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"Gheorghe Asachi" Technical University of Iasi, Romania

THERMAL COMFORT AND VENTILATION CONDITIONS IN HEALTHCARE FACILITIES - PART 2: IMPROVING INDOOR ENVIRONMENT QUALITY (IEQ) THROUGH VENTILATION RETROFITTING

Mawara Khan[1], Muhammad Jamaluddin Thaheem[2*], Musfira Khan[3], Ahsen Maqsoom[4], Muhammad Zeeshan[5]

[1]Department of Construction Engineering & Management, School of Civil and Environmental Engineering, National University of Sciences and Technology, Islamabad, Pakistan
[2]School of Architecture and Built Environment, Faculty of Science, Engineering & Built Environment, Deakin University, Geelong, Australia
[3]Department of Computer Science, School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Islamabad, Pakistan
[4]Department of Civil Engineering, COMSATS University Islamabad, Wah Campus, Pakistan
[5]Institute of Environmental Sciences and Engineering, School of Civil and Environmental Engineering, National University of Sciences and Technology, Islamabad, Pakistan

Abstract

The basic purpose of a hospital is to provide a cure to the ailing patients. Since the patients are already suffering from ailments, the hospital must be a place for comfort and mental peace. Indoor Environmental Quality plays a vital role in maintaining that comfort. The hospital building must be designed on the standards to provide the required thermal comfort. If the building is already built and operational, retrofitting techniques are used to maintain the standard values of indoor environmental quality. In this study, three indoor environmental quality parameters (temperature, relative humidity, and CO_2) are identified after quantitative analysis. Each of the parameters correlates with ventilation rates of the selected location. Based on that relation, the required range of ventilation rates was calculated by simulation of equations, identified from the literature. AnyLogic7 was used for the modeling and simulation of the equations. For the required ventilation rates, retrofitting techniques providing optimum cost and efficiency were identified for each location. It was concluded that the existing indoor environmental quality of hospital buildings can be improved with suitable retrofitting techniques, which can increase the efficiency of the HVAC system, resulting in overall reduced energy consumption.

Keywords: AnyLogic7, hospital building ventilation, HVAC system, indoor air quality, retrofitting

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1. Introduction

Hospitals are designed to provide healthcare services to cure ailments. But if the environment of a hospital is uncomfortable and contaminated, it will cause the spread of diseases, resulting in prolonged hospitalization (Capolongo et al., 2017; Graves et al., 2007). Not only the patients but healthcare professionals including doctors, nurses, and other paramedical staff are also affected by this polluted environment (Capolongo et al., 2017). Owing to the impact of healthcare facilities on the health and safety

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[*]Author to whom all correspondence should be addressed: e-mail: jamal.thaheem@deakin.edu.au, Phone: +61 3 522 73716

of its occupants, the role of their design and engineering becomes important (Lee and Kim, 2008). The accurate and clever design of a healthcare facility is imperative to achieving wellness standards and maintains healthy Indoor Environment Quality (IEQ). In that, air conditioning systems and air supply modes are the basic design elements of a healthcare facility for achieving IEQ standards (Yu et al., 2009).

IEQ and building energy efficiency have a directly proportional relationship. To improve IEQ, it is required to modify the building design, occupancy levels, and operational and maintenance services. Consequently, these changes will improve the energy utilization of buildings (Habibi, 2016; Prabatha et al., 2019). Measures that are taken to improve IEQ in a building directly impact the energy consumption of any ventilation system and enhance the efficiency of the installed system (Fisk, 2000).

In the United States, the trend of improving IEQ by the means of retrofitting technology for the energy efficiency of buildings is increasing (Jacobs et al., 2007). Many factors influence indoor environmental quality such as comfortable indoor temperature, air quality, acoustic quality, odor quality, and visual comfort (Abbaszadeh et al., 2006; Angelova, 2016; Asadi et al., 2017). Fungus, bacteria, and other indoor air pollutants are the cause of bad IEQ (Sautour et al., 2007). Indoor environment quality is a relative measure of comfort perception by people exposed to indoor conditions (Piasecki et al., 2017). Thermal comfort is measured by several parameters such as draughty-ness, the velocity of air, indoor temperature, and moisture content in the air while indoor CO_2 is the basic indicator of ventilation rates (Wan et al., 2011). Research has identified the major sources of indoor CO_2 as combustion sources, biologic sources, and other sources (radon, volatile and semi-volatile organic compounds, and formaldehyde) (Alberts, 1994). But in hospitals, combustion sources are rarely installed in form of gas heaters in a winter, which is not the case in the current study, while other sources such as volatile and semi-volatile compounds are likely to be present for medical use. Biological sources are referred to as the occupants, which are the main source of indoor CO_2 concentrations.

IEQ of various buildings is assessed in the past (Chao and Hu, 2004b). For example, academic institutes are vastly evaluated for their indoor environmental quality (Annesi-Maesano et al., 2013; Asif et al., 2018; Branco et al., 2015; Cartieaux et al., 2011; de Gennaro et al., 2014) and comfortable levels for the occupants are defined (Khodakarami and Nasrollahi, 2012; Lomas and Giridharan, 2012; Pourshaghaghy and Omidvari, 2012). Also, healthcare facilities are assessed for their IEQ level and it is noticed that such studies are mainly carried out in cold regions like Canada, the USA, the UK, and Europe (Candanedo and Feldheim, 2016; St-Jean et al., 2012; Wei et al., 2015). There are few studies on hot and humid areas such as recent research about the inpatient department of a Chinese hospital to physically measure the IEQ and compare it to occupant satisfaction through a questionnaire survey. It was concluded that the practical exposure of IEQ to the users was relatively worse as compared to the analysis of measurements recorded through devices (Tang et al., 2019). Similarly, a study of the three parameters of IEQ (temperature, relative humidity, and bacteria) was carried out for three Portuguese hospitals. The basic purpose was to recognize the improvement of indoor air quality management by real-time data collection for the selected parameters. The results showed evidence of a higher risk of bad indoor air quality with higher occupancy rates; even natural ventilation was not effective in that scenario. The study suggested exploring more mechanical approaches as well as modified techniques for natural ventilation (Fonseca et al., 2019). Another study analyzed the thermal comfort of the occupants by applying the predicted mean vote (PMV) phenomenon. The study was carried out in two healthcare facilities of a tropical region of Bangkok and the recorded data was compared to ASHRAE standards of thermal comfort. It was observed that the formulated PMV model was not endorsed by the subjective staff comfort levels and careful integration of thermal comfort levels for healthcare facility occupants satisfaction was suggested (Sattayakorn et al., 2017). In another study conducted in a hot and humid region of Pakistan, the researchers attempted to design a naturally ventilated tower to reduce energy consumption and utilize maximum natural resources. As a result, a total of 8ºC temperature was reduced by using naturally ventilated assembly. Hence, it is considered that this phenomenon is workable in that region (Sohail, 2017).

Along with the assessment of existing IEQ, studies are also carried out to improve the IEQ through various techniques and devices. A recent study explained that source control is the generally preferred practice of the improvement of IEQ. However, its financial factor and technical constraints have made it an impracticable approach. Secondly, the approach toward natural ventilation has its limitations if the outer environment is not appropriate for the IEQ. Though, if the techniques are modified, both approaches tend to perform well in the case of IEQ (Kelly and Fussell, 2019). Subsequently, researchers have also focused on gadgets for improved IEQ. For example, a device named “Open-source Smart Lamp” is developed based on wireless sensor technology. This device is the part of the building automation system and is programmed to control the lighting and IEQ for the pre-defined required range of parameters (Salamone et al., 2017). Usually, green buildings are also considered as the best in practice for IEQ and occupant comfort. Contrary to this concept, a research was performed on LEED’s (Leadership in Energy and Environmental Design) green-certified office buildings, resulting into the fact that high scores in IEQ assessment by the organization does not practically indicate the comfort level of occupants and workplace satisfaction (Altomonte et al., 2019).

