Understanding Occupant-Centric and Operational Sustainability for Cost-Effectiveness in Tomorrow's Building Trends

FOLUSO ISRAEL TAWIO[1], ADELESE SOLOMON AKINSEYE[2]

[1,2]*Department of Building Technology, City University, Cambodia*

Abstract The building sector stands at a pivotal juncture, grappling with its significant contribution to global energy consumption and carbon emissions while facing escalating pressure to enhance economic viability. Traditional approaches to sustainable design have often prioritized technological efficiency and prescriptive standards, inadvertently creating a "performance gap" where projected savings fail to materialize in operation. This paper posits that the next frontier in sustainable construction lies in the synergistic integration of occupant-centric design principles and data-driven operational sustainability. Through a systematic literature review and conceptual analysis, this article explores the paradigm shift from static, building-centric models to dynamic, human-in-the-loop systems. We investigate how the convergence of the Internet of Things (IoT), Artificial Intelligence (AI), and Building Information Modeling (BIM) facilitates the creation of responsive building ecosystems that learn from and adapt to occupant behavior. The core argument is that by explicitly designing for occupant well-being, comfort, and agency, and by leveraging real-time data for continuous optimization, buildings can achieve a dual objective: superior environmental performance and significant, long-term cost-effectiveness. This paper delineates the key technological pillars—Digital Twins, Federated Learning for privacy-preserving analytics, and AI-driven predictive maintenance—that underpin this transition. It further presents a framework for evaluating the Total Cost of Ownership (TCO) that captures the hidden financial benefits of enhanced productivity, health, and asset resilience. The findings indicate that the occupant-centric and operational sustainability model is not merely an ethical imperative but a robust strategy for de-risking investments, unlocking new value streams, and ensuring the long-term economic and environmental viability of tomorrow's building stock.

Index Terms- Occupant-Centric Design, Operational Sustainability, Cost-Effectiveness, IoT, AI, Digital Twin, Building Performance Gap, Total Cost of Ownership, Healthy Buildings, Predictive Maintenance.

I. INTRODUCTION

The global built environment is a dominant contributor to energy use and greenhouse gas emissions, accounting for approximately 36% of final energy consumption and 39% of energy-related carbon dioxide emissions annually [1]. For decades, the response from the Architecture, Engineering, and Construction (AEC) industry has been a relentless pursuit of efficiency through technological innovation and stricter building codes. This has given rise to high-performance building standards, such as LEED and BREEAM, which have undoubtedly moved the needle towards a more sustainable future. However, a persistent and troubling phenomenon has undermined these efforts: the "performance gap." This term describes the significant discrepancy between the energy and environmental performance predicted during the design phase and the actual, measured performance during building operation [2].

The root causes of this gap are multifaceted, but a primary factor has been the industry's historical neglect of the building's most dynamic component: its occupants. Traditional engineering models often treat occupants as predictable, homogeneous loads,

leading to systems that are over-engineered, rigid, and incapable of adapting to the complex, stochastic nature of human behavior [3]. This results in environments that are either inefficient—heating, cooling, and lighting empty spaces—or uncomfortable, leading occupants to override systems, thereby negating designed efficiencies. The focus has been predominantly on "first-cost" economics and technological specs, overlooking the long-term operational costs and the human capital within.

Simultaneously, the definition of sustainability is evolving. It is no longer sufficient to merely reduce a building's energy footprint. True sustainability encompasses operational efficiency, economic resilience, and the health and well-being of occupants. The World Green Building Council underscores this by advocating for buildings that are not only efficient but also "healthy, comfortable, and productive" for the people inside them [4]. This holistic view reframes the occupant not as a problem to be managed, but as a central stakeholder and an active participant in the building's ecosystem.

This paper argues that the confluence of two powerful paradigms—Occupant-Centric Design (OCD) and Data-Driven Operational Sustainability—powered by advancements in AI and IoT, holds the key to bridging the performance gap and achieving unprecedented levels of cost-effectiveness. We contend that by designing buildings that are inherently responsive to human needs and by using data to optimize their performance in real-time, we can create a virtuous cycle where sustainability and financial returns are mutually reinforcing.

