the external environment.

1 Introduction

The Twin Transition, the simultaneous convergence of digital transformation and green transition [1], is the main driver of a radical shift in the design of modern healthcare facilities. This dual transition requires abandoning the vi-sion of hospitals as static, energy-intensive structures and moving toward seeing them as dynamic, intelligent ecosystems that actively participate in the clinical care process. The Twin Transition's impact on modern healthcare design is profound and encom-passes multiple technological, economic, and social aspects [2].

Traditional logic is being inverted: instead of patients and staff adapting to the rigid constraints of a building, the building-facility system now dynamically adapts to the specific needs of its occupants through IoT sensors and artificial intelligence. De-sign is becoming multidisciplinary and holistic: an integrated approach that combines architecture and

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engineering with ICT, artificial intelligence, and psychology is needed to manage the complexity of healthcare environments [3]. Healthcare design must be undertaken from a "One Health" perspective, recognizing that human health is inextricably linked to the health of the environment and the surrounding urban ecosystem. To achieve this target, designers must utilize BIM, BEM, and Digital Twin methodologies.

The creation of Digital Twins enables real-time monitoring, scenario simulation, and predictive maintenance, ensuring the building becomes "future-proof". This significantly improves the building's environmental performance and achieves zero emissions, as required by the Energy Performance of Buildings Directive (EPBD). Design therefore moves from simply reducing consumption to achieving zero emissions throughout the facility's entire lifecycle.

Bioclimatic and human-centered architecture is crucial in this context: modern projects prioritize bioclimatic principles, using natural elements such as sunlight, air, and greenery as functional "building materials" that promote patient recovery and staff well-being, while maximizing energy efficiency. In this context, energy resilience through microgrids makes a significant contribution: to ensure complete electrical resilience, modern hospitals integrate intelligent microgrids that manage various energy sources, including photovoltaic systems, trigeneration systems, and high-efficiency heat pumps, managed by artificial intelligence to maximize energy efficiency.

Another important aspect is the native integration of telemedicine into all phases of building design or renovation [4]. Indeed, design must now con-sider the elimination of the hospital-territory dualism by providing the telecommunications infrastructure and resilient networks needed to support a continuous and connect-ed care system. with strong functional integration of hospital and territorial structures to optimize the patient's diagnostic and therapeutic care process.

This study proposes a multidisciplinary design model aimed at creating smart, sustainable, and cognitive hospitals. The approach integrates advanced methodologies such as BIM and BEM with artificial intelligence to harmonize the architecture, engineering, and management of healthcare infrastructure [5].

The primary objective is to improve the comfort of patients and staff, adopting a holistic approach that takes into account human well-being and environmental protection, in accordance with the One Health philosophy.

Through the use of digital technologies and data analytics, the system optimizes decision-making processes and asset governance throughout the facility's entire lifecycle [6]. Finally, the proposal establishes a conceptual framework in which technology and social sciences collaborate to ensure the functional and safe adaptation of the building for its users.

2 Redefining innovative healthcare infrastructure

Modernizing healthcare infrastructure is no longer a matter of choice, but a strategic imperative. A series of converging environmental requirements combined with a pervasive digital revolution have rendered infrastructure technologically obsolete, posing significant risks [7].

The construction and management sector is at a turning point, and a new vision is needed to move beyond traditional, static models and forge resilient, efficient, and human-centered healthcare environments capable of meeting the many and complex needs of today's healthcare system [8].

This dual transformation is driven by a series of interconnected challenges that re-define the very purpose and performance of our built environment. In particular, with regard to the ecological transition, the regulatory landscape, following the new EPBD, requires a fundamental shift from a narrow focus on the concept of "Zero Energy" to a global responsibility for "Zero Emissions". This requires a holistic approach that con-siders a building's entire life cycle, a concept known as Whole Life Carbon (WLC).

