AI-based Intelligent Window System for Hospitals in GCC Countries

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Abstract.
Climate change stands as a formidable challenge on a global scale, manifesting through alterations in weather patterns and regional ecosystems, with the Gulf region, in particular, facing pronounced shifts due to its distinct climate and high vulnerability to such changes. These environmental shifts have far-reaching effects, not least on the operational dynamics and internal conditions of hospitals establishments pivotal to the delivery of critical healthcare services. Recognizing the urgent need to address these climatic impacts within healthcare settings, this paper introduces a cutting-edge solution: an artificial intelligence (AI)-powered intelligent window system specifically designed to enhance the hospital environment by mitigating the adverse effects of climate change. These smart windows are engineered to process and react to real-time weather data alongside a variety of relevant environmental inputs, enabling them to dynamically modify their functional properties ranging from filtering capabilities to ventilation mechanisms. This adaptive functionality aims to maintain or improve the indoor environmental quality, ensuring that it remains conducive to patient care and staff well-being. Beyond mere environmental control, the system is innovatively tailored to integrate patient-specific health information and preferences, allowing for the customization of key environmental parameters such as lighting levels, ambient temperature, and air quality. This level of personalization is intended to foster an atmosphere that not only promotes healing and comfort but also significantly enhances the patient experience by supporting the overall recovery process. Through this comprehensive approach, our proposed intelligent window system aspires to bridge the gap between technological innovation and healthcare service enhancement, offering a proactive response to the challenges posed by climate change in the healthcare sector.

Keywords: Intelligent Windows, Air Quality, Artificial Intelligence, Hospital, Sensors.

1 Introduction

Climate change is a global phenomenon that has significant implications for various aspects of life, including the environment, economy, and public health. The countries of the Arab (GCC) are particularly vulnerable to the effects of climate change due to their unique geographical location and arid climate.

The GCC countries have been witnessing significant alterations in climate dynamics, marked by shifting weather patterns and a rising occurrence and severity of extreme weather phenomena such as intense heatwaves, pervasive dust storms, and episodes of heavy rainfall. These climatic variations pose substantial challenges to the region's ecosystems, undermining biodiversity and disrupting natural habitats. Moreover, the resilience of critical infrastructure is tested by these extreme conditions, necessitating advanced planning and reinforced constructions to mitigate potential damages and ensure continuity of essential services.

Beyond environmental and infrastructural implications, the human health dimension within the GCC region is profoundly affected by these climatic shifts. The hospital environment, a cornerstone for public health and well-being, finds itself on the frontline, facing direct and immediate impacts from the changing climate. The increase in temperature and air pollution exacerbates health issues such as respiratory ailments, heat-related illnesses, and conditions triggered by poor air quality, leading to a higher demand for healthcare services.

Hospitals, designed as sanctuaries of healing, must adapt to these evolving environmental challenges to maintain and enhance their capacity to provide care. This involves not only structural and operational adjustments to withstand extreme weather events but also an increased focus on indoor environmental quality (IEQ) [1].

Hospitals are crucial institutions that provide essential healthcare services to the population. However, they are not immune to the effects of climate change. The changing climate poses significant challenges to the hospital environment, affecting the well-being of patients and the ability of healthcare professionals to deliver quality care. Extreme heatwaves, for example, can strain the cooling systems of hospitals, leading to increased energy consumption and decreased indoor air quality. Dust storms can introduce fine particulate matter into hospital facilities, potentially exacerbating respiratory conditions and compromising the health of patients and staff. Heavy rainfall events can result in flooding, further disrupting hospital operations and risking the spread of waterborne diseases [2, 3].

Recognizing the urgent need to address the impact of climate change on hospitals in GCC countries, innovative solutions are required to enhance the hospital environment and ensure the delivery of effective healthcare services. In this context, the integration of intelligent window systems based on artificial intelligence (AI) technology emerges as a promising approach.

In this paper we present an intelligent window system that leverages AI to adaptively respond to the changing climate conditions in GCC hospitals. By utilizing real-time weather data and considering the unique health challenges faced by patients, these intelligent windows can optimize the indoor environment, promoting patient comfort, well-being, and recovery. Through the implementation of intelligent window systems, GCC hospitals can mitigate the adverse effects of climate change, improve energy efficiency, and create a resilient healthcare infrastructure capable of providing quality care in the face of evolving environmental challenges.