The structure of this paper is as follows: Section 2 provides a critical review of the limitations of traditional sustainable design. Section 3 delves into the theory and principles of occupant-centric design, establishing its importance for both well-being and operational efficiency. Section 4 explores the technological enablers—IoT, AI, and Digital Twins—that make this paradigm shift feasible. Section 5 synthesizes these concepts into a model of data-driven operational sustainability. Section 6 presents a detailed cost-benefit analysis, demonstrating the compelling financial case for this integrated approach. Section 7 discusses the challenges and ethical considerations, and Section 8 offers a conclusion and a vision for future building trends.

II. THE LIMITATIONS OF TRADITIONAL SUSTAINABLE DESIGN

For the past half-century, the journey towards sustainable buildings has been largely linear and technology-focused. The prevailing model can be characterized as a "Design-Bid-Build-Occupy" linear process, where sustainability features are locked in during the design and construction phases, with little capacity for adaptation thereafter. This approach, while successful in establishing a baseline, suffers from several critical limitations.

2.1 The Static Model of Occupancy

Conventional building energy modeling and HVAC design rely on standardized occupancy schedules and assumptions about plug loads, lighting use, and thermostat setpoints. For instance, ASHRAE Standard 90.1 provides typical schedules that assume a uniform density of people and a predictable pattern of presence [5]. In reality, occupancy is highly variable. A study by [6] demonstrated that actual occupancy in office buildings can deviate from standard assumptions by more than 30%, leading to significant overestimation or underestimation of cooling and heating loads. This static model forces systems to operate at full capacity for assumed peak loads that rarely occur, resulting in substantial energy waste. When occupants find the resulting environment uncomfortable, they resort to ad-hoc adaptations—using space heaters under their desks, propping open doors, or covering sensors—which further degrade system performance and energy efficiency.

2.2 The "One-Size-Fits-All" Environmental Delivery

Centralized HVAC and lighting systems are designed to deliver a homogeneous environment to large zones. This approach ignores the well-established fact that comfort is a subjective, personal experience influenced by physiological, psychological, and contextual factors [7]. The concept of the "PMV (Predicted Mean Vote)" model, while useful as a

guide, fails to account for individual preferences. By aiming for a single, averaged temperature and lighting level for an entire floor, these systems inevitably dissatisfy a significant portion of the occupants. This dissatisfaction has a direct cost: reduced cognitive function, lower productivity, and increased absenteeism [8]. Furthermore, it creates a battle for control, undermining the very efficiency the system was designed to achieve.

2.3 The Focus on First Costs and Prescriptive Metrics

The traditional procurement and development process is heavily biased towards minimizing initial Capital Expenditure (CapEx). This "first-cost" mentality often leads to the value-engineering of crucial components, such as building automation systems, higher-grade sensors, or more advanced controls, which are essential for fine-tuning performance over the building's lifespan. Sustainability certifications, while valuable, can sometimes become a "check-box" exercise, where points are awarded for installing a technology rather than for its proven, in-use performance [9]. This prescriptive approach can lead to a "build it, certify it, forget it" mentality, where the potential of sustainable features is never fully realized because the operational phase is neglected.

2.4 The Siloed Nature of Building Systems

In a conventional building, other systems often operate in isolation. The BMS (Building Management System) controls HVAC, the lighting system operates on a separate schedule, and the blinds are manually operated. There is no integration or shared intelligence. For example, on a sunny winter day, the solar heat gain might be reducing the heating load, but the blinds may be drawn, and the lights turned on, negating the free energy from the sun. This lack of systemic coordination prevents the building from acting as a cohesive, optimized organism.

In summary, the traditional model creates buildings that are brittle, inefficient, and often uncomfortable. They are designed for a theoretical average occupant and a predicted climate, leaving them ill-equipped to handle the dynamic reality of daily use. It is from the recognition of these shortcomings that the occupant-

centric and operational sustainability paradigm has emerged.

