

Criteria for Selecting Smart Materials and Smart Systems in Hospital Buildings: A Proposed Methodology

Dr. Fatma M. Mohamed¹

Submitted:24/01/2024

Accepted:05/02/2024

Published:12/02/2024

Abstract: Hospital buildings are no longer just buildings with fixed structures but have transformed into smart entities capable of interacting with the demands of the internal and external environment and responding quickly to all changes. This is thanks to the accelerated use of advanced technologies in smart materials and smart systems. However, we find another challenge, which is the lack of a clear scientific methodology in the process of selecting the criteria for smart materials and smart systems in hospital buildings. This leads to the adoption of unsuitable engineering solutions and increased costs without achieving a safe, comfortable, and healthy environment for patients and staff. This study aims to propose a methodology for selecting the criteria for smart materials and smart systems in hospital buildings. It employs a descriptive-analytical approach to establish the theoretical framework, a comparative approach to analyze case studies of leading hospitals, and a deductive approach to formulate the proposed methodology. The study arrives at a five-stage methodology: (1) Assessment and Diagnosis, (2) Criteria Specification, (3) Selection and Evaluation, (4) Application and Integration, and (5) Evaluation and Feedback. The results also revealed that implementing this methodology contributes to creating a healthy and safe indoor environment for patients, effectively improving energy efficiency and reducing long-term operating costs, while also increasing patient satisfaction and recovery rates. This study recommends that this approach be adopted as a basis for developing national hospital design codes.

Keywords: *Smart materials, smart systems, hospital buildings, Indoor Environmental Quality.*

1- Introduction:

Hospital buildings are among the most complex building categories in terms of their functional programs and mechanical and electrical systems. It is important to note the sensitivity of the technical requirements of the indoor environment, as this environment is not merely a place for providing medical services, but rather a comprehensive therapeutic environment. It must contribute positively to making patient recover and maintaining their health sustainable. Furthermore, Indoor Environmental Quality (IEQ) is a fundamental element, encompassing factors such as thermal comfort, visual quality, indoor air quality, and acoustic comfort (Huizenga et al., 2006) [1]. In recent decades, the construction industry has undergone a significant technological

transformation, with the emergence of a new generation of smart materials capable of sensing environmental influences such as heat, light, pressure, and humidity, and reacting to them instantly, automatically, and often in reverse (Addington & Schodek, 2005) [2], (Sobczyk, M., 2022) [3]. In parallel, smart systems have witnessed remarkable development to rise to the level of comprehensive management and control of building performance, most notably the Building Management System (BMS), which is considered the central brain of the building, and is responsible for monitoring and managing various operations such as air conditioning, lighting, security and safety (Wong et al., 2006) [4], (Wong et al., 2005) [5], (Liang et al. 2023) [6].

2- Research Problem:

The absence of a methodology for selecting smart materials and smart systems in hospital buildings.

1-Assist., Professor, Architecture & Environmental Design, Modern Academy for Engineering and Technology, Central plateau-ElMokattam, Cairo, Egypt. Email: fatma.magdy@outlook.com, https://orcid.org/0009-0006-0376-7591

3- Research question:

What are the components of the proposed methodology for selecting smart materials and smart systems standards in hospital buildings to ensure a healthy and safe environment?

4- Main Objective:

To develop a methodology for selecting smart materials and smart systems in hospital buildings to provide a safe and healthy environment for patients.

5- Hypothesis:

Developing a methodology for selecting smart materials and smart systems in hospital buildings

will achieve a safe and healthy environment for patients and improve the quality of the internal environment.

6- Research Methodology:

To achieve the research objectives, a theoretical approach is followed that relies on reviewing previous studies, an analytical approach that reviews case studies of hospital buildings in which smart materials and smart systems have been applied and selected, then the results are explained and compared, and the deductive approach is used in formulating the proposed methodology, and thus determining the validity of the hypothesis within the framework of achieving the desired research objectives.

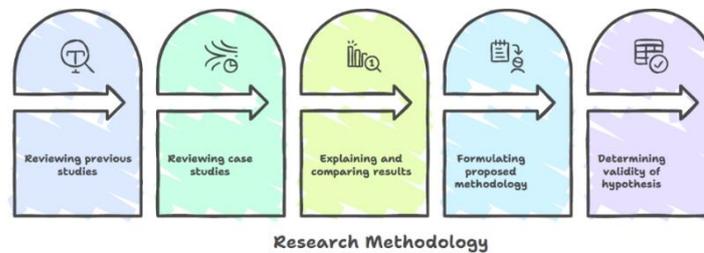


Figure (1) shows Research Methodology

7- Literature Review

Literature Review are essential for understanding the development of smart materials and systems and their applications in medical facilities. The following is a brief overview of key studies and research that have focused on the role of these smart materials and systems in improving the indoor environment, achieving energy efficiency, and enhancing the quality of the therapeutic environment within hospital buildings:

Studies that focus on the basic features of materials applied to these technologies begin, as (Addington and Schodek .,2005) [2] explain that smart materials are a key content that differs from ordinary materials in that they can achieve energy conversion from one form to another and respond to external influences instantly. This opens a field for designers to create building elements that change their properties in response to external conditions. (Abdullah and Al-Alwan ., 2019) [7] reviewed smart material systems and their ability to adapt within a building and pointed out that incorporating them into the exterior wall enables the glass or surface to adjust its transmittance or thermal insulation throughout the day, which is essential in hospitals that require

internal departments whose conditions change precisely. In the field of systems, (Wong et al. 2005) [5] point out that hospital buildings pose a significant challenge in smart building studies due to the complexity of their functions and the need for a high degree of integration between mechanical, electrical, and administrative systems. (Wong et al. 2006) [4] further supported this approach by developing human-adaptive algorithms (HABIT) that are integrated into building management systems (BMS). These algorithms aim to modify the indoor environment to meet the physical and psychological needs of users, directly impacting air quality and thermal comfort—two crucial elements in accelerating patient response to treatment, as noted by (Huizenga et al. 2006) [1] in their research on indoor environmental quality. With the healthcare sector's shift towards digital hospitals, (Woll and Tørresen 2022) [8] reviewed the literature to explain the concept of the smart hospital, describing it as a system that combines automation with human interaction to improve processes and service delivery. (Plageras et al. 2017) [9] investigated technological solutions that ensure connectivity and security within the smart hospital, emphasizing that building efficiency is not limited