The paper will be organized as follows. Section 2 will explore the different types of filters commonly used in hospitals to maintain indoor air quality, emphasizing their role in reducing airborne contaminants, allergens, and pathogens. Section 3 will focus on the design of the intelligent window system based on AI technology. Section 4 will cover the implementation of the intelligent window system and present the results obtained, highlighting improvements in energy efficiency, patient comfort, and overall hospital environment. Finally, we will summarize the potential of intelligent windows to mitigate the impact of climate change on hospital environments and the importance of further research and development in this area.

2 Hospital environments in GCC countries

2.1 Climate Change Impacts on Hospital Environments

The geographic location of GCC countries have the first impact to weather and climatic changes. These countries are situated in the Arabian Peninsula, which is known for its arid and desert-like conditions. As a result, the climate in GCC countries is characterized by: Extreme Heat, Sandstorms, Humidity etc.

As result, the unique climatic conditions in GCC countries have a significant impact on hospital environments, necessitating the implementation of several measures to ensure a healthy and comfortable indoor environment for patients, doctors, and staff [4, 5]. In order to maintain a safe and conducive environment for patient care, hospitals must address various environmental challenge:

- Extreme Heat: Hospitals need to ensure efficient cooling systems to maintain comfortable indoor temperatures for patients, staff, and medical equipment. Adequate insulation, ventilation, and air conditioning are crucial to create a suitable environment for patient care and to prevent heat-related complications.
- Sandstorms: Hospitals must have appropriate filtration systems in place to maintain clean air quality and protect patients and staff from respiratory issues associated with sand and dust particles.
- Humidity: Excessive humidity can affect the performance of medical equipment, increase the risk of microbial growth, and impact the comfort of patients and staff. Hospitals need to implement effective humidity control measures to mitigate these challenges.
- Seasonal Allergies: Hospitals should be prepared to manage and treat allergic reactions, ensuring proper ventilation and filtration systems to minimize pollen infiltration.
- Tropical Cyclones: Hospitals need to have robust disaster management plans in place to ensure the safety of patients, staff, and critical infrastructure during such events.

Window opening behavior in maternity hospital wards plays a crucial role in creating a healthy and comfortable recovery environment through natural ventilation. Unlike other building types, maternity hospitals have unique window operation characteristics due to their 24-hour occupancy. Despite its importance, global research on this behavior in maternity hospitals is scarce. To address this gap, a study was conducted analyzing and modeling window operation data from a Beijing maternity hospital during the summer, using statistical methods and a random forest (RF) algorithm [21]. The study considered nine factors across three wards and a doctors' office, revealing distinct patterns in window opening probabilities—ranging from 10 to 65% in the wards, compared to a consistent ~70% in the doctors' office. Notably, outdoor PM2.5 concentration emerged as a significant factor affecting window status in both room types. The RF model demonstrated satisfactory prediction accuracy, offering a reliable reference for hospital building modeling. This research not only enhances the understanding of window opening behavior in hospitals but also serves as a valuable resource for future building modeling studies.

2.2 Filters in Hospital Environments

According the literature reviews our study various types of filters in hospitals are present to serve the purpose of ensuring cleanliness and maintaining high indoor air quality. These filters play a crucial role in creating a healthy and safe environment within the hospital premises. By employing different types of filters, hospitals can effectively remove impurities and contaminants from the air, thereby promoting a clean and quality indoor atmosphere. These filters are instrumental in mitigating the spread of airborne pathogens and allergens, contributing to the overall well-being of patients, doctors, and staff within the hospital setting [6, 7, 8]. Below the different filters used by hospital [9, 10]:

- High-Efficiency Particulate Air (HEPA) Filters: HEPA filters are highly effective in capturing microscopic particles, including bacteria, viruses, and allergens. They have a high filtration efficiency, typically removing 99.97% of particles that are 0.3 micrometers or larger in size.
- Activated Carbon Filters: Activated carbon filters are designed to remove odors, gases, and volatile organic compounds (VOCs) from the air. These filters contain activated carbon, which has a large surface area and can adsorb and trap various chemicals and odorous substances [18].
- Ultraviolet (UV) Light Filters: UV light filters utilize ultraviolet radiation to kill or inactivate microorganisms such as bacteria, viruses, and molds. These filters are often used in conjunction with other filtration systems to provide an additional layer of protection against airborne pathogens.
- Electrostatic Filters: Electrostatic filters use an electrostatic charge to attract and capture airborne particles. These filters are particularly effective in trapping larger particles such as dust, pollen, and pet dander. They can be either washable or disposable.
- Molecular Filters: Molecular filters, also known as gas-phase filters, are designed to remove specific gases, chemicals, and odors from the air. These filters contain chemically treated media that can absorb or react with targeted pollutants.