This urgency is particularly acute in the healthcare sector, which, according to re-cent analyses, is responsible for as much as 10% of global CO2 emissions. Therefore, the design of healthcare buildings must consider not only energy management and consumption in operational processes but also the carbon embodied in materials, construction, and end-of-life processes. Furthermore, thanks to Digital Transformation, technologies such as BIM [9-10], Digital Twin, and AI are no longer isolated tools, but rather fundamental elements of a new operational design paradigm.

They are the enablers of efficiency, resilience, and sustainability, enabling us to manage complexity, predict outcomes, and optimize performance in ways previously unimaginable.

This new holistic design model facilitates managing the unique complexity of healthcare. Within the broader context of the built environment, healthcare facilities represent the most complex challenge due to their high levels of construction and management complexity, critical and often unsustainable energy consumption, and their direct and profound impact on patient well-being and clinical outcomes.

Digital transformation is therefore not a standalone trend, but the essential enabling factor for managing the data-intensive demands of new green mandates, especially within the unique complexity of the healthcare environment.

In response to these factors, this study addresses the concept of the "Cognitive Healthcare Building" as an intelligent and responsive ecosystem that operates accord-ing to an inverted logic: rather than allowing occupants to adapt to a static structure, the structure dynamically adapts to the needs of its patients and staff, proactively optimizing resources, improving comfort and safety, and actively contributing to improved healthcare outcomes, transforming the physical building into an integral component of the care delivery system.

Achieving this vision requires a radical shift in how we think, design, and manage the digital foundations of these critical infrastructures (Fig.1).

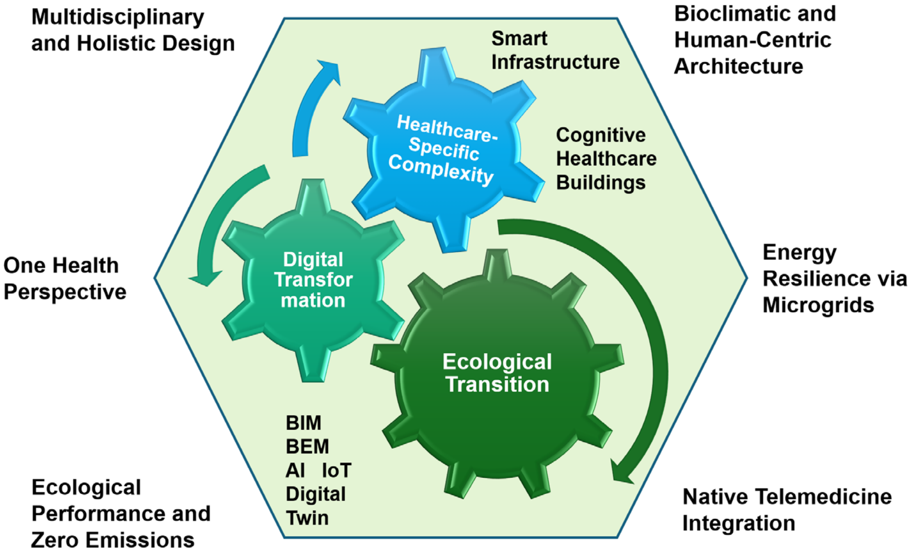

Fig. 1. Conceptual model for redefining innovative healthcare infrastructure.

3 The paradigm shift: from static projects to dynamic data ecosystems

The strategic creation of an intelligent building can only be built on a solid digital foundation by creating a shared, coherent, and dynamic data platform that marks a clear departure from the fragmented methods that have characterized the construction industry for decades. This paradigm shift represents a fundamental shift from static documentation to dynamic operational intelligence—from static drawings (CAD) to shared data platforms (BIM). Traditional 2D computer-aided design (CAD) is characterized by static geometric representations, resulting in information fragmentation and poor collaboration between disciplines. This approach often leads to data loss as a project progresses from one phase to the next. In contrast, BIM is not simply a 3D model [11]; it is a comprehensive data management and sharing platform. It integrates detailed information for every single component, from structural beams to HVAC (Heating, Ventilation, and Air Conditioning) units, into a single, coherent information model. This model accompanies the structure throughout its entire lifecycle, ensuring data consistency from initial design to long-term operational management and enabling real-time collaboration between all stakeholders. The rich, structured data contained in a BIM enables the next logical step: the creation of a BEM. The BEM is the energy specialization of BIM, a dynamic simulation tool that allows stakeholders to predict and optimize a building's energy performance before a single brick is laid. By integrating detailed energy data, such as insulation types, glazing characteristics, HVAC system specifications, and local climate data, the BEM can run sophisticated simulations to compare different design scenarios. This process facilitates the identification of the optimal solution for energy efficiency and occupant comfort, integrating performance directly into the design process from the earliest stages.

