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EDITORIAL

Towards energy efficient buildings by digital transformation of the building lifecycle

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Introduction

The global shift toward sustainability and the urgent need to reduce carbon emissions have placed the building sector at the forefront of climate action efforts. With buildings accounting for approximately 40% of global energy consumption (Jean-Pascal Tricoire, 2024) and a substantial share of greenhouse gas emissions (Ian Hamilton et al. 2024), this sector plays a critical role in determining whether we can meet international climate goals. As rapid urbanization continues to accelerate, the demand for energy-efficient buildings is becoming increasingly urgent (Renilde Becqué et al. 2024; Ma et al. 2021)—not only from an environmental perspective but also from an economic and social standpoint.

Energy-efficient buildings are designed to reduce the amount of energy required for their construction, operation, and eventual decommissioning. These buildings employ a combination of sustainable construction materials, advanced design techniques, and state-of-the-art energy management systems to minimize energy consumption. To measure and certify the energy performance of buildings, several standards and certifications are widely used, including Leadership in Energy and Environmental Design (LEED) (https://www.usgbc.org/leed, 2024), Building Research Establishment Environmental Assessment Method (BREEAM) (Nicholas Dunbar, 2024), and Passive House standards (https://passivehouse-international.org, 2024). These frameworks set stringent criteria for energy efficiency, waste reduction, and sustainability, encouraging the adoption of practices that go beyond regulatory compliance and help create buildings with significantly lower environmental impacts.

Achieving energy efficiency in buildings extends beyond constructing new green structures or retrofitting existing ones with more efficient systems. It requires a fundamental rethinking of the entire building lifecycle, from design and construction to operation, renovation, and eventual decommissioning. The digital transformation of this lifecycle offers a comprehensive solution to these challenges. By utilizing digital technologies such as Building Information Modeling (BIM) (https://globalbim.org/info-collection/the-national-bim-standard-united-states, 2024), IoT (Internet of Things) sensors (Madsen et al. 2021), Digital Twins (Jørgensen et al. 2023), and AI-driven analytics (Himeur et al. 2023) at every stage, we can create energy-efficient buildings that exceed regulatory requirements and set new benchmarks for sustainability. This approach can help optimize both operational costs and occupant comfort while also reducing the long-term environmental impact.

Despite increasing awareness and advancements in digital technologies, the sector still faces significant barriers to achieving optimal energy efficiency (Ma et al. 2016). Buildings are often designed with a narrow focus on minimizing initial construction costs rather than prioritizing long-term energy performance and sustainability (Ghahramani et al. 2024) (Ma and Jørgensen 2018). This short-term focus leads to suboptimal decisions, particularly in areas such as material selection, building automation, and system integration. Moreover, operational inefficiencies—such as poorly maintained systems, lack of real-time energy monitoring, and suboptimal automation settings—worsen energy waste over buildings' lifetime, further contributing to the sector's environmental footprint.

This editorial explores how the digital transformation of the entire building lifecycle can address these challenges, focusing on how the integration of digital technologies creates energy-efficient buildings. In doing so, we will clarify the distinctions between digitization, digitalization, and digital transformation, and how each contributes to the optimization of energy use and sustainability in the building sector. Finally, we propose a research roadmap to overcome the technological, financial, and policy-related barriers to achieving widespread adoption.

Digitization: the foundation of data-driven decision making

At the core of modern energy-efficient building practices is digitization, the process of converting analog data into a digital format. In the early phases of the building lifecycle—Conceptualization, Planning, and Design—digitization plays a crucial role by transforming traditional, paper-based methods into digital formats, allowing for more precise and data-driven decision-making. For instance, Building Information Modeling (BIM) digitizes architectural blueprints, construction documents, and energy performance simulations, enabling stakeholders to explore multiple design scenarios without physically building prototypes.

BIM is a digital representation of a building's physical and functional characteristics. It provides a collaborative platform where architects, engineers, and stakeholders can work together to simulate energy performance, assess material choices, and predict how design decisions will impact the building's lifecycle. By providing a detailed, data-rich model of the building, BIM ensures that decisions made early in the design phase are based on detailed simulations, thereby minimizing energy consumption and environmental impact from the start.

This digitization of information ensures that all project data is stored in a central repository, accessible to all stakeholders involved in the building's lifecycle. It also serves as the foundation upon which more complex digital processes are built. BIM models allow architects and engineers to simulate energy performance, factoring in building orientation, material selection, and other variables that impact sustainability. These models guide decisions throughout subsequent lifecycle phases, ensuring that energy efficiency goals are embedded from the project's inception.

Digitization, while foundational, is only the beginning of the transformation required to meet energy efficiency and sustainability goals. Digitalization and digital transformation take this data and apply it in innovative ways to automate workflows, optimize operations, and continuously improve energy performance.