• Pre-Filters: Pre-filters are the first line of defense in air filtration systems. They capture larger particles such as dust, hair, and lint, preventing them from reaching the main filters. Pre-filters help prolong the lifespan of more specialized filters by reducing the load of larger particles.
• Antimicrobial Filters: Antimicrobial filters are treated with antimicrobial agents that inhibit the growth of bacteria, fungi, and other microorganisms. These filters help maintain a hygienic environment and prevent the spread of airborne pathogens.

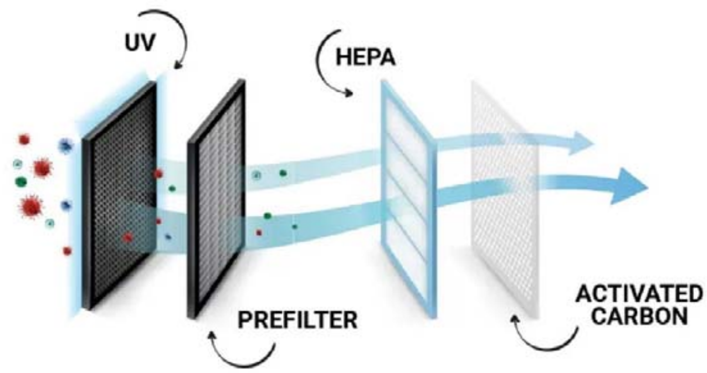


Fig. 1. Various filters types [17].

2.3 Literature review

In this section, we delve into an array of research works that bear relevance to our study, specifically focusing on the pivotal role that indoor air quality plays in sustaining healthy environments within hospital settings. These studies underscore the critical importance of maintaining optimal air conditions, highlighting how such environmental factors are integral to ensuring the overall well-being and recovery of patients. By examining the existing literature, we aim to establish a comprehensive understanding of the methodologies, outcomes, and implications of improving air quality in healthcare facilities, thereby drawing valuable insights and parallels to enhance the foundational knowledge underpinning our research on intelligent window systems designed for hospitals. This exploration not only contextualizes our work within the broader spectrum of environmental health in medical institutions but also reinforces the necessity of adopting innovative solutions to address the challenges posed by indoor air quality in these critical settings.

Javiera et al. [13] explore the impact of natural lighting on the emotional wellbeing of individuals in residential indoor environments during the COVID-19 pandemic. With more people spending a significant amount of time working, living, and studying at home, understanding the factors that influence emotions becomes crucial. Through a randomized control trial involving 750 participants, the study examines the hypothesis that natural lighting improvements in housing contribute to residents' emotional subjective wellbeing (E-SWB). The findings highlight the significant influence of natural lighting conditions on people's perceptions of happiness and sadness, with increased daylight entering the home having the most significant impact.

Cesari et al. [14] examine the impact of different window sizes and glazing types on the energy demand of a hospital patient room. While large fenestration systems are typically avoided in hospitals due to potential energy inefficiency, this research explores the potential energy savings and positive effects on patient and staff well-being that can be achieved with well-designed windows. Simulations were conducted using nine different glazing systems, considering two window areas: a common size opening with a 25% Window-to-Wall Ratio (WWR) and a floor-to-ceiling window with a 77% WWR. The analysis also considered various orientations in four Italian cities and two lighting control strategies. The findings reveal that installing wider windows with appropriate glazing and a daylight-linked dimming lighting control strategy can reduce primary energy demand by up to 17%.

Shahryar Habibi [15] presents on the application of a real-time monitoring system to optimize indoor environmental quality (IEQ) in office buildings. It emphasizes the use of information and communication technology (ICT) and building information modeling (BIM) from an architectural perspective. By integrating ICT applications, buildings can establish connections between users and building systems to enhance energy efficiency and comfort. The research aims to showcase advancements in energy efficiency and management strategies through a cost-effective ICT application. The study conducts daylight and energy performance simulations to explore how users can leverage natural environmental factors during occupied hours in office buildings. The findings highlight the significance of user-centric approaches in improving IEQ and energy efficiency. The results further support the implementation of real-time monitoring systems in office buildings, suggesting the need for individual user control over thermal, ventilation, and lighting systems.