Although studies addressing the three comfort parameters (temperature, relative humidity, and CO_2)

are reported in a multiple disciplinary public building like healthcare facility, there is a need to evaluate and suggest remedies to improve IEQ and comfort levels in a hot and humid region like Pakistan. The country is a victim of poor IEQ because of not having a proper IEQ management system. The scenario is worse in the healthcare sector where the occupancy levels are higher than the designed level of occupants (Gulshan et al., 2015). The situation is endorsed by a recent study of three local hospitals. The result shows the significance of healthcare-associated diseases in Pakistan because the number of victims from the polluted air is increased in numerous reported cases (Ishtiaq et al., 2017). A survey carried out in several local hospitals to evaluate the current hygiene conditions of the hospital revealed the poor practice of infection control. It was also predicted that these results are representative of all other local hospitals (Baqi et al., 2009).

Improved air quality in a healthcare facility reduces energy use because improving airflow and ventilation, maintaining humidity and CO_2 levels can result in the optimization of the HVAC system and ensure the reduction of load on the equipment. Better IEQ is achieved after removing the harmful and toxic agents from the ambiance. These particles and agents can cause allergies, sneezing, congestion, an itchy throat, and irritated eyes. Improved IEQ helps get rid of these possibilities of discomfort. This study can benefit the hospital management to pay attention to the IEQ by improving ventilation strategies which will ensure a comfortable atmosphere for the patients.

The main objective of the study is to provide a better way of improving indoor environmental quality with the help of standard ventilation rates. The level of IEQ for each hospital is measured and low performing hospitals are identified along with suggestions to improve their IEQ conditions. Existing ventilation rates are calculated with the help of three balance equations i.e. temperature, humidity, and CO_2 identified from the literature review. Based on these equations, the simulation model is formed using AnyLogic 7.

Reverse formulas are formed to get required levels of indoor temperature, relative humidity, and indoor CO_2 concentration. Ventilation rates calculated from standard ASHRAE guidelines are confirmed through these simulation models and retrofit suggestions are incorporated (ASHRAE, 2007).

1.1. Ventilation rates and indoor environment

It is recognized that ventilation design is a vital component in the architectural design that impacts the productivity and health of occupants (Meadow et al., 2014). Similarly, in the context of human health, ventilation is also considered as the basic component of indoor air as it circulates outdoor air into the indoor environment and dilutes the polluted indoor atmosphere (Bhattacharya et al., 2012; Sundell et al., 2011). There are many other ways to provide adequate ventilation such as mechanical exhaust fans and HVAC systems but it can also be provided through natural means like temperature difference between outdoor and indoor environment which will create buoyancy effect (Saadatjoo et al., 2018). Natural ventilation is considered an energy-efficient strategy which also increases the occupants' comfort level by improving indoor environmental quality (Alotaibi et al., 2018; Saadatjoo et al., 2018). While at least one opening for exhaust and one source of air conditioning is required in mechanical ventilation (Sasamoto et al., 2010). To avoid excessive energy use, options of completely outdoor air or ventilated air partially mixed with the return air can be considered (Seppänen et al., 1999). It is already discussed that CO_2 is the indicator of indoor environmental quality. It is because CO_2 helps determine the ventilation rates in any building and due to this, ventilation rates per person substitute the concentration of indoor CO_2 (Bhattacharya et al., 2012; Seppänen et al., 1999). Overall, there is an inconsistent trend in the dependency of indoor contamination on the ventilation rate as it varies with the type of pollutant (Sundell et al., 2011).

There is sizeable research on the importance of ventilation requirements and strategies for indoor environmental control. For example, a study was conducted on the operation and maintenance of the HVAC system in a healthcare facility because it has strict ventilation requirements. It was found that the capacity of the HVAC system must be following the occupancy level of the facility. It not only smoothens the operation but also works at the best efficiency to ensure occupants' health and comfort (Moscato et al., 2017). Another study was conducted on an office building to study the impact of ventilation rates on human health, ensuring that these are not continuously occupied as residential buildings and are not exposed to heavy technical activities like an industrial building. The study indicated certain risks of 1.1–6 for sick building syndrome symptoms and 1.5–2 for respirational diseases in case of low or highly inadequate ventilation rates (Seppänen et al., 1999). Moreover, a study in the neighboring country, India, found that most of the buildings are naturally ventilated in the selected area and they have more exchange of outdoor and indoor air as compared to the other buildings which are ventilated through the HVAC system. That results in a notable effect of outdoor air in the quality of the indoor environment (Goyal and Khare, 2011).

Another study shows that for the vast spaced buildings like industrial zones, it is difficult to determine the sources of pollutions in indoor air with the help of local ventilation systems (Wang et al., 2016). According to a recent study, two methods can improve IEQ in breathing areas without altering the energy consumption of ventilation. The first is to control the operation of the ventilation system and the second is to modify the arrangement of the building's internal layout (Zhuang et al., 2014). In the context of healthcare facilities, a study validated the fact that naturally ventilated wards have a more comfortable indoor environment at night-time. Also, these would be a stronger design for future climate change as compared to other ward designs (Lomas and Giridharan, 2012). Using ventilation to dilute contaminants, indoor pollutant source control and air filtration are the major methods of maintaining good IAQ in most of the buildings (Bhattacharya et al., 2012).

Therefore, it is known that ventilation rates in a building have a prominent effect on the indoor environmental quality and its components (Branco et al., 2015; Korjenic et al., 2010; Ramachandran et al., 2005). As a result of an extensive literature review and a two-stepped analysis (qualitative and qualitative analysis) was performed by shortlisting 18 factors from the literature that affect the IEQ of a building. Based on their occurrence in terms of quality and quantity, the top three factors as Temperature (T), Relative Humidity (RH), and Carbon dioxide (CO_2) were selected. The details of this exercise are given in Part-1 of this paper (Khan et al., 2020). These factors are used for data collection and analysis and further considered for the study of ventilation rates and retrofitting suggestions as the ventilation rates can be improved by suitable retrofitting techniques (Santamouris and Dascalaki, 2002).

2. Material and methods

2.1. Balance equations (T, RH, CO_2)

To evaluate the current ventilation conditions in the selected locations, three balance equations were used separately for each of the selected parameters (Pedersen et al., 1998). These equations are formerly used for the determination of ventilation rates in animal houses, but as our research purpose, we have simulated the results with the given inputs values related to human beings (Blanes and Pedersen, 2005).

2.1.1. Heat balance

The heat balance is stated by the Eq. (1) (Pedersen et al., 1998) where S_b is the sensible heat per person 'W', A is the surface area of each selected location in m^2, U is the heat transmission coefficient for building surfaces y in W/m^2 K, Δt is the difference of in indoor and outdoor temperatures in K and while readings were collected in °C, so 273.15 was added in each value for the conversion in K, c is the specific heat of the air in J/m^3 K. Ventilation rates are calculated in m^3/h. The values of sensible and latent heat are multiplied by the maximum number of occupants 'n' (Toolbox, 2004).

$$V = \frac{S_b - AU\Delta t}{c\Delta t} \tag{1}$$

2.1.2. Moisture balance

The ventilation rates calculated with related humidity are expressed as humidity balance Eq. (2) (Pedersen et al., 1998). As L=Δ H V680, therefore:

$$V = \frac{L}{\Delta H \times 680} \tag{2}$$

The difference between indoor and outdoor humidity levels are shown by ΔH in kg/m^3. While L is the latent heat of the human body, which is calculated in W. We have the RH values in percentage so the equation is multiplied by 0.1546 to convert it into kg/m^3.

2.1.3. Carbon dioxide balance

It is already known that the ratio of the concentration of indoor and outdoor CO_2 indicates the ventilation rates in buildings (Zhuang et al., 2014). Alike the mentioned two equations, ventilation rates can also be determined by indoor and outdoor CO_2 levels. The formula for this is expressed as Eq. (3) (Pedersen et al., 1998).

$$V = \frac{C}{\Delta C \times 10^{-6}} \tag{3}$$

where C is the production rate of carbon dioxide calculated in m^3/h. The difference between indoor and outdoor CO_2 is shown by ΔC in ppm.

2.2. Rearrangement of equations for simulation

The above-mentioned equations were rearranged for the calculation of required range of ventilation rates corresponding to the standard values of the selected parameters, all three rearranged equations are given in Eqs. (4, 5 and 6).

$$T_i = T_o - \frac{S_b}{AU + Vc} \tag{4}$$

$$H_i = H_o - \frac{L}{V \times 680} \tag{5}$$

$$C_i = C_o + \frac{C}{V \times 10^{-6}} \tag{6}$$

These equations are further used in the simulation for the calculation of existing ventilation rates, using the values for each variable that are discussed in detail in the results section.