III. THE PARADIGM SHIFT TO OCCUPANT-CENTRIC DESIGN (OCD)

Occupant-Centric Design (OCD) represents a fundamental reorientation of the design and operation process, placing the needs, well-being, and adaptive behaviors of occupants at the core of decision-making. It moves away from viewing occupants as passive recipients of environmental conditions and instead sees them as active participants in a feedback loop that continuously informs and optimizes the building's performance.

3.1 Defining Occupant-Centric Design

OCD is an interdisciplinary approach that leverages insights from environmental psychology, human factors engineering, and data science to create built environments that are responsive, adaptive, and personalized. The goal is to provide individuals with a high degree of control over their immediate environment (thermal, visual, acoustic, and air quality) while using their aggregated interactions and preferences as data to drive systemic efficiency.

3.2 The Pillars of OCD

Occupant-Centric-Design are pinned on the following at its core:

a. Personalization and Adaptive Comfort: Instead of targeting a narrow band of the PMV model, OCD embraces the Adaptive Comfort Model (ASHRAE Standard 55), which allows for a wider range of acceptable temperatures that people can adapt to, for instance, through clothing changes or behavioral adjustments [10]. The key is providing the means for this adaptation. This can be achieved through:

b. Task-Ambient Conditioning (TAC): Delivering heating, cooling, and ventilation locally to the occupant (e.g., via personal desk fans, heaters, or underfloor air diffusers) while allowing background conditions to float within a broader, more energy-efficient range.

c. Personalized Environmental Control Systems: Smartphone apps or desktop interfaces that allow occupants to adjust their local temperature, lighting color temperature, and intensity within a predefined, energy-safe "comfort band."

d. Well-being and Productivity as Key Metrics: The business case for OCD is powerfully made through the lens of human capital. Salaries and benefits typically constitute over 90% of an organization's operating costs, while energy costs account for only about 1% [11]. Therefore, even a marginal improvement in employee productivity, health, or retention yields a financial return that dwarfs energy savings. OCD directly targets these metrics by optimizing for factors known to impact cognitive function:

e. Daylighting and Circadian Lighting: Access to natural light and electric lighting systems that mimic the diurnal pattern of daylight have been shown to improve sleep quality, mood, and alertness [12].

f. Improved Indoor Air Quality (IAQ): IoT sensors can monitor CO_2, PM2.5, and VOCs, allowing AI systems to modulate ventilation rates in real-time. Studies have linked high CO_2 levels to significant reductions in cognitive scores [13].

g. Acoustic Comfort: Designing for speech privacy and noise reduction to minimize distractions.

h. Feedback and Agency: A core tenet of OCD is transparency and engagement. Providing occupants with feedback on their environment (e.g., "Your zone's air quality is excellent") and the impact of their choices (e.g., "Opening your window now will increase energy use by X%") fosters a sense of agency and stewardship. This "shared savings" model aligns occupant behavior with broader sustainability goals, turning them from passive consumers into active partners in resource conservation.

IV. THE TECHNOLOGICAL ENABLERS: IOT, AI, AND DIGITAL TWINS

The theoretical framework of OCD would be impractical without the suite of digital technologies that have matured over the last decade. These technologies provide the nervous system and the brain for the responsive building.

4.1 The Internet of Things (IoT): The Sensory Nervous System

IoT refers to the network of physical devices embedded with sensors, software, and connectivity to collect and exchange data. In a smart building, this includes:

a. Environmental Sensors: Temperature, relative humidity, CO_2, PM2.5, VOC, illuminance, and noise sensors.

b. Occupancy Sensors: Passive Infrared (PIR), chair sensors, and increasingly, computer vision (with privacy filters) or Wi-Fi triangulation to detect presence and count people anonymously.

c. Operational Technology Sensors: Smart meters for energy and water, vibration sensors on pumps and fans, actuator feedback from valves and dampers.

This dense network of sensors provides a high-resolution, real-time picture of the building's state, moving beyond zonal averages to granular, localized data.