Yan et al. [11] focus on developing a smart control framework to reduce indoor PM2.5 concentrations while maintaining thermal comfort in residential environments. The framework combines a portable home air purifier (HAP) and a window control system. The study also evaluates the associated health impacts and additional energy use. Through a simulation-based case study of a low-energy apartment, the results demonstrate that the joint control of HAP and window openings effectively removes PM2.5 while maintaining thermal comfort. This approach leads to significant health benefits at a low additional energy cost. The proposed control framework stands out by integrating window operations and HAPs within the same system, considering both thermal comfort and indoor PM2.5 as control targets. Additionally, the study introduces the concept of linking a building control system with a health impact assessment, showcasing a holistic and responsive approach to building controls.

Neil et al. [20] Designs a new Intensive Care Unit (ICU) requires a clear vision focused on ensuring that the patient room remains central to the ICU experience for patients, staff, and visitors. The ICU layout is divided into three main components: patient rooms, central areas, and universal support services. Each patient room, designed for individual use, should be uniformly equipped and laid out to prioritize functionality, ease of use, healing, safety, infection control, communication, and connectivity. The comprehensive design incorporates the room's infrastructure, designated zones for work, care, and visits, environmental controls, medical devices, privacy measures, logistics, and waste management. Given the advanced nature of medical devices, which essentially function as sophisticated computers, the ICU's design must also support extensive medical informatics. A balanced approach to monitoring and logistics, both centralized and decentralized, enhances flexibility. Moreover, aligning the ICU's support services with the hospital's broader systems ensures consistency and continuity, avoiding redundancy and promoting a unified operational purpose.

3 Intelligent Windows Design

The intelligent window system utilizes AI algorithms to continuously monitor and analyze the air quality within hospital rooms. By integrating a multi-filter system consisting of various filtration mechanisms, including HEPA filters, activated carbon filters, and antimicrobial filters, the intelligent window can efficiently remove contaminants, allergens, pathogens, and odors from the incoming air [12]. This comprehensive filtration process helps create a healthier environment, reducing the risk of airborne infections and promoting faster recovery for patients with specific medical conditions [17, 19].

The AI component of the system enables real-time monitoring of air quality parameters, such as particulate matter levels, humidity, temperature, and volatile organic compounds (VOCs). By continuously analyzing these parameters, the intelligent window can dynamically adjust the filtration process to ensure optimal air quality at all times. Additionally, the system can learn and adapt to specific patient needs, providing personalized air quality settings based on individual requirements.

The proposed intelligent window system offers several advantages over traditional ventilation systems in hospitals. It provides targeted filtration, reducing the spread of airborne contaminants while maintaining a fresh and healthy environment. Furthermore, the AI-based monitoring and control allow for proactive maintenance, ensuring the system operates optimally and alerting hospital staff in case of any anomalies as shown in figure 2.

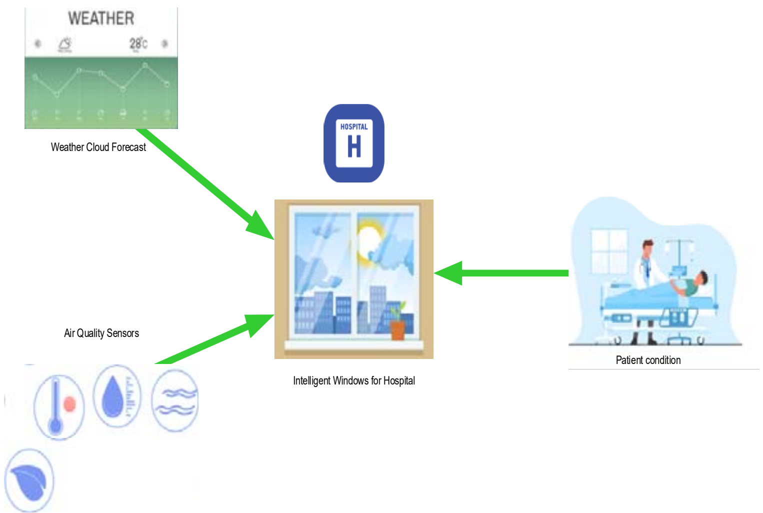


Fig. 2. Different inputs for the intelligent windows

The proposed system has three levels of inputs. First, it establishes a direct link with real-time weather cloud forecasts, providing information about the current weather conditions as well as forecasts for the upcoming hours and days. Mainly, these information are very important for emergency cases such as dust storms.