The Digital Twin represents the definitive evolution of this paradigm, moving from a static or simulated model to a dynamic and real one. It is a real-time virtual replica of the physical building, constantly fed with data from a dense network of IoT sensors. This concept shifts the operational paradigm from "atom to bit". Simulating scenarios, testing optimizations, and predicting maintenance needs on the virtual model before applying them to the physical asset becomes much more efficient and effective. This transforms the building from a fixed asset to a dynamic, data-rich platform, enabling continuous performance improvement and maximizing its value throughout its lifecycle.

With this dynamic data ecosystem as a foundation, the holistic design of a cognitive hospital can determine the specific technological components that constitute the “intelligence” of the cognitive hospital.

4 Anatomy of the cognitive hospital: an integrated technological framework

The intelligence of a cognitive hospital does not come from a single technology, but from the synergy of interconnected systems that function together like a biological organism. This complex "anatomy" can be broken down into its main components: a proactive nervous system for control, a digital brain for learning and optimization, and an intelligent energy ecosystem for sustainability and resilience. The nervous system, a proactive building management system (ABMS), is the foundation of the building's proactive management. A traditional BMS is fundamentally reactive. It operates on fixed, pre-set thresholds, executing simple commands such as "If the temperature exceeds 25°C, turn on the air conditioning." This approach is inefficient and unable to adapt to dynamic conditions. An Advanced Building Management System (ABMS), on the other hand, serves as a proactive governance platform. It manages all building subsystems, including lighting, security, plumbing, and the energy grid, under a single, intelligent control layer. Thanks to integrated Artificial Intelligence, the ABMS doesn't simply react to existing conditions, but predicts future needs, learns from occupant usage patterns, and constantly self-optimizes to maintain optimal environmental conditions at the lowest possible energy costs. It is therefore necessary to leverage artificial intelligence for predictive operations and improved care through the "Digital Brain", the intelligence engine of the Advanced BMS, based on the synergy of three key technologies: Digital Twin, Artificial Intelligence, and Knowledge Management System (KMS). As a central data hub, the Digital Twin is the dynamic 3D model continuously fed by IoT sensors and serves as a single source of data for monitoring, analyzing, and simulating every aspect of the facility's operation. The computational engine, on the other hand, is AI and deep learning. After an initial learning phase, the AI analyzes the immense flow of data from the Digital Twin to predict system failures (enabling predictive maintenance), optimize energy consumption, and adapt environmental conditions in real time to meet occupant needs. The dominant feature of the conceptual model is the KMS. The ABMS learns from operational experience over time, supporting the decision-making process by providing strategic insights to facility managers. Interaction with users occurs through conversational avatars (digital humans), which provide a channel for continuous, non-intrusive feedback, further refining the system's learning (Fig.2).