Digitalization: automating and enhancing building lifecycle processes

Digitalization involves the use of digital technologies to enhance and automate traditional workflows, improving efficiency and accuracy in each phase of the building lifecycle. Digitalization occurs once the data from digitization processes is actively used to optimize workflows, improve decision-making, and create better outcomes.

During the Construction phase, digitalization is brought to life through the use of Building Information Modeling (BIM) and digital project management systems. BIM plays a crucial role in guiding construction teams with precise, data-rich models that provide a detailed blueprint of the building's design, structural specifications, and material requirements (Marcellino et al. 2021). By leveraging BIM, project managers and contractors can coordinate complex tasks, ensuring that different building systems—such as mechanical, electrical, and plumbing—are installed with minimal conflict and optimized for energy efficiency. BIM also allows for real-time updates and adjustments during construction, ensuring that any changes in design or on-site conditions are immediately reflected across all project stakeholders. This collaborative platform improves communication and decision-making, reducing the likelihood of delays or cost overruns. By centralizing all relevant project data, BIM ensures that the construction phase adheres closely to the original design intent, thereby enhancing both the quality and sustainability of the final building.

In parallel with BIM, IoT (Internet of Things) sensors play a crucial role in optimizing the Construction phase by providing real-time monitoring of on-site conditions, particularly the status, usage, and operational efficiency of construction machinery and equipment (Silva dos Santos and Assayag 2022). These sensors deliver valuable data on asset conditions, machine health, and material usage, enabling project managers to proactively address potential issues such as equipment breakdowns or resource shortages. By tracking machine health and material consumption, IoT sensors ensure machinery operates efficiently, minimizing downtime and preventing delays. This real-time data streamlines procurement processes, optimizes resource allocation, and helps maintain equipment efficiency, ensuring the construction project remains on schedule. By reducing waste and preventing costly delays, IoT sensors significantly contribute to a more efficient and sustainable construction process.

In the Operation and Maintenance phase, digitalization includes IoT sensors that continuously monitor building performance in real time. These sensors track a wide range of variables, including temperature, humidity, occupancy, energy usage, air quality, and lighting levels (Madsen et al. 2021). This constant stream of data is fed into Building Management Systems (BMS), which act as centralized platforms for controlling and optimizing building systems. The BMS uses AI-powered analytics to process the data, identifying patterns and making dynamic adjustments to optimize energy consumption, maintain occupant comfort, and ensure efficient operation of heating, ventilation, air conditioning (HVAC), and lighting systems (Al-Ghaili et al. 2021).

AI-driven analytics refers to advanced algorithms that analyze vast amounts of data from IoT sensors to detect patterns, predict future energy demands, and automate building system adjustments (Yan et al. 2021). For instance, if a part of the building is unoccupied, the AI system will adjust the heating, cooling, and lighting systems to reduce energy consumption, ensuring the building operates at optimal efficiency at all times.

Digitalization is critical for improving energy efficiency and reducing operational costs by automating manual processes and creating real-time feedback loops that continuously optimize building performance. This, however, represents only a portion of the potential of digital technologies. To truly revolutionize the building sector, we need to look beyond digitalization to the concept of digital transformation.

Digital transformation: a holistic approach to energy-efficient buildings

Digital transformation refers to the complete rethinking and integration of digital tools across all phases of the building lifecycle. It goes beyond automating specific tasks (as digitalization does) and instead reimagines how the entire lifecycle—from design to decommissioning—can be integrated into a seamless digital ecosystem. The goal of digital transformation is to achieve continuous optimization, where data collected in one phase informs decisions in others, creating a feedback loop that enhances building performance across its entire lifecycle.

A powerful example of digital transformation is the use of Digital Twins. Digital Twins are dynamic, real-time digital replicas of physical buildings. They are continuously updated with data from IoT sensors during the operation phase, simulating how the building behaves under various conditions and providing an accurate representation of its current performance (Cespedes-Cubides and Jradi 2024). Digital Twins store data about the building's operation over time, including environmental conditions, equipment performance, and energy usage, allowing building managers to monitor performance in real-time and adjust accordingly. Digital Twins are created from the as-built BIM model, which accurately represents the final constructed state of the building (Nguyen and Adhikari 2023).

In the Construction phase, Digital Twins store data from IoT sensors on machinery usage, weather conditions, and overall site activity. This information helps project managers ensure that construction processes align with schedules and sustainability targets, creating a digital history of the construction process that informs later phases of the building lifecycle (Salem and Dragomir 2022).