to automation but extends to the systems' ability to securely exchange data to protect the continuity of the healthcare environment. (Kim et al. 2022) [10] addressed current research trends in the design and implementation of smart buildings, noting that future research focuses on transforming the building into a self-aware entity that reduces energy consumption while maintaining user comfort. (Alsawaf, E. S., & Albadry, A. M. 2022). [11] pointed to the need to integrate sustainable design with smart technologies to obtain green building certifications, defining a "green" hospital as one that achieves a balance between technology and resource efficiency. (Baharuddin et al. 2022) [12] reinforced this trend with a case study of public hospitals in Malaysia, demonstrating that leveraging the potential of smart buildings reduces energy loads and enhances the functional performance of medical facilities. (Kaur, A., Bhatia, M., & Ahanger, T. A. 2023) [13] presented an integrated design model that combines the characteristics of green and smart hospitals, based on a bibliometric analysis showing the increasing reliance on clean energy technologies and smart control of the outer envelopes of medical buildings. From an operational perspective, a study by (Li et al. 2022) [14] indicated the use of Building Information Modeling (BIM) for managing hospital building facilities, as it is a tool that helps intelligent systems track malfunctions in smart materials and thus perform maintenance to ensure the building's continued operation for extended periods. A study by (Liang et al. 2023) [6] pointed to the technological infrastructure and suggested developing Internet of Things-based Building Management Systems (IoT-BMS) to enhance building sustainability, as these systems monitor energy efficiency in real time and improve the indoor environment based on accurate and real-time data. A study by (Rodriguez et al. 2021) [15] addressed the performance and availability of smart hospital infrastructure, indicating that investment in smart systems requires a thorough analysis of their sustainability and ability to operate under operational pressure. A study by (Aliero et al. 2022) [16] highlighted the opportunities and challenges associated with smart hospital buildings, noting that while smart hospital buildings offer opportunities for improved energy efficiency, they also present the technical and design challenges of digital transformation. The study by (Sobczyk et al., 2022) [3] also focused on the possibility of using smart materials as sensors and actuators in the structural environment, enabling interaction with variables in hospital buildings biologically and mechanically. (Feng et al., 2020) [17] pointed to a framework for smart healthcare that considers cultural and human

aspects, explaining that the goal of using smart materials and systems in hospital buildings is to produce a sustainable and effective therapeutic environment centered on the human being. This framework benefits from smart residential building technologies, as indicated by (Ben Safar, 2019) [18], as its experience can be applied to the hospital building sector.

8- Smart Materials and Systems in Hospital Buildings

8.1 Smart Materials

Smart materials are a crucial pillar in contemporary architecture, particularly in hospital buildings, which demand high environmental performance and a sophisticated, rapid response to changes. Smart materials can be defined as materials capable of responding quickly to external influences in a predetermined manner, as defined by (Addington & Schodek, 2005) [2]. They can also be defined as materials capable of automatically adapting their properties or some of their characteristics in response to environmental variables such as thermal conductivity, reflectivity, ventilation, and the building's exterior appearance (Abdullah and Al-Alwan, 2019) [7]. (Sobczyk et al. 2022) [3] indicated that smart materials represent a qualitative leap in contemporary architectural thought, transforming buildings from rigid masses into dynamic structures capable of interacting with their surroundings and responding automatically to external and internal changes. In an analytical study of smart material systems, the researchers confirmed that integrating these materials into building envelopes can improve thermal performance by up to 30% while reducing reliance on mechanical air conditioning systems.

8.2 Objectives of Using Smart Materials in Buildings

The objective of using smart materials in buildings depends on several key factors, which (Kim et al. 2022) [10] summarize in their comprehensive review of smart building research trends. They emphasize that the goal is to achieve integration between building performance and user needs. These objectives can be defined as follows:

- Complete self-regulation of energy efficiency.
- The building's ability to regenerate its outer envelope.
- The building's performance level is changing in response to surrounding variables.

- Replacing traditional construction materials with smart materials.
- Achieving design flexibility and ease of installation and manufacturing.
- High self-maintenance and durability.
- Material reuse and recycling.
- Rapid response to external environmental influences.
- The ability to modify their properties for development purposes.

- Availability in the surrounding environment and low cost. (Aliero et al. 2022) [16], in their study, a systematic analysis of the opportunities and challenges of smart buildings, indicates that achieving these goals requires integrating intelligent control systems and smart material design systems, while considering costs, economic feasibility, and compatibility with the local environment for these systems and smart materials. Their study analyzed 124 research papers, with 68% indicating that the high cost of smart technologies represents a major challenge, necessitating the development of locally produced smart material systems to reduce costs.

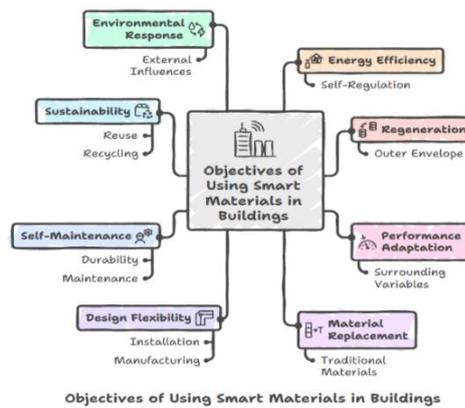


Figure (2) shows Objectives of Using Smart Materials in Buildings

8.3 Characteristics of Smart Materials:

Smart materials differ from traditional materials in that they possess advanced and unique characteristics that make them more efficient in responding to internal and external changes and conditions in buildings. As (Addington and Chuddick 2005) [2] indicated, smart materials and new advanced technologies include the following characteristics:

- **Immediate Response:** Smart materials respond in a timely manner without delay. (Sobczyk et al. 2022) [3] emphasize that this characteristic, immediate response, is very important, especially in healthcare buildings, particularly in wards and intensive care units, where an immediate response to environmental changes in these critical spaces is required.

- **Transiency:** The material's ability to respond quickly to multiple successive environmental conditions. In their study on intelligent material systems, (Abdullah and Al-Alwan 2019) [7] found that transiency materials can adapt to changes in solar radiation throughout the day, thus improving patients' visual and thermal comfort.

- **Predictability** or selectivity refers to the ability to respond appropriately to changing environmental conditions by leveraging past data and circumstances. (Wong et al. 2006) [4] indicates that this property is achieved by integrating smart materials with learning control systems, as in the HABIT algorithm they developed for building management systems. This algorithm teaches user behavior patterns to automatically adapt to their needs.

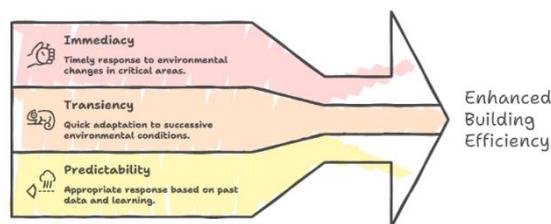


Figure (3) shows Characteristics of smart Building Materials

8.4 Types of Smart Materials

Smart materials are classified into two main categories: property-changing materials and energy-converting materials. (Addington and Schodek 2005) [2] provide a comprehensive classification of these materials based on their mechanism of response to external stimuli.