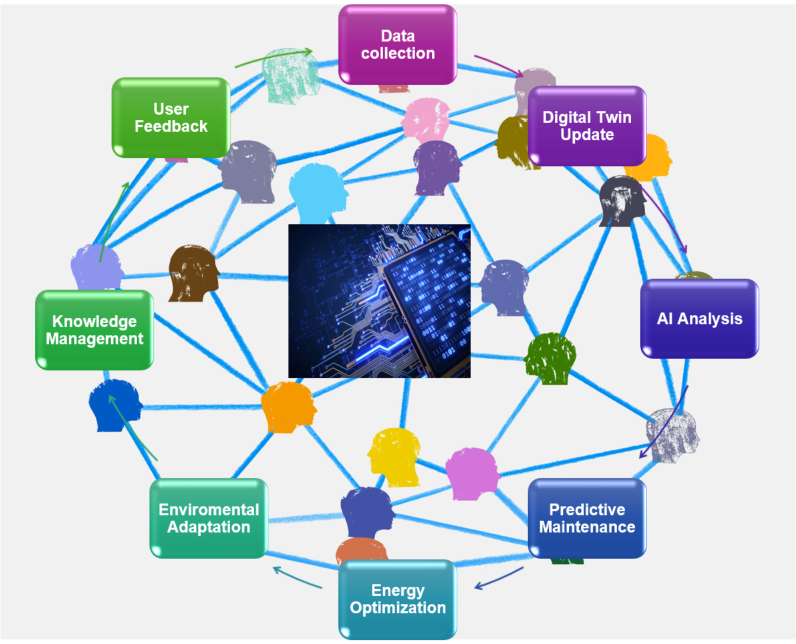

Fig. 2. The new organizational model of cognitive healthcare infrastructure.

This marks the transition from the hospital as a passive, one-way consumer of electricity from the grid to a smart, flexible energy prosumer. The cognitive hospital completely transforms this role, becoming a smart, flexible microgrid. It evolves into a local, intelligent energy ecosystem capable of optimally producing, storing, and managing energy. The key components of this microgrid, enabling sustainability and resilience, include trigeneration and photovoltaics, as well as cold banks (thermal energy storage to cool refrigerant during off-peak hours, for use during peak periods), next-generation photovoltaics, heat pumps, and electric vehicle charging, integrated into the grid management system. These include backup units, i.e., resilient power sources, to ensure operational continuity. Thanks to artificial intelligence, the ABMS selects the most appropriate energy sources in real time based on production costs and load demands, constantly pursuing the goal of maximum efficiency and cost-effectiveness. This integrated system is not simply a technical marvel; It is a strategic resource designed to generate tangible value in critical business and social dimensions (Fig.3).

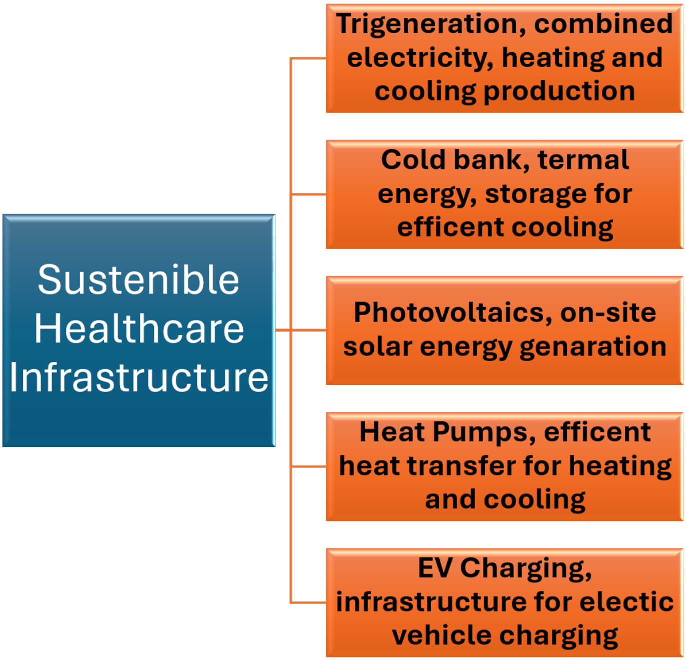

Fig. 3. The components of sustainable health infrastructure.