Second, the system incorporates various sensors to measure different parameters both outside and inside the hospital, enabling real-time monitoring of the air quality in these areas. Further, these sensor use the wireless sensor network technology in order to satisfy the large scale of the building.

Third, patient conditions or medical reports are utilized to determine the appropriate indoor environment for patients. An AI-based algorithm is employed to analyze these inputs and make informed decisions regarding the air quality management. Indeed, an AI-based algorithm is developed using machine learning techniques to assess the patient's situation and determine the suitable environment for them. Specifically, in long-term cases such as coma patients, the algorithm can continuously analyze and update the patient's medical reports to adapt the indoor conditions accordingly.

Furthermore, our approach includes leveraging the recovery processes of similar medical cases as a dataset for training our machine learning models. This dataset, enriched with detailed patient histories, provides a wealth of information that is instrumental in refining the algorithm's decision-making capabilities. Specifically, a multitude of factors are taken into account to fine-tune our system's responses, including but not limited to the patient's age, their specific medical conditions, gender, and a series of periodic medical reports. By integrating these diverse variables, we aim to construct a comprehensive profile that reflects the overall health status of each patient.

This nuanced understanding allows our algorithm to make more informed decisions, tailored to the unique needs of individual patients. The inclusion of periodic medical reports as part of the dataset is particularly crucial, as it enables the continuous updating of patient profiles, ensuring that the care environment evolves in tandem with the patient's recovery journey. By systematically analyzing this multifaceted data, our machine learning models can identify patterns and correlations that may not be immediately obvious to human observers. This capability not only enhances the precision of our environmental adjustments but also contributes to a dynamic and responsive care strategy that actively supports the patient's recovery. Ultimately, our goal is to harness the power of machine learning to create an adaptive healthcare environment that is both reactive and proactive, adjusting in real-time to the changing needs of patients and fostering conditions most conducive to their health and well-being.

4 Implementation of the Intelligent Window

The proposed system is divided into two parts. The first part involves implementing the hardware component using an IoT solution. This includes deploying various sensors and devices to measure and monitor different parameters related to air quality. The second part utilizes a cloud application to collect the information gathered by the different inputs mention in the section 3. The cloud application processes and analyzes the data before generating appropriate orders or actions based on the insights derived. Our AI-based system is implemented in cloud to ensure the real-time process as shown in figure 3.

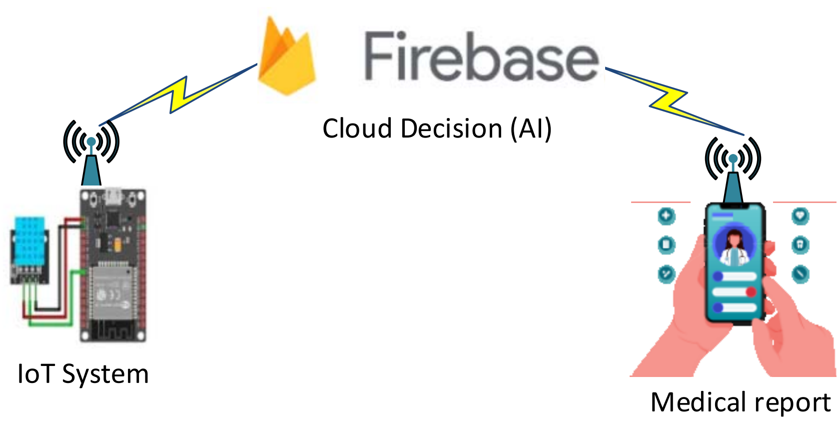
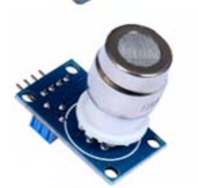


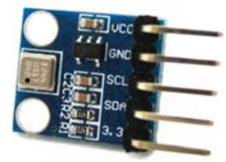
Fig. 3. AI-based Intelligent Window Design