2.3. Modeling and simulation

Modeling and simulation is an effective technique in the fields of academics, decision making, feasibility reporting, and analysis. It has been used as the recent emerging technology tool and attained a position in various domains like industries, defense departments, and healthcare facilities. Consequently, the vast utility of this technique, wide range of simulation and modeling tools are required in the market that will help in reducing time and cost related to the development and authentication of simulation models (Moradi et al., 2008). Spreadsheet modeling is considered the simplest form of computing data and getting the required outputs.

Data needs to be entered in one cell and output is shown in another. But the limitation always remains that there is no visual representation or any inflow-outflow diagram. It also has a limitation of not showing continuous outputs while giving the options of changing input value. Formula based simulation is not possible using simple spreadsheet software because other than static dependencies, the dynamic behavior of any model also needs to be described (Fonseca et al., 2019). Therefore, an alternative modeling tool is required to analyze dynamic systems (Grigoryev, 2015).

AnyLogic is widely used in recent studies as a modeling and simulation tool (Chen et al., 2017). A simulation model was developed using a discrete event method. That model proposed the idea of system modeling as a chain of events, which is operated over the entities in the form of a sequential process (Panova and Korovyakovsky, 2013). In another study, AnyLogic was selected for the validation and execution of the model due to its exceptional specifications. It was also discussed that only AnyLogic can combine the three previously discussed methods: system dynamics, discrete event, and agent-based modeling, in a single model using the same language and environment. The vital feature of the software is that the results are near to the real-world entities (Lupin et al., 2016).

2.4. Modeling of equations in AnyLogic 7

Analytical models of Eqs. (2 to 4) were developed using MS Excel separately. In Eq. (2), the outdoor temperature is taken from the nearest weather station operated under the auspices of the Pakistan Meteorological Department. The temperature is converted to Kelvins (°K) as the recorded values were in Celsius (°C). The sensible heat of a human body at a rested position is considered between 50W to 60W (Toolbox, 2004). The maximum occupancy level was observed and recorded during the primary data collection.

Further, the floor area is converted from ft^2 to m^2. U values are calculated for simple brick and cement plaster system, as all 4 hospitals are constructed with local materials and common techniques. Using these values, maximum and minimum ventilation rates are calculated for each location.

2.5. Research methodology

This study is conducted following a structured and formal research methodology as shown in Fig. 1. The research consists of a seven-stepped flow diagram. The steps are explained below.

1. This step deals with the basic definition of the problem statement and objectives of the research. Literature is thoroughly reviewed to identify the research gap. It is explored as to how this research can be beneficial for the comfort of a common man who visits a public healthcare facility for treatment. The need for this research according to national and international conditions is also considered. A flow chart is developed at the end of this step to illustrate the research methodology.

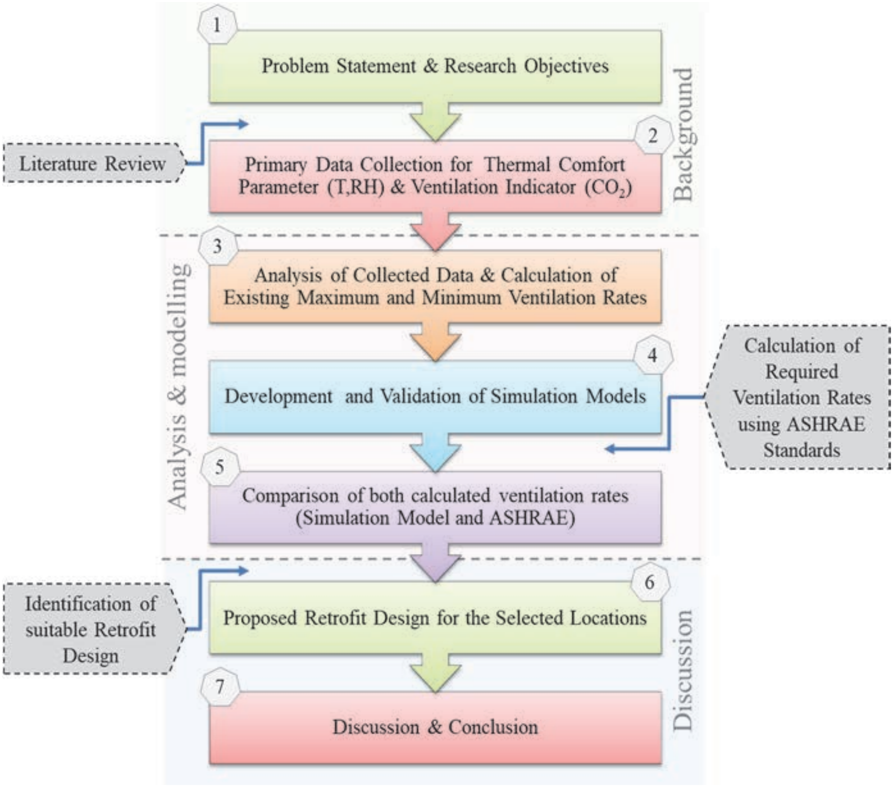

Fig. 1. Research methodology

Table 1. Characteristics of selected locations

Sr. No.	*Hospital Codes*	*Total Beds*	*Existing AC type*	*Location Codes*	*Maximum Occupancy (No.)*	*Floor Area (m^2)*	*U Value (W/m^2 K)*
					n	**A**	**U**
1	Hospital 1 (H1)	3000	Fans and natural ventilation	**H1ER**	90	372	2.15
2				**H1OT**	16	33	2.15
3				**H1ICU**	20	72	2.15
4				**H1MW**	25	85	2.15
5	Hospital 2 (H2)	800	Split units, exhaust and ceiling fans	**H2ER**	35	269	2.15
6				**H2OT**	10	56	2.15
7				**H2ICU**	25	325	2.15
8				**H2MW**	20	122	2.15
9	Hospital 3 (H3)	2500	Split units, exhaust and ceiling fans	**H3ER**	35	465	2.15
10				**H3OT**	15	49	2.15
11				**H3ICU**	20	325	2.15
12				**H3MW**	35	557	2.15
13	Hospital 4 (H4)	1200	Central air conditioning system	**H4ER**	25	353	2.15
14				**H4OT**	10	52	2.15
15				**H4ICU**	8	149	2.15
16				**H4MW**	16	372	2.15

2. According to the research methodology formulated in the first step, three basic parameters for thermal comfort and ventilation were selected after a quantitative analysis. Temperature and relative humidity indicate the level of thermal comfort, while CO_2 concentration indicates the adequate ventilation rates in indoor vicinity (Bakó-Biró et al., 2012; Ng et al., 2011; Turanjanin et al., 2014). Real-time primary data collection is proposed to understand the existing conditions of selected parameters. For this purpose, four hospitals are selected and further four locations in each hospital are considered. The four locations are emergency room (ER), operation theater (OT), intensive care unit (ICU), and medical wards (MW). The data was collected for 6 days at each location, day and night, with data logging at an interval of 5 minutes (Khan et al., 2020). Table 1 shows the basic characteristics of each selected location in terms of hospital bed capacity, existing AC type, location codes, maximum occupancy, floor area, and U value.

This article is the second part of a large study of which basic statistical analysis and detail of primary data collection and organization are explained in the first part (Khan et al., 2020).

3. In the third step, the prearranged data is assessed based on international standards, and it is found that most of the values have a deviation from the international standards (ASHRAE, 2007). Three balance equations are identified from the literature, including T, RH, and CO_2 separately, while the factor of ventilation rates is common in all three equations (Pedersen et al., 1998). The maximum and minimum existing ventilation rates are calculated based on these equations.

4. The equations are rearranged for the calculation of the required range of ventilation rates corresponding to the standard values of the selected parameters. Using AnyLogic 7, three different simulation models are developed based on three balance equations (Borshchev and Filippov, 2004; Pedersen et al., 1998). To ensure maximum accuracy in measuring the percentage exceedance from the standards, three standards for each selected parameter were studied: ASHRAE 2003 HVAC Design Manual for Hospitals and Clinics (Geshwiler et al., 2003), United States Department of Veterans Affairs 2001 HVAC requirements in Surgery Area (Khodakarami and Nasrollahi, 2012) and ASHRAE standards (ASHRAE, 2007, Lee and Chang, 2000). The closest value available in any of the selected standards was considered for comparison i.e. 20-24ºC for indoor temperature, 45%-55% for relative humidity, and 600ppm-1000ppm for indoor CO_2. This was done to observe the minimum level of exceedance. Also, larger values are preferred and reported in such building types where the sensitivity of IEQ is relatively lower such as academic facilities (Asif et al., 2018).