5 Generating tangible value: an ESG-based benefit analisys

Adopting the cognitive model does not represent a technological cost, but a strategic investment that generates measurable value across all Environmental, Social, and Governance (ESG) dimensions. This framework allows for a clear articulated return on investment, going beyond simple cost savings, aligning infrastructure development with broader corporate and social objectives. Specifically, the pro-posed conceptual framework bases its approach on ESG impact areas to achieve concrete results in Environmental (E), Social (S), and Governance (G) terms. Specifically, it aims to achieve energy independence and zero emissions through a drastic reduction in primary energy demand and associated emissions, in line with the EPBD and WLC objectives; optimized management of the smart microgrid, transforming the building from a passive energy consumer into an active "prosumer"; and continuous monitoring and reporting of key sustainability indicators, such as Smart Readiness Indicator (SRI).

To improve the patient experience and the well-being of staff and operators, the framework proposes tangible improvements in the comfort, safety, and overall experience of all building occupants, including patients, staff, and visitors; the creation of healthier and more efficient work and care environments thanks to superior air quality using air handling units (AHUs) with double-coil recovery to prevent cross-contamination, proactive prevention of health risks through continuous circulation anti-legionella systems, and increased environmental safety, such as shielding from electromagnetic fields and meaningful integration with the surrounding urban fabric in a "One Health" perspective, which recognizes the interconnection between human, ani-mal, and environmental health. In terms of governance, the framework aims to promote operational efficiency and cost reduction through there Optimized management of all assets, resulting in significant operational savings and the transformation of a major cost center into a highly efficient asset; and the fundamental shift from failure-based reactive maintenance to data-driven predictive maintenance, which significantly improves sys-tem uptime and increases operational resilience through "resilience by design," using architectures such as ring-type electrical distribution that allow sections to be isolated during a failure without disrupting the operation of the entire facility.

These concepts must then leverage the ABMS's Knowledge Management System to directly support strategic decision-making processes through actionable, data-driven information (BIM, BEM, IoT, and Digital Twin). Based on these assumptions, the framework considers understanding the value of holistic design as a fundamental first step (Fig.4); the next step is to outline a pragmatic path for implementing the innovative design model.

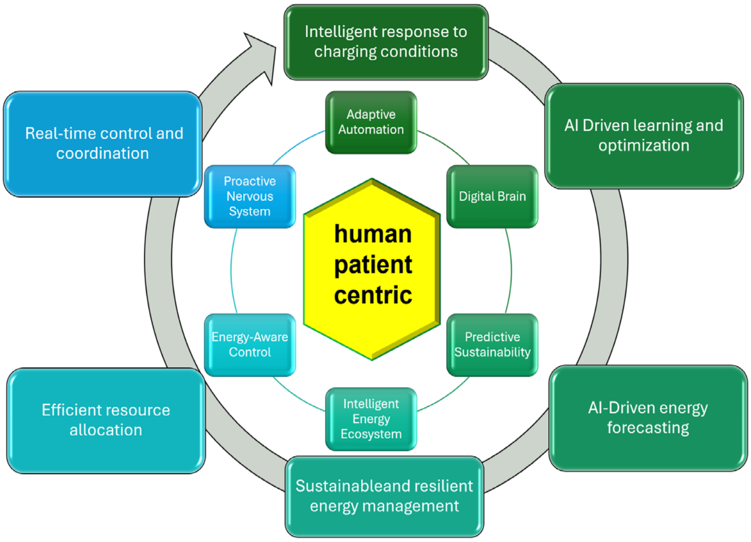

Fig. 4. The cognitive hospital systems framework.

The integration of BIM, BEM, and AI optimizes sustainable hospital design, transforming healthcare facilities into "Cognitive Buildings" that proactively manage energy, resources, and patient well-being. This multidisciplinary approach is essential for modern hospitals, which consume 2 to 5 times more energy than standard commercial buildings and are responsible for approximately 4% of global CO2 emissions.

The primary role of BIM and BEM is to provide a comprehensive digital database for the entire building lifecycle.