1. Property-Changing Smart Materials:

1.1 Chromics :

These are materials whose optical properties change because of changes in the external energy source (such as temperature or light). When thermal energy is applied to a material, its molecular structure changes, leading to a change in spectral reflectivity compared to the original molecular structure. This, in turn, results in a change in the material's reflected radiation within the visible range of the electromagnetic spectrum. Such a material is called a "thermochromic material." Materials are named according to the external stimulus: if a material is exposed to light energy and undergoes a color change, it is called a "photochromic material," and if exposed to a chemical environment, it is called a "chemochromic material" (Badr, 2010) [19].

In hospital applications, (Alsawaf, E. S., & Albadry, A. M. 2022). [11], in his study on integrating sustainable design with smart technologies, demonstrates that using electrochromic glass in hospital facades can reduce energy consumption by 25% while improving visual comfort for patients, particularly in long-term care units where patients need to control the amount of natural light without compromising privacy or connection to the outside world.

1-2 Rheological Property Changing Materials:

These are materials that change their properties in response to an electric or magnetic field by altering the orientation of their microstructure. The viscosity of the fluid increases when exposed to an electric or magnetic field (Addington & Schodek, 2005) [2]. (Baharuddin et al. 2022) [12], in their applied study at a Malaysian hospital, found that using electrorheological fluids in vibration damping systems can improve the stability of hospital buildings in seismically active areas, thus enhancing the safety of patients and sensitive medical equipment.

1-3 Conductor Materials:

- **Photo-conductors:** These materials undergo changes in their electrical conductivity when exposed to light.

- **Pyro-conductors:** These materials have temperature-dependent conductivity and can achieve their lowest conductivity close to critical low temperatures.

- **Magneto-conductors:** These are materials whose conductivity responds to a magnetic field.

The most significant application of smart connectors, such as motion sensors, in sensor devices is their use of various types of connectors or photoresistors. These sensors provide the building control unit with a diverse range of information to make decisions during use and to ensure users have everything they need to make appropriate choices (Badr, 2010) [19]. (Plageras et al. 2017) [9] indicated that a smart hospital network, comprised of a set of sensors, is the essential element that can be used as the building's nervous system, continuously monitoring air quality, temperature, humidity, and the movement of patients and staff. Although the researchers proposed security protocols for connecting these sensors to a control center to ensure the confidentiality of patient data within the hospital.

2- Energy-Changing Smart Materials:

Energy-changing materials are defined as "materials that convert energy from one form to another, both directly and inversely" (Addington & Schodek, 2005) [2]. These include the following types:

2-1 Photo-voltaic Materials:

The term "photovoltaic" is derived from the Arabic word's "photo" and "voltaic," meaning "light" or "electric." These materials directly convert light energy into electrical energy.

(Kaur, A., Bhatia, M., & Ahanger, T. A. 2023) [13], in their bibliometric analysis of green and smart hospital buildings, indicate that integrating photovoltaic cells into hospital facades and roofs can meet 20-40% of a hospital's electricity needs, especially in sunny areas. Furthermore, the use of transparent photovoltaic glass allows for energy generation while preserving natural light.

2.2 Thermo-electric Materials:

When an electric current is applied to a thermoelectric material, a temperature difference occurs across its opposite sides. If the circuit is subjected to an external voltage, one junction will heat up while the other will cool down. When heat is applied to the material, the temperature difference between its ends causes charge carriers (electrons or holes) to diffuse from the heat to the colder.

(Liang et al. 2023) [6], in their study on IoT-based building management systems, demonstrate that using thermoelectric materials in local heating and cooling systems can improve energy efficiency by 15% compared to conventional systems. It also allows for individual temperature control in each room, which is crucial in hospitals where thermal needs differ between operating rooms (which require lower temperatures) and intensive care units (which require moderate temperatures).

2.3 Piezo-electric Materials: These are materials that generate an electric current when subjected to mechanical stress or pressure (Addington & Schodek, 2005) [2]. The mechanical force causes a change in shape, which in turn leads to the generation of electric potential. According to (Sobczyk et al. 2022) [3], one possible application for piezoelectric materials in healthcare settings is to

use them as flooring materials in hospitals and medical facilities that generate electricity whenever patients, visitors or medical personnel walk over them. Such energy could be used to run sensors or to charge mobile devices thereby increasing the hospitals' overall energy use.

2.4 Magneto-strictive materials and electro-strictive materials: These are two kinds of material that experience changes in physical shape when acted upon by electricity and magnetic fields, respectively. According to (Feng et al. 2020) [17], in their advanced Smart Hospital environment, such materials can be successfully implemented into accuracy guidance systems of medical devices, particularly within a surgical application where extremely accurate motion can be achieved through existing mechanical systems.

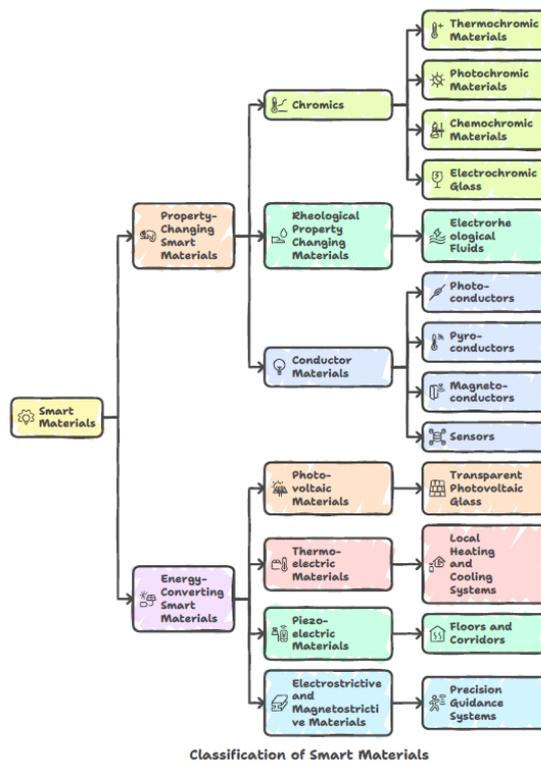


Figure (4) shows Types of Smart Materials

9- Intelligent Hospital Buildings

An intelligent hospital is a major development in designing and operating healthcare facilities. According to (Woll and Tørresen 2022) [8] and their detailed literature review, the definition of the intelligent hospital includes "a building that combines digital technologies, automation systems, and smart materials to create a unified building with the goal of enhancing quality of care, operating efficiency, and the patient's experience." The

researchers emphasize that the intelligent hospital is characterized by three key features: digital interconnection of systems, operational autonomy, and the ability to adapt to the needs of patients and medical staff.