5. The models are then executed by altering the input values, keeping the minimum and maximum ventilation rates in consideration, to determine the variation in selected IEQ parameter. An acceptable range of ventilation rates for each selected parameter is determined through this practice. In parallel, the required ventilation rates are calculated using the ASHRAE standard formula for ventilation rates (ASHRAE, 2007). These allowable values are compared to the given standards to validate the simulation model. A staked diagram is developed to compare the variation in both existing and required ventilation rates 6. After determining the variation in the required and existing ventilation rates, literature was again consulted to identify the suitable retrofitting techniques for the current situation such that they can control the process of ventilation rates. The controlled ventilation rates have a vital role in enhancing the IEQ in the indoor facility.

7. In the end, findings are discussed, and conclusions are inferred to reach practical implications and recommendations for practitioners as

well as researchers. Limitations of the study and recommendations for further research are also discussed.

3. Results and discussion

3.1. Simulation results

3.1.1. The simulation model for T

Fig. 2 shows the model developed in AnyLogic 7. Eq. (1) is rearranged to get the required minimum and maximum temperatures as output by substituting a range of suitable ventilation rates. The input ventilation rates were altered using already calculated ventilation rates. The new equation is given in Eq. (4) where T_i is the required indoor temperature in K, T_o is the outdoor temperature in K, S_b is the sensible heat of the human body multiplied with the number of persons (n). The equation is divided into two parts to simplify the model. The first part is the calculation of area, U value, and calculated ventilation rates, and the results are collected as stock. This stock value is further used in the main equation.

3.1.2. Input data for T

Corresponding input values for Eq. (4) for all the locations are given in Table 2. The minimum and maximum ventilation rates are calculated using recorded indoor temperature for each location.

3.1.3. The simulation model for RH

Similarly, a simulation model, shown in Fig. 3, is developed to get the required levels of suitable relative humidity.

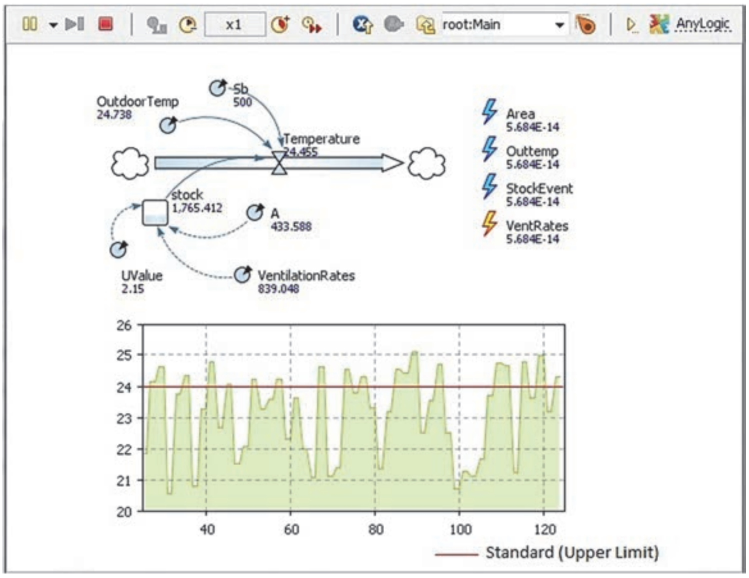

Fig. 2. The simulation model for indoor temperature

Table 2. Input values for Eq. (4)

	Outdoor Temp. (ºC)		*Sensible Heat (W)*	*Maximum Occupancy (No.)*	*Floor Area (m^2)*	*U Value (W/m^{2}K)*	*Observed Indoor Temp. (ºC)*		*Existing Ventilation Rates (m^3/h)*	
	T_o *(Min)*	T_o *(Max)*	*S*	*n*	*A*	*U*	T_i *(Min)*	T_i *(Max)*	*Vt-(Max)*	*Vt-(Min)*
H1ER	9.5	26.1	60	90	372	2.15	24.8	28.1	861	800
H1OT	9.4	26.1	60	16	33	2.15	23.8	27.8	83	73
H1ICU	9.1	26.2	60	20	72	2.15	25.6	27.2	170	157
H1MW	9.1	26.2	60	25	85	2.15	26.2	28.9	201	184
H2ER	20.5	37.5	60	35	269	2.15	18.4	25.6	605	580
H2OT	17.2	36.0	60	10	56	2.15	21.4	29.3	127	121
H2ICU	17.1	36.1	60	25	325	2.15	23.5	27.7	717	700
H2MW	20.1	37.4	60	20	122	2.15	21.8	28.6	276	262
H3ER	15.4	34.7	60	35	465	2.15	21.7	24.7	1024	999
H3OT	17.1	35.0	60	15	49	2.15	19.4	26	116	106
H3ICU	16.9	35.7	60	20	325	2.15	19.9	25	714	700
H3MW	15.1	34.7	60	35	557	2.15	21.7	24.6	1223	1199
H4ER	13.2	34.6	60	25	353	2.15	22.3	25.1	777	760
H4OT	13.1	30.1	60	10	52	2.15	21.0	29.2	119	113
H4ICU	13.1	30.3	60	8	149	2.15	21.7	24.8	325	320
H4MW	13.0	34.3	60	16	372	2.15	21.9	26.3	810	800

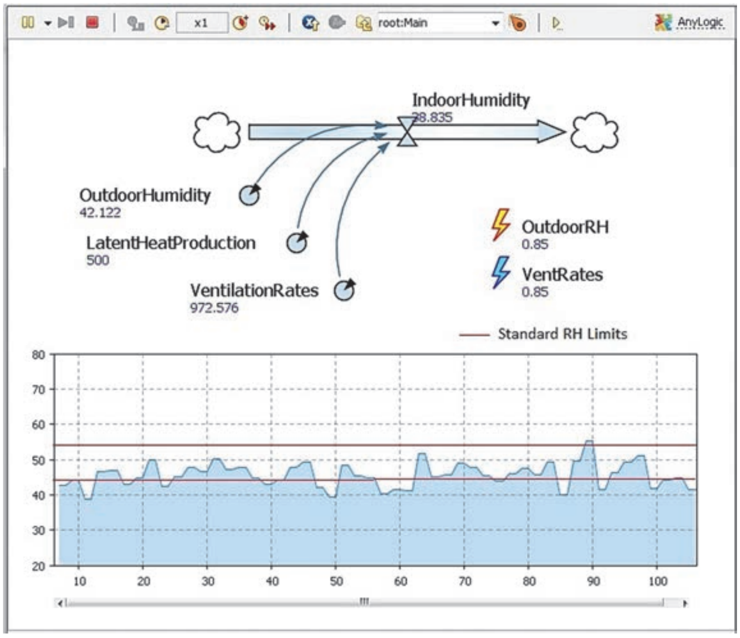

Fig. 3. The simulation model for Relative Humidity

Eq. (2) is rearranged for this purpose and Eq. (5) is formed where H_i is the indoor humidity level in kg/m^3, H_o is the outdoor humidity level in kg/m^3, V is the maximum or minimum ventilation rates in m^3/h and humidity levels are recorded in *RH%* levels which were then converted to kg/m^3 for the calculation.

3.1.4. Input data for RH

Corresponding input values for Eq. (5) are given in Table 3. The minimum and maximum ventilation rates in the table are calculated using recorded indoor relative humidity for each location.

3.1.5. The simulation model for CO2

Likewise, the third simulation model, shown in Fig. 4, is prepared to calculate the required range of indoor CO_2 concentration. Eq. (3) was rearranged, and Eq. (6) is achieved where C_i is the required indoor CO_2 concentration, C_o is the outdoor CO_2 concentration in ppm, C is the rate of CO_2 production, and V is the ventilation rate.

3.1.6. Input data for CO2

Corresponding input values for Eq. (6) are given in Table 4. The minimum and maximum ventilation rates are calculated using recorded indoor CO_2 concentrations for each location.