BEM serves as BIM's "energy specialization," allowing designers to run dynamic simulations that predict the hospital's actual behavior before construction begins. Linking these methodologies allows for the calculation of Energy Use Intensity (EUI) and the comparison of different HVAC systems and materials, reducing design time by approximately 7%. Furthermore, the synergy between BIM and BEM shifts the focus from "Zero Energy" to "Zero Emissions," taking into account both operational and embodied carbon throughout the building's life cycle.

Artificial intelligence acts as a "digital brain," shifting hospital management from reactive control to proactive governance, and generates ABMS: unlike traditional systems that react to current conditions, AI-integrated platforms can predict needs and learn user patterns to maintain optimal conditions at the lowest energy costs. Through generative artificial intelligence (GenAI), new generative models can automate the creation of building energy models from natural language descriptions and propose new configurations for multi-objective optimization (for example, balancing energy savings with maximum thermal comfort). AI also contributes to predictive maintenance: AI analyzes data from digital twins - virtual replicas connected via IoT " digital threads " - to anticipate equipment failures before they occur, significantly reducing operating costs and risks.

In the context of the "Smart Hospital" these technologies deliver measurable improvements in sustainability and performance through energy savings, resource optimization, and environmental and economic sustainability [12]. The combination of a holistic, integrated approach and AI-based building energy management systems (BEMS) can lead to energy savings of up to 50%. AI supports decision-making by simulating workflows and patient flows, helping managers allocate resources and investments more effectively, while also improving the patient experience. Furthermore, while initial investments may be higher, efficient, user-centric hospital projects can generate significant annual savings, increased value and quality of clinical services, and a more humanized care process thanks to improved environmental comfort and enhanced organizational well-being.

6 A phased implementation roadmap for transformation

A practical four-phase roadmap is proposed for transforming existing or planned healthcare infrastructure into a cognitive asset. This structured approach reduces the risks of the transformation process, enabling incremental value generation and ensuring that each phase builds logically on the previous one.

Phase 1: Digital Substrate Design (BIM); the first and most critical step is the creation or consolidation of a complete BIM model for the facility. This model serves as a single source of truth, integrating all architectural, structural, and system data. It represents the essential digital foundation upon which all subsequent phases are based, ensuring data integrity and consistency throughout the project lifecycle.

Phase 2: Low-risk design through simulation (BEM); once BIM model is implemented, the next phase is to use this data to create a BEM model. The goal is to run dynamic simulations to analyze and refine the design. This allows for optimization of energy performance, thermal comfort, and various operating scenarios, ensuring the design is optimized for maximum efficiency and resilience before any construction or physical implementation begins.

Phase 3: Creation of the sentient infrastructure (IoT and ABMS); This phase marks the transition from the digital to the physical world. The building is equipped with a dense network of IoT sensors and the ABMS is implemented. This phase creates the building's "nervous system," enabling real-time monitoring of all environmental and operational parameters and providing the capability for proactive and intelligent control.

Phase 4: Unleash cognitive operations (digital twin and artificial intelligence); in the final phase, real-time data streaming from the IoT network is integrated with BIM to activate the live digital twin. In this phase, artificial intelligence and machine learning algorithms are implemented. The system begins its continuous optimization cycle, enables predictive maintenance, and begins generating strategic insights for management via the KMS, fully leveraging the hospital's cognitive capabilities.
This structured roadmap, using the proposed framework, transforms a complex technology review into a manageable, value-driven journey (Fig.5).