(Kim et al. 2022) [10] add that an intelligent building, in general, is one that "provides productive efficiency, cost-effectiveness, an optimized internal and natural environment, and optimal utilization of the structural framework, management systems, and

coordination of their interrelationships." The following are the most important features of intelligent buildings:

1- Intelligent Building Characteristics

(Wong et al. 2005) [5], in their review of intelligent building research, identify three key characteristics:

- **Automated Control:** where building systems are managed without direct human intervention.
- **Achieving appropriate responsiveness to the needs of building occupants and spatial requirements:** i.e., the building's ability to understand and meet the needs of its users.
- **The ability to learn new things (adapting based on changing environmental performance and the needs of building occupants):** This characteristic represents the third generation of smart buildings, where artificial intelligence and machine learning systems are used to continuously improve performance.

In a recent study, (Rodrigues et al. 2021) [15] demonstrates that achieving these characteristics in hospitals requires a robust technological infrastructure with at least 99.9% availability (Five Nines) to ensure patient safety and the continuity of essential services.

2- Building Management:

Building management encompasses the management of all control systems, automation, lighting control, efficiency monitoring and energy conservation, access control, video surveillance, fire alarms, and central energy storage batteries. This is integrated with the Building Operating System (BOS), and the integration and interoperability of systems are determined according to the architect's requirements. (Liang et al. 2023) [6] confirms that smart building management achieves cost-effectiveness, enables employees to easily monitor the various statuses of services and facilities, and respond quickly to improve comfort and reduce consumption. In their application of an IoT-BMS system to a model hospital, the results showed a 35% improvement in energy consumption management and a 40% reduction in operational downtime thanks to predictive maintenance. (Li, Y., Pan, X., Han, Y., & Lavy, S. 2022) [14], in their systematic review on Building Information Modeling (BIM) in hospital facility management, add that integrating BIM with building management systems allows for the creation of a "digital twin" of the hospital. This enables the simulation of operational scenarios and performance optimization

before actual implementation, resulting in a 20-30% reduction in maintenance costs.

3- Smart Building System Levels

Research shows smart building automation systems use a hierarchical structure (Wong et al 2005) [5]; (Kim et al 2022) [10]. The top of the hierarchy has the integrated management systems, then the automation level and finally at the bottom is the implementation of smart devices at a spatial level (Plageras et al 2017) [9]. This hierarchy provides flexibility and scalability of the building automation systems so that new devices can easily be added to existing automated/building systems without impacting system stability.

4- Building Automation

According to (Addington & Schodek 2005) [2], "The entire building will be monitored, and each item within the building (heating, cooling, ventilation, water tanks, elevators, mechanical systems, and electrical systems) will be monitored and controlled by a network of intelligent control systems". With a building automation system, the following benefits can be realized: centralized control and management of climate control (HVAC), lighting, security, and safety; improved energy efficiency; improved comfort for the building occupants; reduced harmful emissions (through energy efficiency); and increased productivity. As (Huizenga et al. 2006) [1] point out in their comprehensive analysis of indoor environmental quality, sensors and motion actuators are key components of the intelligent building automation system. Sensors are the 'eyes and ears' of the building and provide data to the intelligent control systems so that those systems can make decisions on behalf of the building about what actions should be taken. Cables are the 'nervous systems' that connect the sensors to the control systems, while motion actuators are like the 'arms' in a human body that allow the control system to efficiently operate the building by providing the necessary physical actions.

5- Levels of Smart Building Automation Systems

A smart building can be defined as a three-level integrated system that works together in a continuous feedback loop (Wong et al., 2005) [5]; (Badr, 2010) [19]:

- **Level 1: Input Systems.** These consist of the elements that collect environmental information (sensors) and transmit it via cables to the building control unit. (Rodrigues et al. 2021) [15] explain that hospitals need a dense network of sensors to monitor

air quality, temperature, humidity, and occupancy, with redundancy in the biosensors to ensure data reliability.

- **Level 2: Analyzing and Processing Systems.** These consist of the computer unit and the software installed on it, based on databases or artificial intelligence programs. (Feng et al. 2020) [17] point to the importance of using advanced artificial intelligence algorithms to analyze the massive amounts of data coming from the sensors and extract patterns and conclusions that help improve hospital performance.

- **Level Three: Output Systems.** These systems represent the responses occurring at the level of different elements within the building, whether they're moving or directing certain elements, or switching lighting units on or off, and so on. These three systems continue to operate (feedback) because, based on the output systems' results, the internal environment changes. Sensors read a lower temperature and inform the computer of this new information, prompting it to reduce the amount of cool air pumped into the room, and so forth.

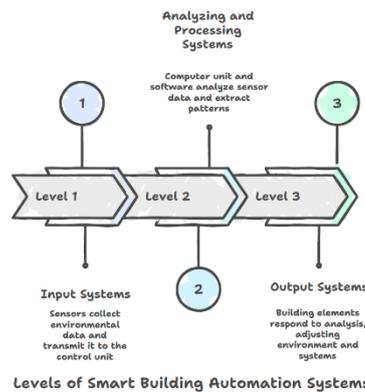


Figure (5) shows Levels of Smart Building Automation Systems

6- Classification of Automation and Smart Building Control Systems

Building elements can be controlled to achieve the desired response in one of two main ways (Wong et al., 2005) [5] ; (Aliero et al., 2022) [16]:

- **Centralized Systems:** These consist of a single control unit that manages all aspects of the building. They are characterized by their ability to integrate all building systems, make comprehensive and optimal decisions, and derive decisions that combine various factors, whether related to energy or other aspects, resulting in more accurate choices.

- **Decentralized Systems:** These consist of multiple control units located at various points within the building, providing autonomy in decision-making without recourse to a central unit. The ability to quickly adjust to local fluctuations makes these systems very flexible. Further, they have built-in protection against total system failure if one control unit fails. In their integrated model for designing green and smart hospitals, (Kaur, A., Bhatia, M., & Ahanger, T. A. 2023) [13] recommend adopting a hybrid system that combines centralization at the strategic planning level with decentralization at the local implementation level, achieving the best balance between overall efficiency and partial flexibility.