In the Operation phase, Digital Twins provide predictive insights into future energy needs and potential areas for improvement by comparing real-time data with initial design expectations (Clausen et al. 2021). By analyzing patterns of building use and environmental changes, Digital Twins allow for predictive maintenance and proactive energy management, helping to ensure that energy performance remains optimized over time.

In the Renovation and Retrofit phase, digital transformation facilitates data-driven retrofitting strategies (Jradi et al. 2018). Performance data collected during the operation phase informs decisions on which systems need upgrading or replacement to further reduce energy consumption. For example, IoT data might reveal that an HVAC system is underperforming and in need of an upgrade, and this information directly feeds into the planning for future renovations.

Digital transformation connects each phase of the building lifecycle, ensuring that buildings evolve in response to real-time data, environmental changes, and user behavior. This level of integration sets the stage for truly energy-efficient buildings that not only meet sustainability targets but continuously improve to exceed them.

Research agenda

To unlock the full potential of digital transformation within the building sector, a well-defined research agenda is essential. This agenda must address the key barriers that limit the adoption and scalability of digital tools while simultaneously encouraging innovation across the building lifecycle. The following research challenges are presented in a sequence that reflects their interdependencies and the urgency of addressing them to enable a more strategic and scalable approach.

Challenge 1: Interoperability and Standardization Across the Building Lifecycle.

- Challenge: The current lack of standardized data exchange protocols between different digital tools like BIM, IoT, Digital Twins, and AI-driven analytics hinders collaboration across the building lifecycle.
- Research Objectives: Develop universal standards for data formats and communication protocols that enable seamless data integration across all lifecycle phases. This includes ensuring compatibility between older, legacy systems and new technologies, so that digitalization can scale effectively.
- Rationale: Interoperability is the foundational challenge for digital transformation because it enables seamless integration of various digital tools across the building lifecycle. Without standardized data exchange protocols, different systems (BIM, IoT, Digital Twins, AI-driven analytics) cannot work together effectively. Achieving interoperability is essential for facilitating collaboration and ensuring that data can be shared across all phases of the lifecycle, making it the highest priority.

Challenge 2. Data Security and Privacy.

- Challenge: The increasing use of IoT sensors and real-time data streams raises significant concerns about data security and privacy, especially in smart buildings that rely on interconnected systems.
- Research Objectives: Explore data encryption, privacy-preserving technologies, and cybersecurity measures to protect sensitive building data. Investigate compliance with regulations such as GDPR, while enabling real-time data analysis for optimized building performance.
- Rationale: Once interoperability is achieved, data security and privacy become critical for ensuring the safe and trusted use of digital tools and real-time data streams. As more data is collected from IoT sensors and shared across platforms, the risk of data breaches or misuse increases. Addressing security challenges at this stage ensures that stakeholders feel confident adopting these technologies. Therefore, solving security concerns directly follows interoperability to maintain stakeholder trust and ensure widespread use.

Challenge 3. Accelerating the Adoption of Digital Tools in the Building Industry.

- Challenge: Many building sector stakeholders are hesitant to adopt new digital tools due to concerns over costs, complexity, and a lack of technical expertise.
- Research Objectives: Investigate financial, regulatory, and cultural barriers to adoption. Develop scalable digital solutions with pilot projects, case studies, and collaboration between academia, industry, and policymakers to demonstrate the value of digitalization.
- Rationale: After addressing the technical prerequisites of interoperability and security, the next logical step is to focus on accelerating adoption. Adoption challenges, such as cost concerns and a lack of expertise, must be overcome to ensure that digital tools are used widely throughout the industry. Without widespread adoption, the benefits of digital transformation will remain limited to isolated projects. Prioritizing adoption here builds on the technical groundwork and ensures that digital tools are embraced industry wide.

Challenge 4. Digital Platforms for Collaboration and Decision-Making.

- Challenge: The complexity of the building lifecycle requires collaborative digital platforms that allow all stakeholders, from architects to facility managers, to make informed, real-time decisions.
- Research Objectives: Develop intuitive, user-friendly digital platforms that offer integrated data visualization, scenario analysis, and decision-making tools. Ensure that non-experts can engage with real-time data without requiring advanced technical skills.
- Rationale: User-centric digital platforms are necessary to facilitate collaboration among the various stakeholders in the building lifecycle. As adoption increases, it becomes crucial that these tools are intuitive and accessible to non-experts, enabling all stakeholders to make data-driven decisions. Platforms that offer real-time collaboration and decision-making capabilities enhance the effectiveness of digital tools and streamline workflows. This challenge builds on adoption and ensures that all users can engage effectively with digitalized processes.

Challenge 5. Real-Time Data for Predictive Maintenance and Energy Optimization.