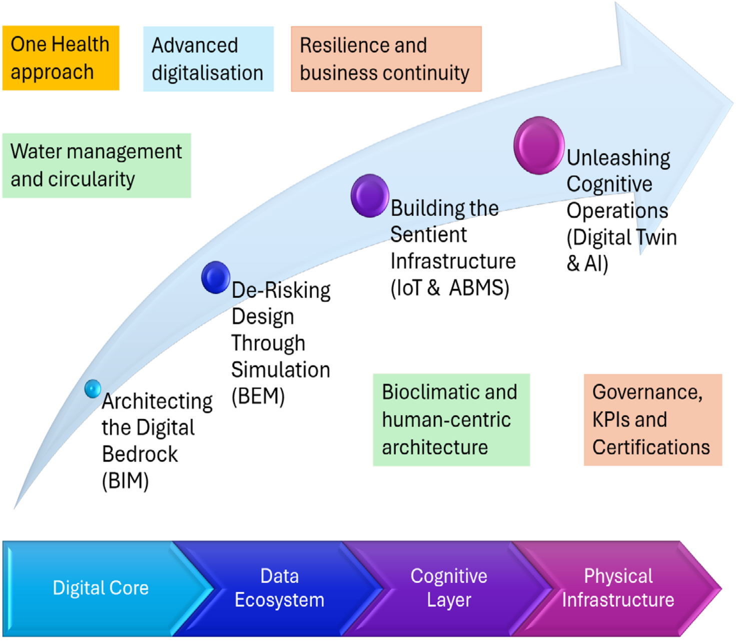

Fig. 5. The sustainable, cognitive and intelligent hospital conceptual framework and roadmap.

The conceptual framework consistently addresses digital transformation and ecological transition through BEM integration; reactive BMS control; proactive advanced BMS governance (ABMS), as well as the use of innovative materials such as nanowire photovoltaic solar cells [13-14], which guarantee higher yields than current ones with a significant impact on energy optimization and environmental sustainability.
The BEM serves as the technical basis for achieving these goals, integrating data related to insulation, glazing, and HVAC specifications into the design process. This allows designers to simulate the building's real-world behavior and optimize energy efficiency without compromising mandatory comfort parameters.
Model-based predictive control (MPC) plays a key role in BEMS as a sophisticated tool for anticipating future conditions and subsequently optimizing building operations.
Unlike traditional rule-based control (RBC) systems that react to current data, MPC algorithms are designed to proactively predict and adjust energy needs. Research highlighted in the sources indicates that implementing MPC can lead to significant reductions in energy consumption, ranging from 15% to 50%, while also helping to mitigate greenhouse gas (GHG) emissions.
This technology is particularly important for buildings using building-integrated photovoltaics (BIPV) and other renewable sources, as it allows the system to manage the inherent uncertainty of fluctuating energy supply and demand. MPC is a key strategy for

driving the transition to zero and nearly zero-energy buildings (ZEB/nZEB) by maximizing the efficiency of on-site energy production.

Traditional BMSs are characterized by reactive control logic that operates based on fixed thresholds and preset commands. The system only operates after a condition has already occurred, for example, activating the air conditioning only when a sensor registers a temperature above a specific limit (e.g., >25°C). Operation often follows a "fix-after-failure" model, leading to unplanned interventions, high maintenance costs, and fragile operational continuity. In terms of power, a reactive building acts as a passive user of the electricity grid, absorbing energy unidirectionally without optimizing costs or production fluctuations.

An ABMS serves as a governance platform that orchestrates all building subsystems through the integration of AI. Rather than simply reacting, the ABMS predicts needs by learning from user behavior patterns and environmental data to maintain optimal conditions at the lowest energy costs. It is powered by the synergy of digital twins, which function as a dynamic simulation center, and KMS, which allow the building to learn from past experiences and provide strategic insights to managers. By analyzing data in real time via a "digital thread", the system can predict failures before they occur, enabling planned maintenance that maximizes asset life and reduces downtime.

Proactive governance transforms the building into an intelligent microgrid, capable of producing, storing, and selecting the most economical energy sources (such as solar or trigeneration) in real time based on load demands.

While reactive control focuses on maintaining basic functionality through fixed rules, proactive governance aims for multi-objective optimization, balancing occupant comfort, safety, and drastic reductions in primary energy demand and emissions. This shift enables the creation of "cognitive buildings" that dynamically adapt to users, rather than forcing them to adapt to the structure.

Conclusions

This study allows us to define the elements for a holistic BEM-based and AI-supported design that can be useful for building a future-proof healthcare asset.