3.2. Trends in simulation results

By simulation of all the three equations, the trends in the existing ventilation rates were studied. As the data was recorded for a specific period, the simulation was required to document the trend and behavior of all the factors or parameters that influence the change in ventilation rates. Thus, Figs. 2, 3, and 4, which are the output from the AnyLogic7 simulation, describe the trends in ventilation rates considering all the factors.

The simulation results for the ventilation equation related to indoor temperature show that by using the parameters, defined in Table 1, the upper limits of the standard have deviated. While the lower limits of standards have not deviated. Contrary to that, in the case of the simulation model related to RH, the lower limits of standards are violated, while fewer deviations in upper limits of standards are observed.

In the case of the indoor CO_2 simulation model, the lower limits have deviated from the standards, although it is different than the trends shown in the previous analysis (Khan et al., 2020). But it was obvious that the standards have deviated in all the three cases.

3.3. Ventilation rates calculation

Table 4 shows the calculated value from the Eq. (7) acquired from the ASHRAE standards (ASHRAE, 2007), where A is the area in Sq. ft., R_a is the required cfm (cubic ft/minute) per square foot of area, N is the number of occupants at peak hour and R_p is the required cfm per person. These values of the required cfm of fresh air are used in the retrofit design for each location. These values for each location are listed in Table 5.

$$V_r = A \times R_a + N \times R_p \tag{7}$$

3.3.1. Comparison of the three balance equations and standard required ventilation rates

A comparison was drawn between the minimum and maximum ventilation rates calculated using three equations from the literature and the required ventilation rates using ASHRAE equations. Three continuous lines show the existing ventilation rates in the selected locations.

Table 3. Input values for Eq. (5)

	Outdoor Humidity Level (kg/m^3)		***Maximum Occupancy (No.)***	***Latent Heat (W)***	***Observed Indoor Humidity (%)***		***Existing Ventilation Rates (m^3/h)***	
	H_o *(Min)*	***H_o*** *(Max)*	***n***	***L***	***H_i*** *(Min)*	***H_i*** *(Max)*	***V RH****-(Max)*	***V RH****-(Min)*
H1ER	16.0	75.4	90	50	30.9	52.8	1954	1311
H1OT	16.0	75.3	16	50	34.7	66.1	277	581
H1ICU	16.1	75.5	20	50	35.9	52.9	325	293
H1MW	16.4	75.4	25	50	28	53.7	674	380
H2ER	22.1	85.0	35	50	44.1	70.5	512	781
H2OT	21.5	83.4	10	50	25.5	61.8	719	153
H2ICU	21.5	83.1	25	50	39.1	62.9	447	402
H2MW	22.5	78.7	20	50	41.5	69.1	332	727
H3ER	19.4	77.8	35	50	39.2	53.9	560	490
H3OT	13.4	78.3	15	50	33.4	72.9	238	951
H3ICU	13.0	78.7	20	50	34	62.4	308	415
H3MW	19.8	77.4	35	50	39.1	55.8	563	534
H4ER	18.4	82.1	25	50	27.9	55.4	817	304
H4OT	26.1	88.1	10	50	32.7	75.2	483	253
H4ICU	26.4	88.1	8	50	34.1	53.1	319	74
H4MW	18.4	82.0	16	50	24.1	50	848	162

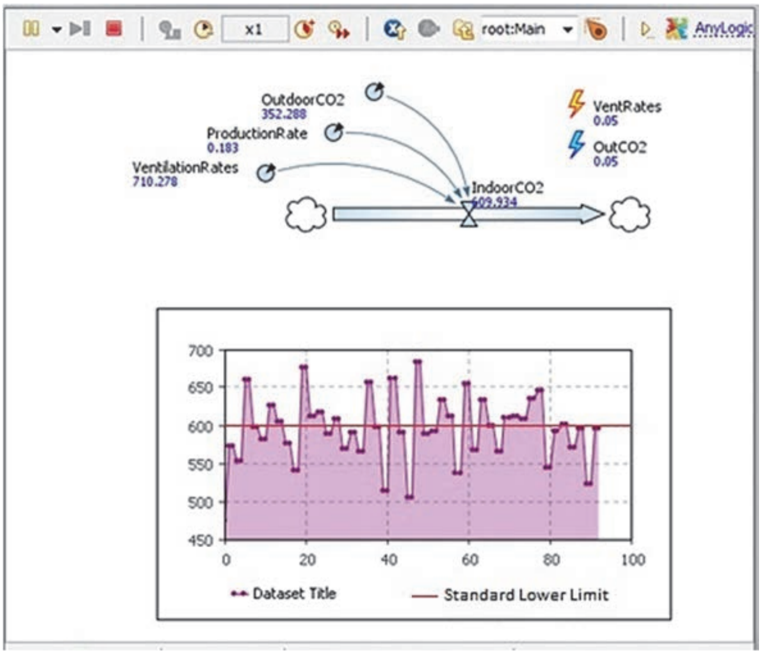

Fig. 4. The simulation model for indoor CO$_2$

Table 4. Input values for Eq. (6)

	Production Rates (m^3/h)	***Outdoor CO$_2$ (ppm)***		***Observed Indoor CO$_2$ (ppm)***		***Existing Ventilation Rates (m^3/h)***	
	C	***C_o*** *(Min)*	***C_o*** *(Max)*	***C_i*** *(Min)*	***C_i*** *(Max)*	***VCO$_2$****- (Max)*	***VCO$_2$****-(Min)*
H1ER	0.183	300	450	683	2781	478	79
H1OT	0.183	300	450	589	2640	633	84
H1ICU	0.183.	300	450	847	2186	335	105
H1MW	0.183	300	450	627	2596	560	85
H2ER	0.183	300	450	609	1614	592	157
H2OT	0.183	300	450	452	806	1204	514
H2ICU	0.183	300	450	525	1036	813	312
H2MW	0.183	300	450	441	1637	1298	154
H3ER	0.183	300	450	698	1308	460	213
H3OT	0.183	300	450	731	2256	425	101
H3ICU	0.183	300	450	674	1082	489	290
H3MW	0.183	300	450	439	1237	1317	233
H4ER	0.183	300	450	399	749	1848	612
H4OT	0.183	300	450	389	738	2056	635
H4ICU	0.183	300	450	422	649	1500	920
H4MW	0.183	300	450	410	956	1664	362

Table 5. Required ventilation rates (Calculated from ASHRAE)

Sr. No	***Location***	***Total Area (A)*** *(Sft.)*	***No. of Persons (N)***	***Cfm per Person (R_p)***	***Cfm per Sft (R_a)***	***Ventilation Rates Fresh Air Requirement ($R_p + R_a$)*** *(cfm)*	***Ventilation Rates*** *(m^3/h)*
1	**H1ER**	3998	90	25	0.5	4249	7219
2	**H1OT**	360	16	30	0.5	660	1121
3	**H1ICU**	780	20	15	0.5	690	1172
4	**H1MW**	920	25	15	0.5	835	1419
5	**H2ER**	2899	35	25	0.5	2324	3948
6	**H2OT**	600	10	30	0.5	600	1019
7	**H2ICU**	3499	25	15	0.5	2124	3609
8	**H2MW**	1309	20	15	0.5	955	1623
9	**H3ER**	4998	35	25	0.5	3374	5732
10	**H3OT**	525	15	30	0.5	712	1210
11	**H3ICU**	3499	20	15	0.5	2049	3481
12	**H3MW**	5998	35	15	0.5	3524	5987
13	**H4ER**	3798	25	25	0.5	2524	4288
14	**H4OT**	560	10	30	0.5	580	985
15	**H4ICU**	1599	8	15	0.5	920	1563
16	**H4MW**	4000	16	15	0.5	2240	3806

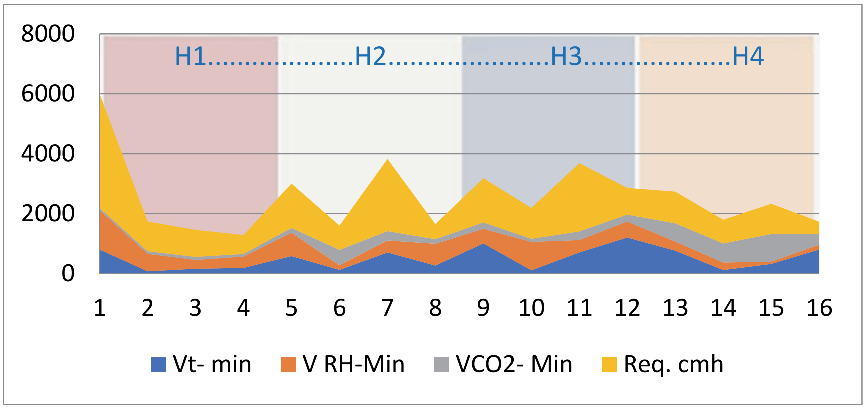

Fig. 5. Minimum ventilation rates (T, RH, CO_2)