4.1 Hardware Design

Drawing upon data from weather forecasts and real-time information sourced directly from weather stations, we have implemented a comprehensive array of sensors designed to monitor air quality continuously. These sensors are strategically deployed to capture a wide range of environmental parameters, ensuring that our system remains responsive to both external weather conditions and internal air quality levels. Table 1 provides a detailed overview of the various sensors utilized in our setup, including specifications on their type, sensitivity, and the specific environmental factors they monitor. This multi-faceted approach to data collection allows us to gather precise and up-to-date information on environmental conditions that could impact the indoor atmosphere of healthcare facilities. By integrating data from both weather forecasts and our network of sensors, we can achieve a holistic understanding of the environmental context. This enables the system to make informed decisions about adjusting indoor conditions to maintain optimal air quality for patient health and comfort. The deployment of these sensors plays a critical role in our ability to provide a safe, comfortable, and healing environment, adapting in real-time to changes in both the internal and external milieu.

Table 1. Different type of sensors used in the proposed system.

Sensor	Function	Schematic
Laser PM2.5 Sensor (HM3301)	Laser dust detection sensor, which is used for continuous and real-time detection of dust in the air.	
MG811 Carbon Dioxide CO2 Sensor	CO2 sensors are used to monitor the concentration of carbon dioxide in the air.	
Gas Sensor (O2)	Measure the current oxygen concentration	
Temperature & Humidity Sensor (SHT31)	Measure with high accuracy the temperature and humidity	

Pressure Sensor BMP180 Digital	Measure accurate atmospheric pressure	
RM5.00 Light sensor	measure the intensity of light in the environment	

The figure 4 show the different connection of this sensors to our microcontroller (ESP32).

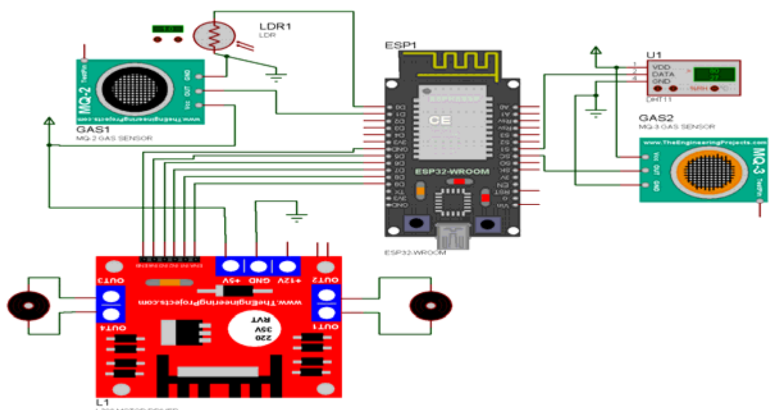


Fig. 4. Hardware part of the intelligent windows

For the simulation, we created various scenarios based on room size to measure light intensity, power consumption, and the air quality index. The size of a single-patient hospital room in our study ranges from 16 m² to 22 m².

The Air Quality Index (AQI) is a tool used to communicate how polluted the air currently is or how polluted it is forecast to become. The AQI is calculated as follows:

$$AQI = \left(\frac{I_{high} - I_{low}}{C_{high} - C_{low}}\right) \times (C - C_{low}) + I_{low} \qquad (1)$$

Where:

- C is the concentration of the pollutant

- C_{low}, C_{high} *are the concentration breakpoints that bracket* C
- I_{low}, I_{high} *are the AQI values corresponding to* C_{low}, C_{high}

The AQI scale, defined by the US Environmental Protection Agency (EPA) [22], ranges from 0 to 500, divided into six categories that signify increasing levels of health concern from "Good" to "Hazardous" as shown in table 2.

Table 2. AQI category.

AQI category	Index Values	Description
Good	0 - 50	Air quality is considered satisfactory, and air pollution poses little or no risk.
Moderate	51 – 100	Air quality is acceptable; however, there may be a risk for some people, particularly those who are unusually sensitive to air pollution
Unhealthy for Sensitive Groups	101 – 150	Members of sensitive groups may experience health effects. The general public is not likely to be affected
Unhealthy	151 - 200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects
Very Unhealthy	201- 300	Health warnings of emergency conditions. The entire population is more likely to be affected
Hazardous	301 - 500	Health alert: everyone may experience more serious health effects

The simulation scenarios was baesd on the size of the hospital room which it select as the standard in GCC countries from 16 m² to 22 m². Further, we evaluate the light intensity as show in figure 5. The light intensity is higher for the room with size 16 m² than the others based on the size of the window which is the same.