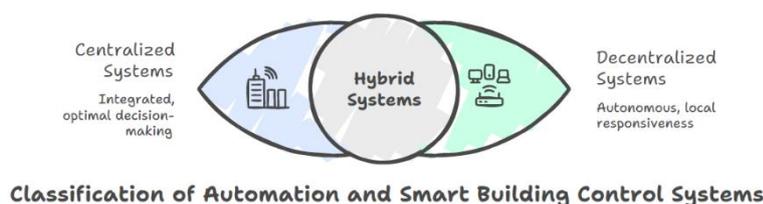


Figure (6) shows Classification of Automation and Smart Building Control Systems

10- Proposed integrated methodology for selecting standards for materials and smart systems in hospital buildings

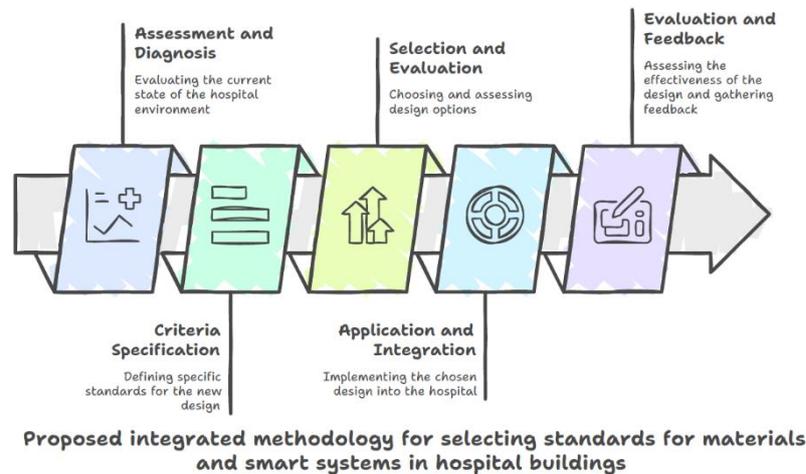


Figure (7) shows Proposed integrated methodology for selecting standards for materials and smart systems in hospital buildings

Table (1): Proposed integrated methodology for selecting standards for materials and smart systems in hospital buildings, with supporting references

| Phases | Objective | Steps | Outputs | References |
|--|--|---|--|---|
| Phase One: (Assessment & Diagnosis) | Understanding the hospital's unique needs and context before seeking smart solutions | 1.1 Context Analysis: Study of local climate, location, wind directions, sun paths | (Climate & Site Analysis Report) | [20]-Givoni, B. (1998). <i>Climate considerations in building and urban design</i> . John Wiley & Sons. [21]-Olgyay, V. (1963). <i>Design with climate: Bioclimatic approach to architectural regionalism</i> . Princeton University Press. |
| | | 1.2 Space Prioritization: Classify hospital spaces according to their sensitivity (operating rooms > patient wards > corridors > administrative offices) and assign an IEQ priority to each space. | (Space Priority Matrix) | [22]-Ulrich, R. S., Zimring, C., Zhu, X., DuBose, J., Seo, H. B., Choi, Y. S., ... & Joseph, A. (2008). A review of the research literature on evidence-based healthcare design. <i>HERD: Health Environments Research & Design Journal</i> , 1(3), 61-125. |
| | | 1.3 Engaging stakeholders: Conduct workshops with the design team, biomedical engineers, nursing staff, and hospital management to identify "needs" and "current problems". | Workshop Report: List of Needs and Problems | [23]-Sanoff, H. (2007). Special issue on participatory design. <i>Design Studies</i> , 28(3), 213-215. [24]-Luck, R. (2003). Dialogue in participatory design. <i>Design Studies</i> , 24(6), 523-535. |
| | | 1.4 Current performance measurement: In the case of rehabilitation, measure the current IEQ indicators (temperature, humidity, CO ₂ , lighting) | Baseline Environmental Performance Report (BEPS) | [25]-ASHRAE. (2021). <i>ASHRAE Handbook: Fundamentals</i> . American Society of Heating, Refrigerating and Air-Conditioning Engineers. |

| | | | | |
|--|--|---|--|---|
| Phase Two: (Criteria Specification) | Translating qualitative needs into measurable quantitative performance standards | 2.1 Formulating performance standards: Converting "need" into "standard" (Example: Need: "Comfortable room for the patient" ← Standard: "Temperature 24±1°C, lighting 50-500 Lux, noise <35 dB at night") | Performance Criteria Table | [26]-Preiser, W. F., & Vischer, J. C. (Eds.). (2005). <i>Assessing building performance</i> . Elsevier. [27]-CIBSE. (2015). <i>CIBSE Guide A: Environmental design</i> . Chartered Institution of Building Services Engineers. |
| | | 2.2 Defining Key Performance Indicators: For each criterion, define a quantitative KPI (U-value, response time, energy saving ratio) | Key Performance Indicators (KPIs) Scorecard | [28]-Beatham, S., Anumba, C., Thorpe, T., & Hedges, I. (2004). KPIs: A critical appraisal of their use in construction. <i>Benchmarking: An International Journal</i> , 11(1), 93-117. |
| Phase Three: A (Selection & Evaluation) | Surveying available technological alternatives and selecting the most suitable one according to a scientific methodology | 3.1 Technological Survey: Identifying potential smart materials and systems that meet the specified criteria | Technology Alternatives Database | [2]-Addington, M., & Schodek, D. (2005). <i>Smart materials and technologies in architecture</i> . Architectural Press, Elsevier. [29]-Ritter, A. (2007). <i>Smart materials in architecture, interior architecture and design</i> . Birkhäuser. |
| | | 3.2 Evaluation using a Decision Matrix: Developing a Multi-Criteria Assessment Matrix (MCDA) with the following weights: • Functionality: 35% • Lifecycle Cost: 25% • Compatibility: 15% • Maintainability: 15% • Sustainability: 10% | Final Decision Matrix | [30]-Saaty, T. L. (2008). Decision making with the analytic hierarchy process. <i>International Journal of Services Sciences</i> , 1(1), 83-98. [31]-Keeney, R. L., & Raiffa, H. (1993). <i>Decisions with multiple objectives: Preferences and value trade-offs</i> . Cambridge University Press. |
| | | 3.3 Simulation and Modeling: For complex systems, use dynamic simulation software (EnergyPlus, IESVE) | Simulation Report and Performance Comparison | [32]-Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., & Pedersen, C. O. (2001). EnergyPlus: New, capable, and linked. <i>Journal of Architectural and Planning Research</i> , 18(4), 292-302. [33]-Hensen, J. L., & Lamberts, R. (Eds.). (2011). <i>Building performance simulation for design and operation</i> . Routledge. |
| Phase Four: (Application & Integration) | Ensuring the integration of selected materials and systems with each other and with the architectural design | 4.1 Integrated Design: Ensuring smart window specifications communicate with HVAC designers and BMS systems | (Technical Integration Report) | [34]-Bachman, L. R. (2003). <i>Integrated buildings: The systems basis of architecture</i> . John Wiley & Sons. [35]-Reed, W. G., & Gordon, E. B. (2000). <i>Integrated design and building process: What research and methodologies are</i> |