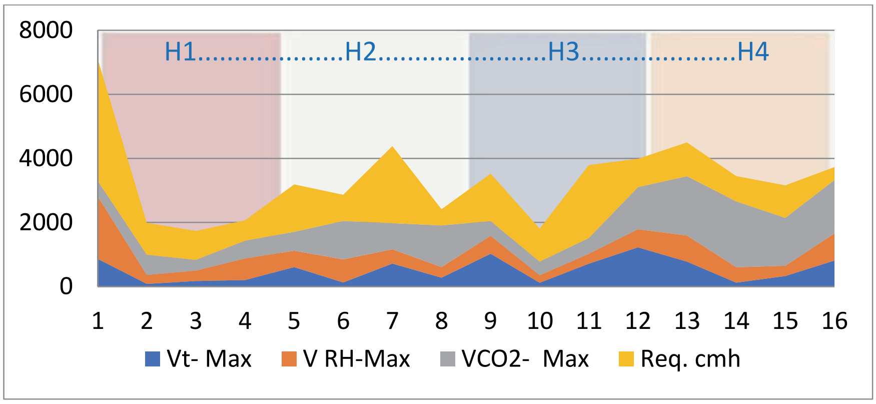

Fig. 6. Maximum ventilation rates (T, RH, CO_2)

Fig. 5 shows the minimum ventilation rates which are calculated through the maximum values of indoor parameters. It shows that the maximum deviation is obtained from the calculation of CO_2, while temperature has the minimum range of ventilation rates.

Fig. 6 shows the graph of maximum values of ventilation rates calculated through minimum values of T, RH, and CO_2. A similar trend was noticed in the graph i.e. CO_2 shows the highest values of existing ventilation rates while temperature shows the lowest. This trend is because the maximum exceedance from standards is in case of CO_2 as compared to RH and T. The required ventilation rates, in both cases, have the highest values which will be incorporated in the further simulation process. Hence, a retrofit scheme is required to maintain the required ventilation rates as per ASHRAE standards (ASHRAE, 2007).

3.4. Proposed retrofitting techniques for IEQ of hospitals

To determine the best suitable solution for the retrofit scheme, which should be designed for each selected location, literature was consulted to explore the existing retrofit techniques. The following techniques were found suitable in the case discussed above.

3.4.1. Hybrid ventilation

Hybrid ventilation is described as a method that utilizes both natural and mechanical strategies to acquire comfortable indoor environmental quality (Awbi, 2000). Indoor air quality is maintained through a method of ventilation. If the outdoor atmosphere is cleaner and pollution-free, the fresh air supplied from the ambient environment will more likely improve the indoor environmental quality (Chao and Hu, 2004a). To achieve functional needs, operationally significant buildings such as hospitals and high-performance laboratories should be adequately ventilated. An eminent way of maintaining comfort conditions is hybrid ventilation in buildings. Relying on various characteristics of comfort conditions including indoor and outdoor conditions in terms of temperature and humidity, these places can be suitably conditioned through hybrid ventilation (Taylor and Menassa, 2012). The typical and simplest assembly for hybrid ventilation is an auxiliary fan and an outlet for natural ventilation. It is already known that mere an opening for ventilation purposes cannot provide adequate ventilation, but when both techniques are used in combination, it can fulfill the purpose in a better way (Kim et al., 2016). This is the most cost-effective system and best for the areas where the mobility of occupants is not controlled and is not allowed to be air controlled. Thus, such a system is recommended for emergency rooms.

3.4.2. Demand control ventilation

For hot and humid climate, CO_2 based demand control ventilation (DCV) gives better energy efficiency as compared to economizer ventilation (Chao and Hu, 2004b). Two main factors that influence the control strategies of the HVAC system are temperature and CO_2 (Erickson and Cerpa, 2010). The CO_2 level in the atmosphere is the basic parameter to measure occupancy for the DCV system because it is the best substitute gas for the saturation of contaminants related to the occupants (Chao and Hu, 2004b; Fisk, 2010; Nielsen and Drivsholm, 2010). It is verified that DCV is a cost-effective and energy-efficient replacement for the CAV system. In large public areas like schools and hospitals where occupancy level and time of use is not constant, DCV is an appropriate strategy to control indoor parameters (Mysen et al., 2005). Sensors control the ventilation flow during varied occupancy levels in the building. These sensors may include temperature sensors, infrared sensors, CO_2 sensors, and occupancy sensors (Norbäck et al., 2013). DCV should be preferred to improve air quality and lower energy consumption (Nielsen and Drivsholm, 2010). A DCV system not only controls the IEQ in the indoor facility but also perform a vital role in reducing energy efficiency. The cost of this control system is very nominal compared to the benefit gained through the reduction in utility bills. Thus, this control is recommended with each system in all the locations.

3.4.3. Energy recovery ventilator (ERV)

Recently, the concept of ERV is broadly used in industrial, commercial, and residential facilities (Liu et al., 2010; Zhou et al., 2007). Energy recovery is an efficient method for heat exchange between the indoor and outdoor environments. It expels the exhaust air outside while supplying fresh air inside and maintains the comfortable humidity levels for the occupants (Liu et al., 2010). The ERV unit comprises of a core that maintains enthalpy, a pair of filtering devices at the entering point of both airflows, and a connection of four pipes into a metallic frame with enough insulation (Zhang and Fung, 2015). Fig. 7 shows the mechanism of airflow in an ERV, how energy recovery device encounters the supply and return air.

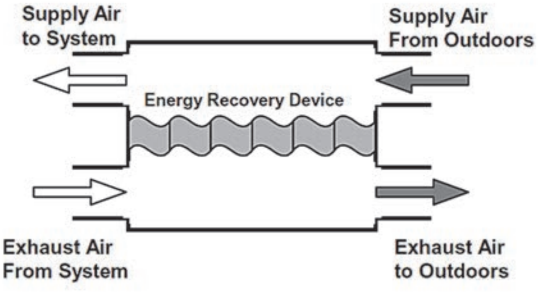

Fig. 7. Counter-flow heat exchange pattern (Rabbia and Dowse, 2000)

When it comes to comfort level, ERV operates in two dimensions. The first dimension is to transfer heat and moisture to the inside environment from the exhaust airflow to the incoming airflow in colder months and the second is the inverse of the same operation in the summer season (Fan and Ito, 2012; Rabbia and Dowse, 2000). The application of this system is widespread, and it is most suitable to use where there is a significant difference in outdoor comfort conditions. It also depends on the level of occupancy and the time of the day when it is utilized. There are many commercial applications of the phenomenon and the typical applications of the system may include hospitals and nursing rooms (Rabbia and Dowse, 2000). This technique is very useful were the outdoor environmental conditions are not suitable to be transported inside, but with some alteration in the mid-way, the outdoor air is made more suitable for circulation. According to the local market and HVAC experts, it falls in the range of medium-cost retrofit strategy, which makes it suitable for medical wards and intensive care units, where indoor conditions are required to be controlled.

3.4.4. Laminar airflow system

ASHRAE guidelines have suggested using laminar airflow systems in operating rooms to prevent airborne bacteria and particulate matters present in the air (Memarzadeh and Manning, 2002). Laminar airflow systems are used to reduce the infectious viruses in operating rooms by producing a constant flow of clean air. There are two types of laminar airflow systems; one operates with the horizontal airflow, while the other one is vertical airflow. The vertical laminar airflow system is widely used and is considered most capable for its influence on patient protection (Melhado et al., 2016). Its formation comprises of ceiling-mounted HEPA filters. Vertical air passes and gets cleaned through these HEPA filters and is thrown over to the operation area. The airflow is sometimes hindered with the positioning of the scrub team but it goes back to the AHU through the return air ducts placed in the bottom four corners of the room (James et al., 2015). Laminar airflow-ventilated operating rooms maintain high levels of clean air and are less likely to produce and sustain any bacterial colony in the indoor air. It is imperative to maintain and clean HEPA filters on regular basis for the optimized operations of the system otherwise minor failure in the maintenance can result in disastrous air contamination and endanger the health of occupants (Andersson et al., 2014). It is deemed suitable for the retrofit design in the operation theater selected in this study. A similar study was carried out in Lahore in which T, RH, and CO_2 concentrations for operation theaters were observed. To control the poor IEQ in the operation theaters, the laminar airflow system was suggested (Nimra et al., 2015). Although it is not cost-effective for initial investment, its use is very limited, especially in controlled environments like operation theaters.