4.2 Artificial Intelligence (AI) and Machine Learning (ML): The Cognitive Brain

The vast streams of IoT data are meaningless without analytical power. These are where AI and ML algorithms turn these data into actionable intelligence. For the purpose of this work the following are actionable points:

a. Supervised Learning for Anomaly Detection: ML models can be trained on historical data to recognize normal operating patterns for equipment. Deviations from these patterns can signal impending failures, allowing for

predictive maintenance before a catastrophic breakdown occurs [14].

b. Reinforcement Learning (RL) for Optimal Control: RL is particularly powerful for building control. An RL agent learns the optimal control policy (e.g., for HVAC setpoints) by continuously interacting with the environment. It is rewarded for actions that save energy and maintain comfort, learning over time to make increasingly sophisticated decisions that account for complex, non-linear dynamics that are impossible to program with traditional rules [15].

c. Federated Learning for Personalized Comfort: A major challenge in personalization is data privacy. Federated learning offers a solution. Instead of sending raw personal preference data to a central cloud, the ML model is sent to the user's device (e.g., their phone). The model trains locally on their private data and only the model updates (weights and biases) are sent back to the central server to be aggregated. This allows the system to learn collective comfort patterns without ever centrally storing or viewing individual occupant data [16].

4.3 The Digital Twin: The Living Avatar

A Digital Twin is a dynamic, virtual representation of a physical building or system that is updated in real-time with data from its physical counterpart [17]. It is more than a sophisticated BIM model; it is a living simulation.

4.3.1 Components of a Building Digital Twin:

1. Physical Building: The actual asset with its IoT sensors and actuators.

2. Virtual Model: A data-rich 3D model, often built on the BIM created during design and construction.

3. Bidirectional Data Link: A continuous flow of data from the physical to the virtual (sensor data) and from the virtual to the physical (control commands, setpoint adjustments).

4.3.2 Applications for OCD and Sustainability:

The following applicable used-cases can be created on the Digital Twin Platform where one variable can be tweaked to simulated an expected possible outcome:

a. What-If Scenario Analysis: Facility managers can use the Digital Twin to simulate the impact of a change—e.g., "What if we change the chilled water temperature by 1°C?" or "How will reconfiguring this open-plan office affect airflow and comfort?"—without disrupting the actual building.

b. Continuous Commissioning: The Digital Twin continuously compares simulated performance (the "should be") with actual performance (the "is"). Any growing discrepancy flags a performance drift, enabling proactive correction and ensuring the building perpetually operates at its design intent.

c. Lifecycle Management: It becomes a single source of truth for the building, containing all operational history, maintenance records, and component data, invaluable for planning retrofits and managing the asset over its entire lifespan.

The synergy of IoT, AI, and Digital Twins creates a closed-loop, intelligent system that can learn, adapt, and predict, making the vision of a truly occupant-centric and operationally sustainable building a reality.

V. THE SYNERGY: DATA-DRIVEN OPERATIONAL SUSTAINABILITY

Operational Sustainability moves the focus from the design-phase predictions to the day-to-day, year-to-year performance of the building. It is the practice of using data and analytics to continuously optimize resource use, maintain system health, and adapt to changing conditions throughout the building's lifecycle. When fused with OCD, it creates a powerful, self-improving ecosystem.

5.1 Closing the Performance Gap with Real-Time Analytics

The Digital Twin is the primary tool for closing the performance gap. By constantly calibrating itself against real-world data, it provides an accurate baseline for performance measurement. AI algorithms can then drill down into the data to diagnose the root causes of inefficiencies. For example, if a particular zone consistently uses more energy than simulated, the AI can cross-reference occupancy data, equipment runtime, and weather data to determine if the cause is a faulty sensor, an incorrectly sequenced heat pump, or unanticipated occupant behavior. This moves facility management from a reactive, "break-fix" model to a proactive, diagnostic one.