| | | | | |
|--|--|---|--|--|
| | | | | needed?. <i>Building Research & Information</i> , 28(5-6), 325-337. |
| | | 4.2 Specifications Documentation: Write the technical specifications accurately in the terms and conditions booklet. | Technical Specifications Booklet | [36]-Cox, B. J., & Hamilton, F. (2012). <i>Specifying buildings: A design management perspective</i> . Routledge. |
| | | 4.3 Change Management: Training contractors and implementation technicians to deal with new technologies | (Training Plan) | [37]-Kotter, J. P. (1996). <i>Leading change</i> . Harvard Business Press. |
| Phase Five: Evaluation & Feedback | Verifying that actual performance matches expectations, and feeding the knowledge base | 5.1 Post-Occupancy Performance Evaluation: Measuring KPIs one year after the building is operational | POE (Post-Occupancy Evaluation Report) | [38]-Preiser, W. F., Rabinowitz, H. Z., & White, E. T. (1988). <i>Post-occupancy evaluation</i> . Van Nostrand Reinhold. [39]-Zimring, C., & Reizenstein, J. E. (1980). Post-occupancy evaluation: An overview. <i>Environment and Behavior</i> , 12(4), 429-450. |
| | | 5.2 Measuring user satisfaction: Questionnaires for patients and medical staff regarding the quality of the internal environment | (Satisfaction Survey Analysis) | [40]-Ulrich, R. S. (1991). Effects of interior design on wellness: Theory and recent scientific research. <i>Journal of Health Care Interior Design</i> , 3(1), 97-109. |
| | | 5.3 Adjustment and Configuration: Adjusting BMS settings based on evaluation results | (Commissioning Log) | [41]-ASHRAE. (2018). *ASHRAE Guideline 0-2018: The commissioning process*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. |
| | | 5.4 Documenting lessons learned: Adding new knowledge to the organization's "knowledge base" | Lessons Learned Report | [42]-Carrillo, P., Ruikar, K., & Fuller, P. (2013). When will we learn? Improving lessons learned practice in construction. <i>International Journal of Project Management</i> , 31(4), 567-578. |

11- Case studies analysis of smart materials and systems in hospital buildings:

1- Cleveland Clinic Abu Dhabi hospital building

- Project Description and Context

Location: Al Maryah Island, Abu Dhabi, United Arab Emirates.

Project Type: A multi-service specialty hospital with a capacity of 364 beds, expandable to 490 beds.

Area: 371,600 square meters.

Year of Opening: 2015 (Phase 1), 2019 (Phase 2).

Designer: HDR Architecture (USA) in collaboration with PERKINS+WILL.

Awards: Middle East Healthcare Interior Design Award 2016, LEED Gold certification.



Figure (8) shows Cleveland Clinic Abu Dhabi hospital building

Source :<https://www.hdrinc.com/portfolio/cleveland-clinic-abu-dhabi> 10-1-2023

- **Smart Materials and Smart Systems in Cleveland Clinic Abu Dhabi**

Cleveland Clinic Abu Dhabi (CCAD) represents a benchmark in the integration of smart materials and intelligent systems within healthcare infrastructure. Since its inception, the hospital has been designed and continuously upgraded to embody the concept of a "smart hospital," combining sustainable building materials with advanced cyber-physical systems. The analysis that follows organizes the various types of innovations into two major categories; Smart Building Materials (passively or semi-actively functioning physical building materials), and Smart Systems (the active technological networks/devices used to create and control buildings).

1. Smart Building Materials and Envelope Technologies

The building fabric of CCAD consists of sophisticated materials that passively act to assist in regulating energy use and controlling the environment of the building, which sets it apart from traditional hospital construction.

1.1. The Active Double-Skin Façade

One of the most important smart material uses is in the double-skin façade of the hospital. The double-skin façade (or building envelope) of the hospital serves as a dynamic thermal barrier. The exterior wall is a point-supported glazing system composed of diamond-shaped units and the interior wall is made up of a high-performance window wall system. Notably, the air cavity between the interior and exterior is not a passive system; it is supplied with exhaust air from the HVAC system. The exhaust air is ejected into the cavity at the base of the cavity and is drawn out of the cavity at the top of the cavity. By actively ventilating the inside of the exterior and inner façades, the air cavity dissipates the heat generated by the exterior façade (which can reach temperatures of up to 49°C) and significantly reduces the cooling load for the entire building. Overall, this double-skin system functions as a smart, responsive interface between the external environment and the internal conditioned spaces. <https://www.cdc-usa.com/projects/cleveland-clinic-abu-dhabi> 11-1-2023

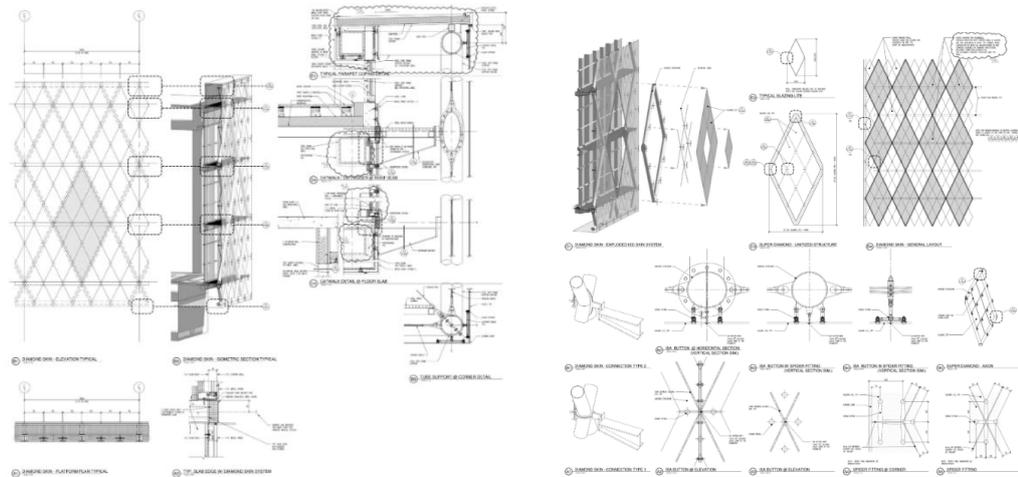


Figure (9) shows Double-Skin Façade details in Cleveland Clinic Abu Dhabi hospital building

Source : <https://archinect.com/Chi-ChungTsai/project/cleveland-clinic-abu-dhabi-hospital-and-clinic-buildings-5-2-2023>

1.2. High-Performance Interior Finishes

Strikingly strict worldwide health standards require, in the construction of the interior space, to use a particular grade of superior materials. The specifications outlined USG gypsums as the partitioning product and UL- approved doors. All of the products used must have extremely high levels of fire resistance and durability as well as meet the most rigorous guidelines for infection prevention and cleanroom construction in order to contribute to the LEED Gold designation of the hospital.