- Challenge: Real-time data streams from IoT sensors offer opportunities for optimizing building operations, predicting maintenance needs, and improving energy efficiency, but techniques to fully leverage these streams are still underdeveloped.
- Research Objectives: Develop advanced AI and machine learning techniques to analyze real-time data from IoT sensors. Investigate how predictive analytics can dynamically adjust building systems (e.g., HVAC, lighting) to optimize energy efficiency and occupant comfort.
- Rationale: With user adoption and collaboration platforms in place, the next step is to leverage real-time data for predictive maintenance and energy optimization. IoT sensors provide vast amounts of data that, when analyzed through AI-driven systems, allow for dynamic adjustments to building operations, reducing energy con-

sumption and preventing system failures. This challenge builds on the earlier steps by utilizing the infrastructure (interoperability, security, and collaboration platforms) to achieve tangible operational improvements in energy efficiency and building performance.

Challenge 6. Lifecycle Digitalization Strategies for Retrofitting and Renovation.

- Challenge: Retrofitting existing buildings is essential for improving global energy efficiency, but the complexity and lack of real-time data on older buildings make it challenging to prioritize retrofit strategies.
- Research Objectives: Investigate data-driven approaches to retrofitting strategies, particularly around balancing cost-effectiveness and sustainability. Research how IoT sensors can be retrofitted into existing buildings to generate performance data that informs renovation decisions.
- Rationale: Once digital tools are widely adopted and operational efficiency is optimized for new buildings, attention can turn to retrofitting and renovating existing buildings. This is essential for improving the energy efficiency of older buildings, which represent most of the building stock. Applying digital tools to retrofits is inherently more complex than new builds, so addressing this challenge comes after foundational issues like data usage and collaboration have been resolved. By this stage, digital strategies can be applied effectively to modernize and optimize existing structures.

Challenge 7. Scalability of Digital Twin Technologies for Lifecycle Integration.

- Challenge: While Digital Twins hold significant potential for optimizing building performance, their implementation at scale remains costly and technically complex, especially for large or older buildings.
- Research Objectives: Develop scalable methodologies for creating Digital Twins that evolve throughout the building lifecycle. Investigate how to integrate real-time IoT sensor data with Digital Twins to enable dynamic simulations and scenario testing.
- Rationale: Digital Twins offer immense potential for enhancing building performance, but their scalability remains a challenge, particularly for large or older buildings. At this stage of the digital transformation, scalability is addressed because the technical foundation—interoperability, security, data utilization, and retrofitting—is in place. By resolving scalability, Digital Twins can be applied across a wide range of building types and phases, further enhancing lifecycle integration and performance optimization.

Challenge 8. End-to-End Sustainability Assessment and Optimization.

- Challenge: While digital tools like BIM, IoT, and Digital Twins can optimize specific lifecycle phases, there is a need for a comprehensive sustainability assessment framework that spans the entire building lifecycle.
- Research Objectives: Develop sustainability metrics that are consistently applied across all lifecycle phases to measure environmental impact. Investigate methods for

embedding sustainability goals into early design decisions and explore strategies to maintain sustainability throughout the building's lifecycle.

- Rationale: The final challenge focuses on developing a comprehensive sustainability assessment framework that spans the entire building lifecycle. Sustainability goals can only be fully embedded and optimized once the earlier challenges—interoperability, security, adoption, data utilization, retrofitting, and Digital Twin scalability—have been addressed. This final step ensures that all phases of the building lifecycle are aligned with sustainability targets, enabling continuous optimization and long-term energy efficiency.

Conclusion

The digital transformation of the building lifecycle—from digitization to digitalization and full-scale digital transformation—offers a comprehensive framework for addressing the energy efficiency challenges facing the building sector. Digitization lays the groundwork by converting traditional building plans and data into digital formats, providing a foundation for more automated processes. Digitalization takes this data and automates workflows, enabling real-time monitoring and optimization of building systems. Finally, digital transformation integrates all phases of the lifecycle into a seamless digital ecosystem, ensuring continuous feedback, real-time adjustments, and long-term energy-efficiency over the building's lifespan.

To realize the full potential of digital transformation, a well-defined and targeted research agenda is essential. This agenda must address key barriers—such as financial, technical, and regulatory challenges—and promote innovation across the building lifecycle. By focusing on critical areas like standardization, scalable Digital Twin technologies, predictive analytics, and data-driven retrofitting strategies, this editorial propose a research agenda that offers a clear, actionable plan for the building sector to move beyond current industry practice and become a driving force for energy efficiency and thereby sustainability in the building sector.

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This Editorial was written as a collaborative effort between the two authors. Both authors contributed equally to the development of the ideas, research, and writing of the manuscript. Both authors have read and approved the final manuscript.

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