3.4.5. Proposed retrofit design

Concerning the calculated ventilation rates, the above retrofitting techniques were identified to improve the selected indoor environmental parameters which were further shortlisted depending on their influence on the parameters. These selected techniques are then assessed based on their cost. A short survey was performed with the help of professional HVAC consultants and cost ranks were developed to compare the costs of each selected technique. After this exercise, a retrofit scheme was proposed in each location of the selected hospitals, as given in Table 6.

The retrofit design for hospital 1 is given in Fig. 8. Exhaust fans are suggested in the ER because it is the most populated and unscheduled area of the hospital and requires continuous ventilation. Fresh air inlets are given at different points for better air circulation. In MW and ICU, an ERV system is suggested because these places are mostly entry restricted, and occupancy rates are controlled.

Table 6. Proposed retrofit techniques

Sr. No.	***Location***	***Retrofit Scheme***	***Cost Analysis for Maximum Requirement of 1300cfm (PKR)***	***Cost Ranks***
1	Emergency Room	Exhaust fan System (Hybrid Ventilation)	30,000/pc + GI ducting 300/Sft	Low
2	Operation Theater	Laminar Air flow with ERV System (Recommended DCV)	225,000/ton 80-150cfm/ton	High
3	Intensive Care Unit	Energy Recovery Unit and DVC	400,000/Pc + Air devices 1800/Sft	Medium
4	Medical Ward	Energy Recovery Unit and DCV	400,000/Pc + Air devices 1800/Sft	Medium