1.3. Sustainable and Green Materials:

The entire process of construction followed the principle of intelligent sustainability with a recycling rate of 75% as well as the use of methods to eliminate dust from construction practices. Additionally, the project implemented systems to recover waste heat produced from kitchen appliances and recover condensation from heating, ventilation, and air conditioning (HVAC) systems for reuse for cooling and landscaping irrigation - viewing the waste materials generated in that process as resources.

<https://www.clevelandclinicabudhabi.ae/en/about-us/annual-reports-10-5-2023>

2. Smart Systems for Clinical Excellence and Patient Care

In addition to its smart building envelope, CCAD also utilizes modern technology to

impact patient care and deliver smart buildings in the hospital. CCAD has been named the #1 Smart Hospital in the UAE and GCC by Newsweek magazine for utilizing smart systems that provide improved patient outcomes.

3. Building Management and Sustainability Systems

The intelligent building has advanced operational technologies to help manage the facility efficiently.

-Innovative HVAC technology: As a pioneer in the region, displacement ventilation allows for maximum efficiency and infection control through direct supply of air to occupied areas while reducing the cooling requirement.

-Building Information Modeling (BIM): The project's logistics were coordinated using this technology throughout the construction of the building, providing a better way to manage the large number of design and logistical aspects involved in the project.

-Continued implementation of retrofitting: The project is committed to ongoing development of smart systems. Two recent initiatives will support the use of advanced control/monitoring software (MatrixAir) to increase energy efficiency and provide optimal air flow through retrofitting of the Air Handling Units (AHU) serving the operating rooms. <https://www.worldhealthexpo.com/i>

nsights/sustainability/hospitals-spearhead-sustainable-healthcare-initiatives 9-4-2023

2- Ng Teng Fong General Hospital – Singapore

- Project Description and Context

Location: Jurong East, Singapore.

Project Type: Government General Hospital, 700 beds.

Area: 240,000 m².

Year of Opening: 2015.

Designer: CPG Consultants (Singapore) in collaboration with HOK (USA).

Total Cost: S\$780 million (approximately US\$580 million).

Awards: BCA Green Mark Platinum Award (Singapore's highest sustainability rating), FIABCI International Excellence Award 2016.



Figure (10) shows Ng Teng Fong General Hospital – Singapore

<https://www.archello.com/story/47383/attachments/photos-videos/11-5-2023>

Ng Teng Fong General Hospital (NTFGH) in Singapore is a pioneer in integrating smart architectural design with technological materials and systems and has been awarded the highest sustainability rating (BCA Green Mark Platinum). (Bulakh, et al.2020) [43].

1. Smart Materials & Design

- **Aerodynamic Building Envelope:** Unique fan-shaped building materials and facades were used. This design is not only aesthetically pleasing but also acts as a passive smart material, providing 100% natural ventilation to standard patient wards, thus reducing reliance on mechanical air conditioning.

- **External Sun-shading Fins:** The facades are equipped with precisely designed external sun-shading fins to deflect wind and provide shade. These fins are made of highly durable materials that reduce glare and heat while maintaining clear visibility.

- **Integrated Healing Gardens:** Green spaces are integrated into each floor as part of the building's structural fabric. These living materials act as natural air filters and thermostats for the indoor environment. <https://www.ttsh.com.sg/About-TTSH/TTSH-News/Pages/Ng-Teng-Fong-Centre-for-healthcare-innovation-opens-up-Singapore's-healthcare-to-the-world.aspx> 10-2-2023

2. Smart Systems:

- **Automated Logistics:** The hospital utilizes a fleet of automated guided vehicles (AGVs) equipped with robots to transport medications, food, and supplies throughout the hospital, minimizing human intervention and ensuring the most efficient flow of resources.

- **Patient-Centric Smart Systems:** Digital systems allow patients to customize their personal environment (lighting and entertainment) using their tablets and provide immediate access to vital information directly to the nursing center.

-Smart Energy Management: The hospital employs a highly efficient central cooling system that uses sensors to detect patient presence and monitor air quality, resulting in a 38% improvement in energy consumption compared to traditional hospitals.

- Smart Water Management: The hospital uses sensors to detect water leaks from its water sources and recycles greywater for garden irrigation. <https://www.hok.com/projects/view/ng-teng-fong-general-hospital-jurong-community-hospital-ntfgh-jch/10-2-2023>, <https://www.archello.com/project/ng-teng-fong-general-hospital-10-2-2023>

12- The results:

•Double-glazed facades can work well in desert climates: The findings of this study indicate that double-glazed facades (naturally ventilated) can function effectively, even in extreme climates. This goes against the popular opinion that they can only work well in moderate climates.

•Accurate simulation is crucial: The results from the study showed a 32% decrease in energy usage, while the simulation predicted a corresponding 35% decrease, which demonstrates the reliability of simulation programs when used appropriately.

•System integration is required for energy reduction: The smart facade alone did not result in these energy savings; this was achieved through an integration of the smart facade with a smart lighting system, occupancy sensors, and an advanced building management system (BMS).

• Allowing a patient to have manual control :(within certain limits) of their blind system increases the patient's level of satisfaction without adversely affecting energy usage.

• The additional expenditure for a double-glazed facade will be recovered over eight years: The time taken to pay back this investment is reasonable for large capital works given the expected life of the building (50+ years).

13- Recommendation:

•Adopt this methodology as a national hospital design code; it is recommended that this methodology be adopted as the approach to develop National Hospital Design Codes .

•In order to maximize the benefits of smart materials and systems for hospitals, a specific methodology for selecting “Smart” materials and systems that minimize energy and lighting use while minimizing the operational costs of the building should be used .

•Smart materials (such as facades) should not be considered as an independent component, but rather integrated into an overall integrated system consisting of Smart Lighting System (SLS) and occupancy sensors and an Advanced Building Management System (BMS), which ultimately leads to maximum energy efficiency.

•High-Precision Digital Simulation tools will be important in the early design phase; by running simulations throughout the process of creating & building a facility, designers will be able to see how the behavior of their materials and systems will look, and design mistakes can be avoided before actual construction starts.

14- References

- [1]-Huizenga, C., Abbaszadeh, S., Zagreus, L., & Arens, E. A. (2006). Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey.
- [2]-Addington, M. and Schodek, D. (2005) Smart Materials and New Technologies: For the Architecture and Design Professions. Architectural Press, Boston.
- [3]-Sobczyk, M., Wiesenhütter, S., Noennig, J. R., & Wallmersperger, T. (2022). Smart materials in architecture for actuator and sensor applications: A review. *Journal of Intelligent Material Systems and Structures*, 33(3), 379-399.
- [4]-Wong, L. T., Mui, K. W., & Fong, N. K. (2006). A humanized adaptive baseline information technology (HABIT) algorithm for a building management system. *Building Services Engineering Research and Technology*, 27(4), 341-347.