The "Cognitive Building" model represents a significant step forward from viewing healthcare facilities as mere operating expenses. It reframes them as a new class of strategic assets: intelligent, sustainable, and fundamentally human-centered. This isn't just a technology investment; it's an investment that creates lasting value across the four pillars of a new generation of healthcare infrastructure:

performance-based asset cost savings: dramatically reduce operating costs throughout the lifecycle by moving from a reactive to a predictive and optimized maintenance model;

regulatory-compliant sustainable assets: ensuring compliance with the most stringent ESG and “Zero Emission” regulatory criteria, positioning the structure to meet current mandates and adapt to future environmental needs;

human-centered healing environments: creating environments that are not only functional, but actively enhance the well-being of patients and staff, recognizing that physical space is an integral part of the healing process;

resilient and future-proof platforms: provide inherently flexible structures, ready to integrate new technologies and capable of adapting with agility to changing healthcare needs.

To translate this strategic vision into an actionable plan, the next logical step is to launch a feasibility study to contextualize this framework to specific organizational needs. This represents the first decisive step toward transforming the organization's real estate portfolio from a cost center to a strategic asset capable of generating value.

List of acronyms

- ABMS: Advanced Buildings Management System
- AHU: Air Handling Unit
- AI: Artificial Intelligence
- AVR: Augmented Virtual Reality
- BEM: Building Energy Modeling
- BEMS: Building Energy Management System
- BIM: Building Information Modeling
- BMS: Building Management System
- BIPV: Building-Integrated PhotoVoltaics
- CAD: Computer Aided Design
- EPBD: Energy Performance and Buildings Directive
- ESG: Environmental, Social, and Governance
- EUI: Energy Use Intensity
- GenAI: Generative Artificial Intelligence
- GHG: Green-House Gas
- HVAC: Heating, Ventilation, and Air Conditioning
- ICT: Information and Communications Technology
- IoT: Internet of Things
- KMS: Knowledge Management System
- MPC: Model-based Predictive Control
- SRI: Smart Readiness Indicator
- WLC: Whole Life Carbon
- ZEB/nZEB: Zero Energy Building/nearly Zero Energy Buildings

Nomenclature section

AHU is an essential component of HVAC systems, used to condition and circulate air in commercial, industrial, and residential buildings. It regulates temperature, humidity, filtration, and ventilation, ensuring healthy and comfortable indoor air quality.

BEM is a physics-based, computer-generated simulation of a building's energy use, analyzing geometry, construction materials, lighting, HVAC, and operational schedules to optimize energy efficiency and performance.

BEMS are advanced, computer-based platforms that monitor, control, and optimize a building's energy consumption, primarily focusing on HVAC, lighting, and, and environmental systems to improve efficiency. They collect real-time data from sensors and meters to reduce operational costs, boost sustainability, and ensure occupant comfort through automated, intelligent, and predictive adjustments.

BIM, ISO 19650:2019 defines BIM as the: 'Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions.'

EUI is a key metric measuring a building's annual energy consumption relative to its size, calculated as total energy (kBtu) divided by gross floor area (sq ft). A lower EUI indicates better energy efficiency. It is essential for benchmarking, compliance, and tracking sustainability performance.

GHG, the standard covers the accounting and reporting of seven greenhouse gases covered by the Kyoto Protocol – carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3); they are measured by converting them into CO2 equivalent (CO2e).

HVAC refers to the integrated technology and systems used to regulate indoor environmental conditions, providing thermal comfort (heating/cooling), moisture control (humidity), and improved air quality (filtration/fresh air exchange) in residential, commercial, and industrial buildings.

SRI is a common rating system introduced by the European Union to measure the ability of buildings to integrate and use smart technologies. Introduced by EPBD, the SRI evaluates not only insulation or generator efficiency, but also how well a building can dynamically adapt its operation to its occupants and the energy grid. The evaluation is based on a matrix that combines 9 technical domains and 7 impact criteria, the final score is expressed as a percentage (0-100%), indicating how close the building is to the maximum theoretical "smart readiness."

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