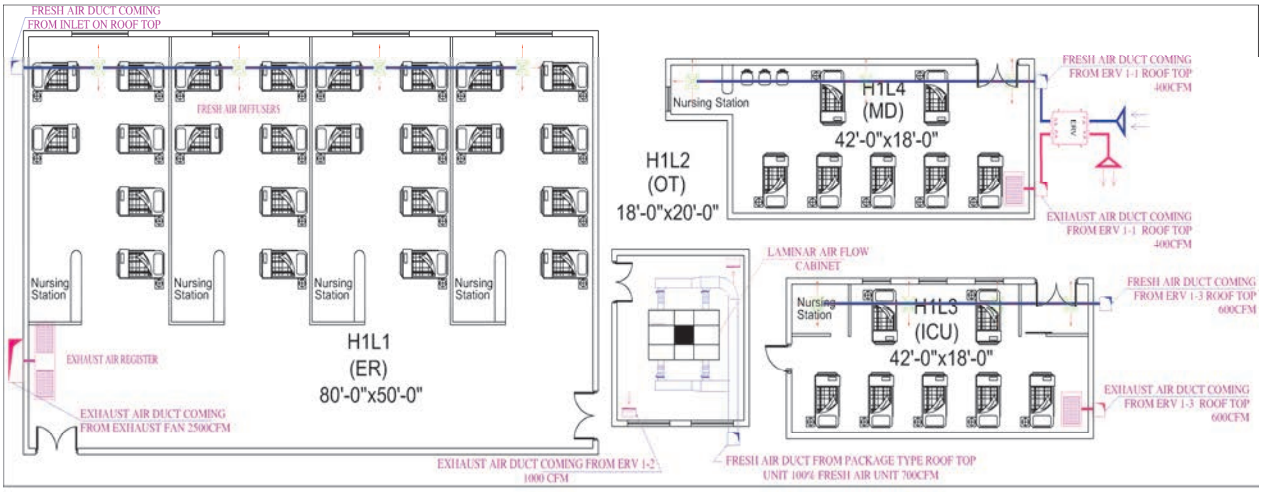

Fig. 8. Retrofit designs for Hospital 1

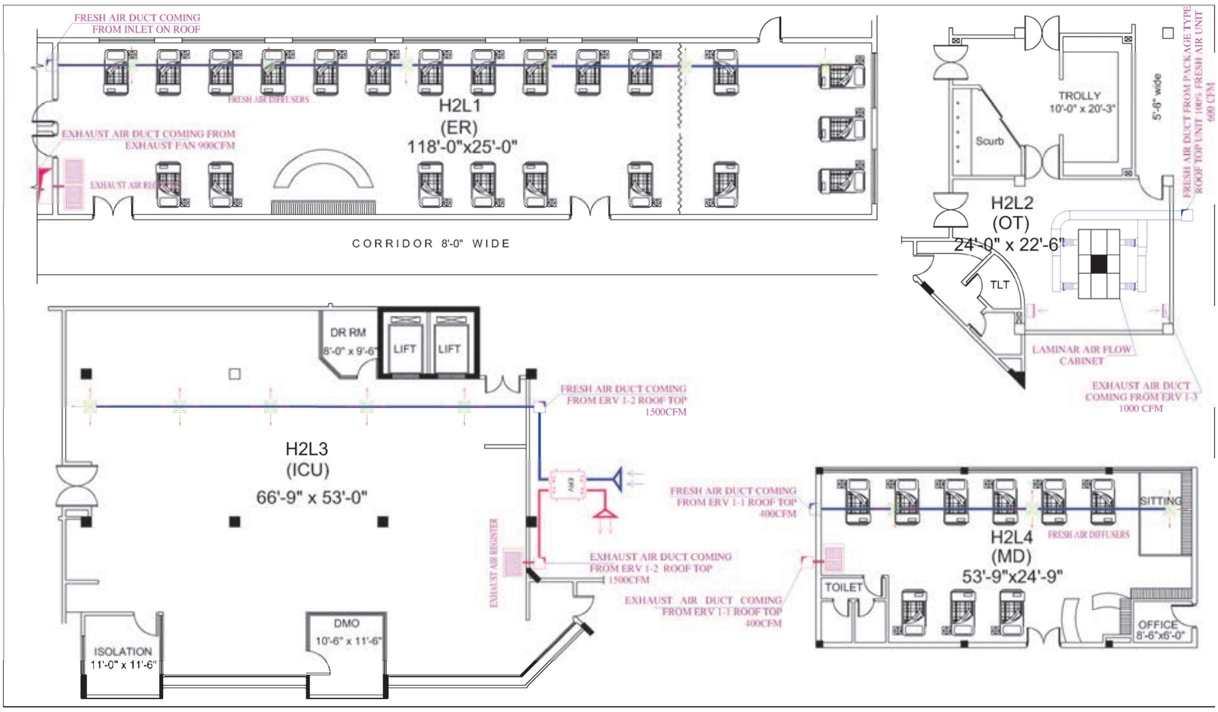

Fig. 9. Retrofit design for Hospital 2

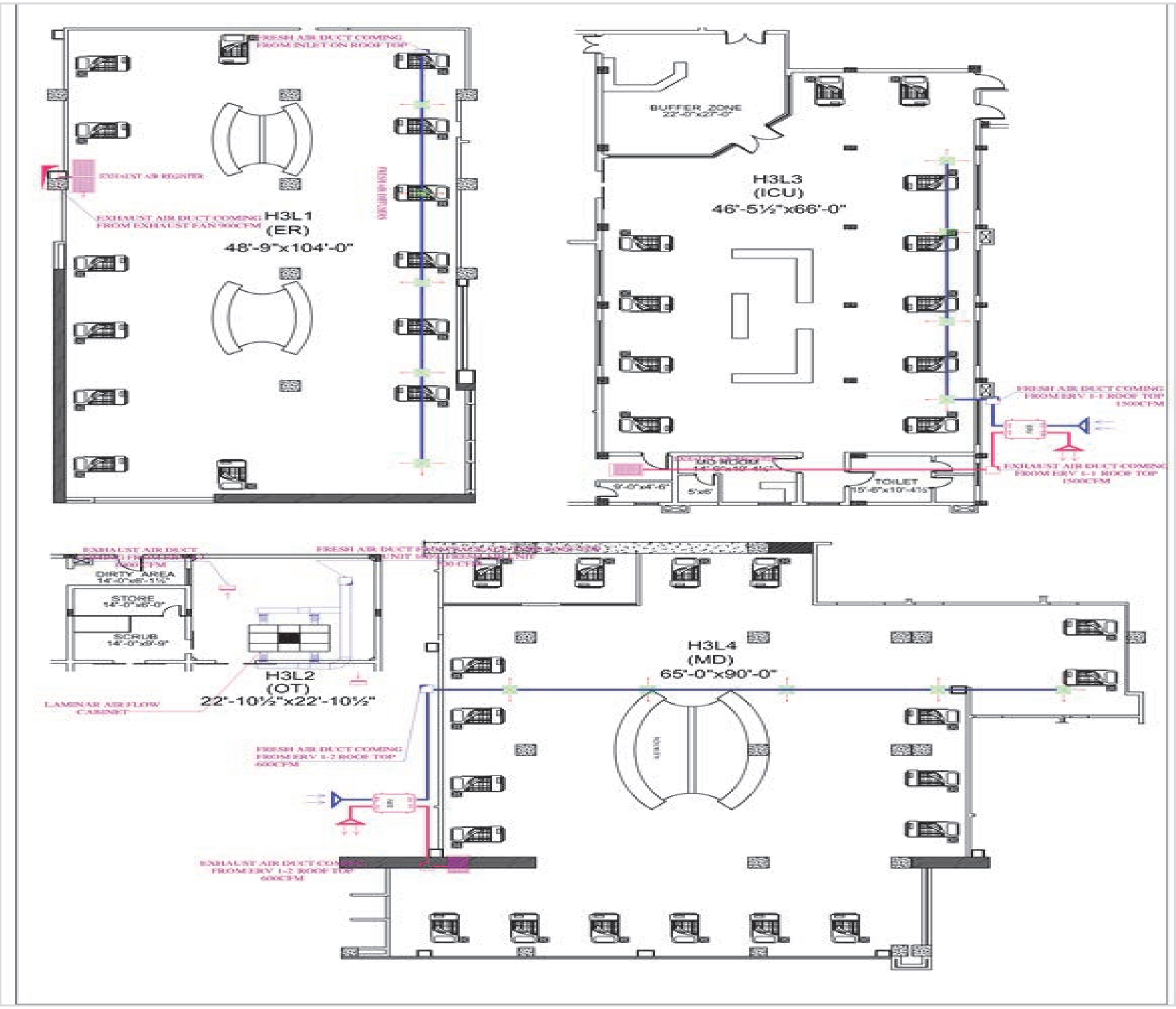

Fig. 10. Retrofit design for Hospital 3

While providing fresh air into the indoor environment, energy conservation is also possible in these areas. The laminar airflow system is proposed in the OT. Recent studies have validated the importance of a laminar airflow system in operation theaters (Andersson et al., 2014).

It is imperative to use the laminar airflow systems with a proper AHU system as it is the basic requirement to control the cfm levels. A DCV system can also be used to maintain the required comfort levels. The retrofit designs for all other hospitals (Hospital 2, Hospital 3, and Hospital 4) are based on the same retrofitting scheme and the drawings related to the retrofit design are given as Fig. 9, Fig. 10 and Fig. 11.

4. Conclusions

The simulation performed in this study shows a clear difference in existing and required results for ventilation in the selected hospitals. The result for ventilation rates strongly endorses the requirement of retrofitting design in the selected locations. The suggestions of the above discussed retrofitting techniques can help improve the IEQ in the hospitals and healthcare buildings.

This study can help the hospital management to pay attention to the IEQ and develop a suitable retrofit strategy, which will ensure a comfortable atmosphere for the patients as well as the medical staff.

Since the new construction of existing buildings is not feasible, the hospital management can retrofit their existing facilities using the proposed strategies. The limitation of the study is that the collection of data is performed in the transition period of autumn which reduced the applicability of data for summer and winter. It is recommended to perform the same assessment for the extreme weather and compare the results for a more suitable solution. Future studies can be performed by implementing these strategies in real-time and the conclusion will help in endorsing the result of this study. Due to a lack of funds in government hospitals in developing countries, research on cheaper technologies to improve indoor conditions in the healthcare facilities is also suggested.

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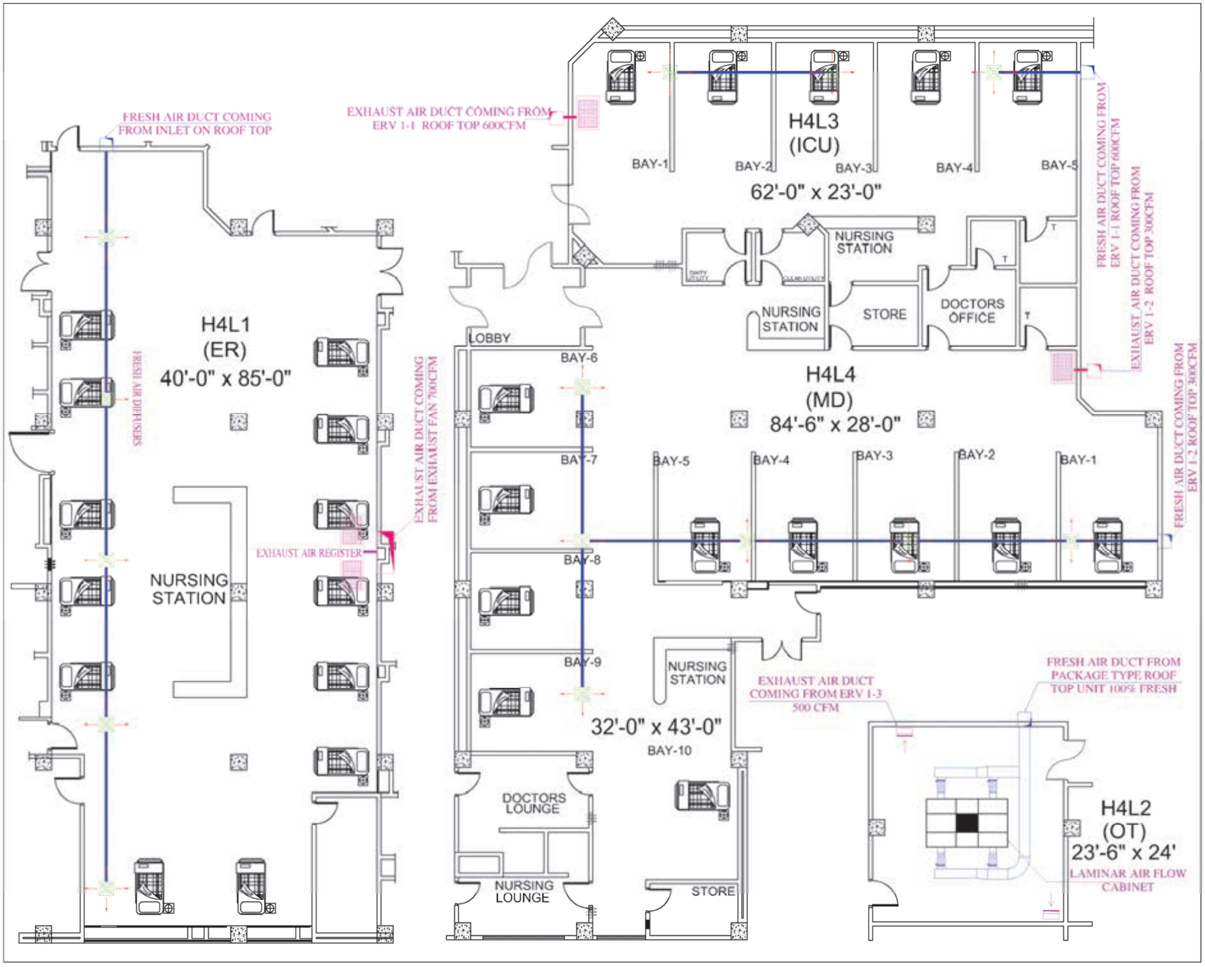

Fig. 11. Retrofit design for Hospital 4

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