5.2 Predictive and Prescriptive Maintenance

Traditional maintenance is either reactive (fixing things after they break) or preventive (scheduled maintenance at fixed intervals), both of which are inefficient. Reactive maintenance leads to downtime and emergency costs, while preventive maintenance can result in replacing parts that still have useful life.

a. Predictive Maintenance: By analyzing vibration, temperature, and energy consumption data from critical assets, ML models can detect subtle signatures that indicate a component is beginning to degrade. This allows maintenance to be scheduled just-in-time, before failure, maximizing component lifespan and minimizing disruptive downtime [14].

b. Prescriptive Maintenance: An advanced form of predictive maintenance, where the AI not only predicts a failure but also recommends specific interventions—for instance, "Tightening the belt on Air Handler Unit 3 will extend its life by 6 months and improve efficiency by 5%." This transforms the facility team from technicians to data-driven analysts.

5.3 Dynamic Resource Optimization

The building becomes an active player in the smart grid. With on-site generation (e.g., solar PV) and battery storage, an AI optimizer can decide the most cost-effective and sustainable way to meet building loads. It can consider:

a. Real-time electricity pricing: Pre-cooling the building when grid electricity is cheap and clean, and drawing from batteries during expensive, peak demand periods.

b. Carbon intensity of the grid: Automatically shifting loads to times when the grid is powered by more renewable sources, thus minimizing the building's carbon footprint.

c. Occupancy forecasts: Using historical and real-time data to predict building occupancy and adjust system setpoints accordingly, ensuring comfort only when and where it is needed.

This dynamic optimization turns the building from a passive energy consumer into a flexible grid asset, creating new revenue streams and enhancing its overall economic and environmental performance.

VI. THE COST-EFFECTIVENESS AND FINANCIAL ARGUMENT

The integrated model of OCD and operational sustainability requires an upfront investment in technology, design integration, and software. However, a sophisticated analysis of the Total Cost of Ownership (TCO) reveals a compelling financial case that extends far beyond simple utility bill savings.

6.1 Reframing the Business Case: Total Cost of Ownership (TCO)

TCO analysis accounts for all direct and indirect costs associated with a building asset over its entire service life. This includes not only initial CapEx and operational utilities (OpEx) but also maintenance, repairs, replacement, and—crucially—the cost of the people inside.

6.2 Quantifying the Benefits

1. Direct Operational Savings (Hard Savings):

a. Energy: Studies of buildings with advanced AI-based control systems consistently report energy savings of 15-30% compared to conventional BMS operation [18]. For a large

commercial office, this can translate to hundreds of thousands of dollars annually.

b. Water: Smart irrigation and leak detection systems can reduce water consumption by 20-30%.

c. Maintenance: Predictive maintenance can reduce maintenance costs by 20-25% and eliminate up to 70% of breakdowns [19].

2. Human Capital Benefits (Soft Savings, High Impact):

a. Productivity Gains: Even a 1% increase in productivity, attributable to improved thermal comfort, lighting, and IAQ, can yield an annual financial benefit per employee that is greater than their entire annual energy cost [11]. For a 1,000-person organization with an average salary of $80,000, a 1% productivity gain is worth $800,000 per year.

b. Reduced Absenteeism and Presenteeism: Healthier indoor environments, with better ventilation and lower pollutant levels, have been linked to a reduction in sick building syndrome symptoms and a decrease in absenteeism. A study by [20] found a 35% reduction in respiratory illness in buildings with superior IAQ.

c. Talent Attraction and Retention: Modern tenants and employees, particularly from younger generations, are increasingly valuing sustainability and well-being. A building with a certified healthy interior (e.g., WELL Certified) and a reputation for superior comfort becomes a powerful tool for attracting and retaining top talent, reducing recruitment and onboarding costs.

3. Asset Value and Risk Mitigation:

a. Increased Rental Premiums and Occupancy Rates: "Green" and "healthy" buildings consistently command rental premiums of 3-7% and have higher occupancy rates than their conventional counterparts [21]. This directly enhances the property's Net Operating Income (NOI) and, by extension, its capital value.

b. Future-Proofing and Regulatory Resilience: As governments worldwide impose stricter carbon emissions regulations and disclosure requirements (e.g., EU's Energy Performance of Buildings Directive), buildings that are already optimized for low operational carbon will face lower compliance costs and avoid potential "brown discounts" or stranded asset risk.

c. Enhanced Resilience: The ability to dynamically respond to extreme weather events or grid instability through load shifting and on-site generation makes the building more resilient, protecting the business operations within.