We notice that the energy consumption decrease based on the room size which it is less than the normal average which is 650 watt per day as shown in figure 6. Furthermore, the study highlights a consistent maintenance of air quality within the range of 20 to 50, categorizing it within the 'Good' index category. This consistency underscores the effectiveness of the implemented air quality management strategies, which may include regular ventilation, use of air purifiers, and maintenance of optimal humidity levels. Such measures contribute to an indoor environment that not only promotes the well-being and comfort of occupants but also aligns with health and safety standards.

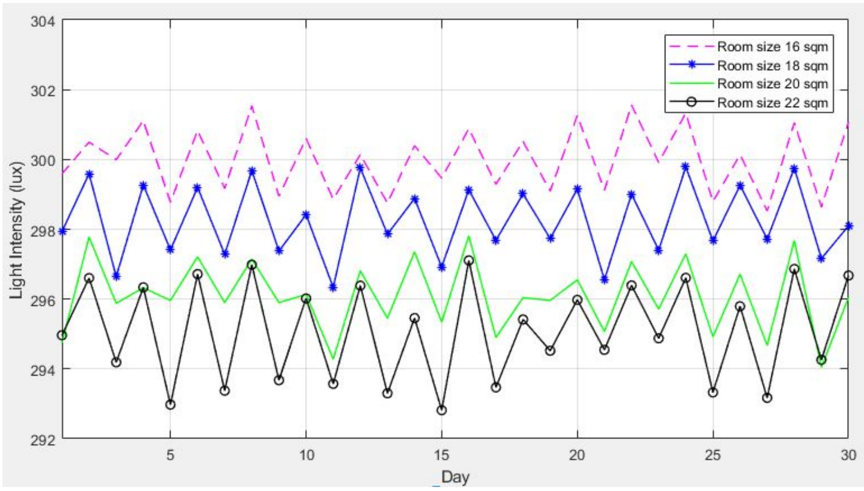


Fig. 5. Natural light intensity

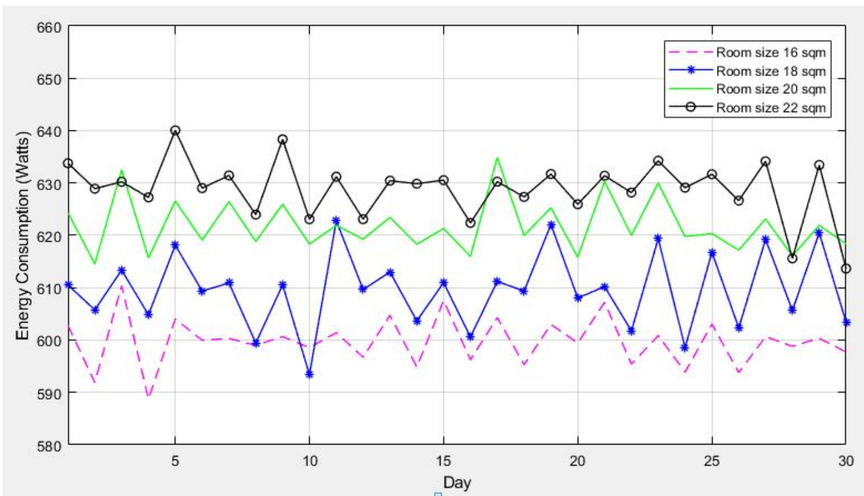


Fig. 6. Energy consumption

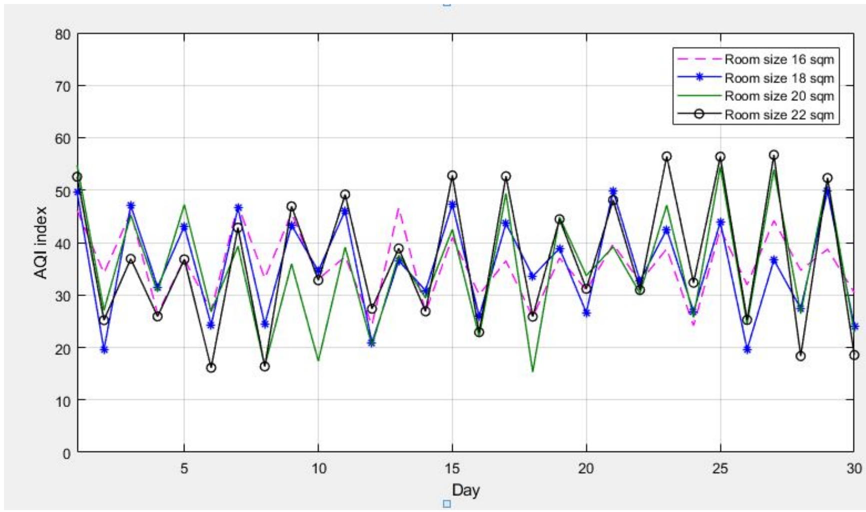


Fig. 7. Air quality AQI index

4.2 AI-based machine learning

This section delves into the utilization of AI-driven machine learning techniques to ascertain the most effective operation of the intelligent window system, tailored specifically to align with the insights gleaned from patient reports. Our focus extends to scenarios that necessitate prolonged hospital stays due to acute exacerbations of chronic illnesses, including Chronic Obstructive Pulmonary Disease (COPD), heart failure, and diabetes. These conditions often require meticulous environmental control to facilitate patient recovery and comfort, making the intelligent window's adaptability crucial.

The machine learning model, illustrated in Figure **, embodies the core of our system's ability to dynamically adjust the hospital room's conditions. By integrating real-time data from weather forecasts, indoor environmental parameters, and specific patient health information, the model predicts the optimal window settings for ventilation, light intensity, and temperature regulation. The predictive model is based on a comprehensive dataset that includes historical patient outcomes, environmental conditions, and treatment durations for similar health scenarios. Further, we predict the recovery time δ in days for patients based on three factors:

- Average daily temperature x_1 during the patient's stay (in °C).
- Severity score from the medical report x_2, on a scale of 1 to 10.
- Current health status x_3, encoded as 0 (stable), 1 (moderate), or 2 (critical).

Our prediction model βcould be represented by a linear equation of these variables:

$$\delta = \theta_0 + \theta_1 x_1 + \theta_2 x_2 + \theta_3 x_3 + \varepsilon \qquad (2)$$

Where:

- δ is the predicted recovery time.
- θ_0 is the y-intercept, representing the base recovery time irrespective of the input features.
- $\theta_1, \theta_2, \theta_3$ are the coefficients for each of the input features, representing how much each factor weighs into the recovery time.
- x_1, x_2, x_3 are the input features mentioned above.
- ε is the error term, capturing the deviation of our predictions from actual recovery times.

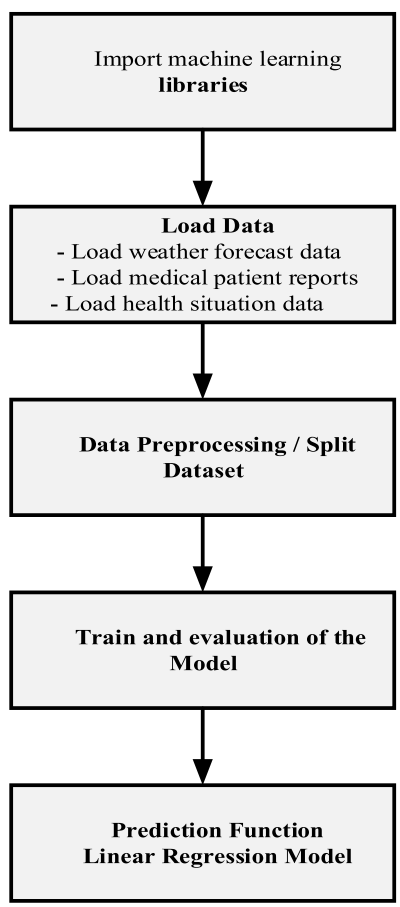


Fig. . Hardware part of the intelligent windows

5 Conclusion

The AI-based Intelligent Window System for hospitals in GCC countries offers a promising solution for enhancing the indoor environment and patient experience. This system brings several benefits, including optimized natural lighting, improved thermal comfort, and enhanced energy efficiency. It also considers factors such as outdoor temperature, humidity, air quality, and patient preferences to create a comfortable and healing environment. The AI component enables intelligent decision-making and continuous learning, allowing the system to adapt and optimize its operations over time. By integrating AI algorithms with smart window technology, the system can dynamically adjust window settings based on real-time data and patient needs. In fact, as future works we try to implement in order to evaluate and analyses the different benefits already mention before.

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