- [5]-Wong, J. K., Li, H., & Wang, S. W. (2005). Intelligent building research: a review. *Automation in construction*, 14(1), 143-159.
- [6]-Liang, X., Chen, K., Chen, S., Zhu, X., Jin, X., & Du, Z. (2023). IoT-based intelligent energy management system for optimal planning of HVAC devices in net-zero emissions PV-battery building considering demand compliance. *Energy Conversion and Management*, 292, 117369..
- [7]-Abdullah, Y. S., & Al-Alwan, H. A. (2019). Smart material systems and adaptiveness in architecture. *Ain Shams Engineering Journal*, 10(3), 623-638.
- [8]-Woll, A., & Tørresen, J. (2022). What is a smart hospital? A review of the literature. *Human-Automation Interaction: Manufacturing, Services and User Experience*, 145-165.
- [9]-Plageras, A. P., Psannis, K. E., Gupta, B., Stergiou, C., Kim, B. G., & Ishibashi, Y. (2017, July). Solutions for inter-connectivity and security in a smart hospital building. In *2017 IEEE 15th International Conference on Industrial Informatics (INDIN)* (pp. 174-179). IEEE.
- [10]-Kim, D., Yoon, Y., Lee, J., Mago, P. J., Lee, K., & Cho, H. (2022). Design and implementation of smart buildings: A review of current research trend. *Energies*, 15(12), 4278.
- [11]-Alsawaf, E. S., & Albadry, A. M. (2022). Principles for the sustainable design of hospital buildings. *International Journal of Sustainable Development and Planning*, 17(6), 1797-1808.
- [12]-Baharuddin, M. F., Lim, C. H., & Fazlizan, A. (2022). Enhancing the potential of smart building for general hospital: a case study in Malaysian hospital. *International Journal of Energetica*, 7(2), 33-40.
- [13]-Kaur, A., Bhatia, M., & Ahanger, T. A. (2023). Bibliometric analysis of smart healthcare. *IEEE Systems Journal*, 17(3), 3993-4001..
- [14]-Li, Y., Pan, X., Han, Y., & Lavy, S. (2022). From building information modeling to hospital information modeling. In *Research Companion to Building Information Modeling* (pp. 593-613). Edward Elgar Publishing.
- [15]-Rodrigues, L., Gonçalves, I., Fé, I., Endo, P. T., & Silva, F. A. (2021). Performance and availability evaluation of an smart hospital architecture. *Computing*, 103(10), 2401-2435.
- [16]-Aliero, M. S., Asif, M., Ghani, I., Pasha, M. F., & Jeong, S. R. (2022). Systematic review analysis on smart building: Challenges and opportunities. *Sustainability*, 14(5), 3009.
- [17]-Feng, B. & Li, P.& Yao, H.& Ji, Y& He, J. (2020) Developing a smart healthcare framework with an ‘Aboriginal lens ’, 7th International Conference on Information Technology and Quantitive Management, Elsevier.
- [18]-Ben Safar, S. (2019) A Review in Smart Homes Systems and Technologies.
- [19]-Badr, A. I. M. (2010). *Smart architecture as an approach to applying technological development in environmental control and energy conservation in buildings (An analytical study to evaluate the environmental performance of smart buildings)* [Master's thesis, Cairo University]. CairoUniversity Repository.
- [20]-Givoni, B. (1998). Climate considerations in building and urban design. John Wiley & Sons.
- [21]-Olgyay, V. (1963). Design with climate: Bioclimatic approach to architectural regionalism. Princeton University Press.
- [22]-Ulrich, R. S., Zimring, C., Zhu, X., DuBose, J., Seo, H. B., Choi, Y. S., ... & Joseph, A. (2008). A review of the research literature on evidence-based healthcare design. *HERD: Health environments Research & Design Journal*, 1(3), 61-125.
- [23]-Sanoff, H. (2007). Special issue on participatory design. *Design Studies*, 28(3), 213-215.
- [24]-Luck, R. (2003). Dialogue in participatory design. *Design Studies*, 24(6), 523-535.
- [25]-ASHRAE. (2021). *ASHRAE Handbook: Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- [26]-Preiser, W. F., & Vischer, J. C. (Eds.). (2005). *Assessing building performance*. Elsevier.
- [27]-CIBSE. (2015). *CIBSE Guide A: Environmental design*. Chartered Institution of Building Services Engineers.
- [28]-Beatham, S., Anumba, C., Thorpe, T., & Hedges, I. (2004). KPIs: A critical appraisal of their use in construction. *Benchmarking: An International Journal*, 11(1), 93-117.
- [29]-Ritter, A. (2007). *Smart materials in architecture, interior architecture and design*. Birkhäuser.
- [30]-Saaty, T. L. (2008). Decision making with the analytic hierarchy rocess. *International Journal of Services Sciences*, 1(1), 83-98.
- [31]-Keeney, R. L., & Raiffa, H. (1993). *Decisions with multiple objectives: Preferences and value trade-offs*. Cambridge University Press.

- [32]-Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., & Pedersen, C. O. (2001). EnergyPlus: New, capable, and linked. *Journal of Architectural and Planning Research*, 18(4), 292-302.
- [33]-Hensen, J. L., & Lamberts, R. (Eds.). (2011). *Building performance simulation for design and operation*. Routledge.
- [34]-Bachman, L. R. (2003). *Integrated buildings: The systems basis of architecture*. John Wiley & Sons.
- [35]-Reed, W. G., & Gordon, E. B. (2000). Integrated design and building process: What research and methodologies are needed?. *Building Research & Information*, 28(5-6), 325-337.
- [36]-Cox, B. J., & Hamilton, F. (2012). *Specifying buildings: A design management perspective*. Routledge
- [37]-Kotter, J. P. (1996). *Leading change*. Harvard Business Press.
- [38]-Preiser, W. F., Rabinowitz, H. Z., & White, E. T. (1988). *Post-occupancy evaluation*. Van Nostrand Reinhold.
- [39]-Zimring, C., & Reizenstein, J. E. (1980). Post-occupancy evaluation: An overview. *Environment and Behavior*, 12(4), 429-450.
- [40]-Ulrich, R. S. (1991). Effects of interior design on wellness: Theory and recent scientific research. *Journal of Health Care Interior Design*, 3(1), 97-109.
- [41]-ASHRAE. (2018). *ASHRAE Guideline 0-2018: The commissioning process*. American Society of Heating, Refrigerating and Air-Conditioning Engineers
- [42]-Carrillo, P., Ruikar, K., & Fuller, P. (2013). When will we learn? Improving lessons learned practice in construction. *International Journal of Project Management*, 31(4), 567-578.
- [43]-Bulakh, I., Didichenko, M., Kozakova, O., & Chala, O. (2020). Sustainable futures in the context of architectural design of hospitals. In *E3S Web of Conferences* (Vol. 166, p. 08001). EDP Sciences.