6.3 Return on Investment (ROI) Analysis

While the ROI for a comprehensive system will vary, the payback period is becoming increasingly attractive. The cost of IoT sensors and computing power continues to fall. When the business case is constructed to include the massive, albeit previously unaccounted for, human capital benefits, the ROI calculation is transformed. The investment is no longer just an energy-saving measure; it is a strategic investment in the core operational efficiency and human potential of the organization.

VII. CHALLENGES AND ETHICAL CONSIDERATIONS

Despite its promise, the widespread adoption of this integrated model faces significant hurdles that must be addressed.

7.1 Data Privacy and Security

The pervasive data collection required for OCD raises legitimate privacy concerns. For an instance, the continuous monitoring of occupancy, even if anonymized, can feel intrusive.

❖ Mitigation: Implement Privacy by Design principles. Use privacy-preserving technologies like federated learning. Ensure robust data encryption and access controls. Be transparent with occupants about what data is collected, how it is used, and who has access.

Provide clear opt-out mechanisms for personal data collection.

7.2 Initial Cost and Perceived Risk

The higher initial CapEx for advanced technology and integrated design can be a barrier, especially for developers working with tight budgets.

❖ Mitigation: Develop new financial models, such as "Efficiency-as-a-Service," where a third-party financier covers the upfront cost and is paid back from the achieved savings. Strengthen the business case by fully quantifying TCO and human capital benefits.

7.3 Skills Gap and Change Management

Facility management teams are traditionally trained in mechanical systems, not data science. Operating and maintaining an AI-driven Digital Twin requires new skills.

❖ Mitigation: Invest in training and upskilling for existing staff. Foster closer collaboration between facility managers, data scientists, and IT departments. The technology must be designed with a user-friendly interface that empowers, rather than overwhelms, the operations team.

7.4 Technological Interoperability

The AEC industry is plagued by proprietary systems and a lack of data standards, making it difficult to integrate different components into a seamless Digital Twin.

Mitigation: Advocate for and adopt open standards like Project Haystack for data tagging and Brick Schema for building metadata. Specify interoperable systems during the procurement process.

VIII. CONCLUSION AND FUTURE OUTLOOK

The trajectory of sustainable building is unmistakably shifting. The era of treating sustainability as a static, technological feature to be bolted onto a design is ending. Tomorrow's building trends will be defined by dynamic, intelligent, and human-centered ecosystems. This paper has articulated the powerful synergy between Occupant-Centric Design and Data-Driven Operational Sustainability, demonstrating that this integration is the most viable path to bridging the performance gap and achieving deep, cost-effective sustainability.

By designing for the well-being and agency of occupants, we unlock immense value in the form of enhanced productivity, health, and satisfaction—benefits that dwarf traditional energy savings. By leveraging IoT, AI, and Digital Twins, we can operate buildings with a level of precision and adaptability previously unimaginable, transforming them from inert structures into responsive, learning partners.

The financial argument is clear and compelling. When evaluated through the comprehensive lens of Total Cost of Ownership, the initial investment in this integrated model yields a substantial return through direct operational savings, human capital gains, and enhanced asset value. It represents a strategic pivot from cost minimization to value maximization.

The challenges of privacy, cost, and skills are real but surmountable. They call for a collaborative effort from designers, engineers, technologists, investors, and policymakers to create the frameworks, standards, and business models that will enable this transition at scale.

The building of tomorrow will not be defined by its static form, but by its dynamic performance. It will be a building that sees, learns, and adapts. It will be a building that prioritizes the health of its occupants and the planet, not as competing goals, but as two sides of the same coin. By embracing the occupant-centric and operational sustainability paradigm, we can create a built environment that is not only smarter and greener but also more productive, resilient, and profoundly more humane.

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