IMPROVING INDOOR ENVIRONMENTAL QUALITY (IEQ) IN HEALTH CARE FACILITIES THROUGH RETROFITTING

Thesis of

Master in Science

Construction Engineering and Management

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December, 2018

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has been accepted towards the partial fulfillment

of the requirements for the degree of

Masters of Science in Construction Engineering and Management

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Dedication

This thesis is dedicated to my supporting husband; Haris Khan, my hardworking and dedicated parents and my loving siblings

ACKNOWLEDGEMENTS

First of all I thank and praise to ALLAH AMIGHTY for making me able to complete this endeavor. I am also grateful to NUST for allowing me to study here and providing me every facility for the completion of this research. I am also thankful to my thesis advisor Dr. M. Jamaluddin Thaheem, who has helped me in each and every difficulty during this journey specially in arranging the additional research fund from the university. I would like to thank all my committee members Dr. Hamza Farooq Gabriel, Dr. Ahsen Maqsoom and Dr. Zeeshan Ali Khan for their utmost supervision and valuable insights to complete this research. Without their support and encouragement it would not have been possible for me to come over all obstacles I faced in the course of my research.

CONTENTS

LIST OF TABLES

ABSTRACT

Healthcare facilities ensure cure from the ailment while providing a better and clean environment. A good indoor environmental quality (IEQ) can improve the recovery process and create a pleasant working environment. And, a poor IEQ causes nosocomial diseases which are harmful for the patients as well the hospital staff. To assess the state of IEQ in selected local hospitals, current study investigates critical IEQ parameters. Based on a detailed literature synthesis, three parameters are selected (temperature, relative humidity and CO_2) for IEQ assessment in four local hospitals. Four different locations (emergency room, operation theater, intensive care unit and medical ward) in each hospital are considered with respect to the existing HVAC system. Data is recorded on 5 minutes interval for 6 days uninterruptedly and mean hourly value for each location is calculated for 24 hours. Statistical analysis is performed to compare the day- and night-time IEQ trends. Significant difference is found in day- and night-time observations for operation theaters while random trends are noticed in emergency areas. The results govern that fact that occupancy rate, ambient thermal conditions, type of HVAC system and building orientation are vital drivers of IEQ. Ventilation rates for each location are calculated through three balance equations identified from the literature review. Required ventilation rates for the three selected parameters are calculated through the equation provided in ASHRAE guidelines and validated through modeling and simulation using AnyLogic 8. In conclusion, design and retrofitting recommendations are provided.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND:

Healthcare facilities are built to ensure better quality medical treatment and nursing care to the patients (Michael Leung, 2006). To achieve these and other wellness standards, accurate design of a healthcare facility is imperative. The design accuracy demands to ensure effective ventilation, air conditioning and air supply since they ensure wellness standards of a healthcare facility (Yu et al., 2009). Noncompliance of such standards results into an unhealthy, stale and poor ambiance which can cause indoor environmental pollution and result into exposure to hospital-associated infections (HAIs) (CDPH, 2016; Mohammadpour et al., 2017; Ishtiaq et al., 2017; Baqi et al., 2009). Making matters worse, patients affected with HAIs remain hospitalized for an average of 20.6 days, while the same duration for a normal patient is 4.5 days. This prolonged stay increases the hospital expenditure almost six times as compared to average (Kluger et al., 2007). A major factor in controlling the HAIs is the provision of good indoor environmental quality (IEQ) that can help in preventing the hazardous viruses and bacteria to propel through the air. Contrary to that, bad IEQ can cause sick building syndrome, fatigue, nausea, eye and skin irritation and many other symptoms of discomfort (Sundell et al., 2011; Leung and Chan, 2006; Mohammadpour et al., 2017). Generally, the indoor air pollution accounts for 28,000 deaths a year and 40 million cases of acute respiratory illness (Colbeck et al., 2010).

As the occupants and nature of services are different in hospitals, its environment also varies from a normal commercial or industrial building, demanding special architectural and mechanical design considerations. Therefore, major design guidelines for healthcare facilities given by World Health Organization (WHO) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) are very particular about physical and functional features of these buildings (Organization, 2016; ASHRAE, 2007). Compliance of these guidelines can help achieve the standard levels of IEQ. In doing so, ASHRAE supports the mechanical interventions such as ventilation for circulation of air which enhances the IEQ (ASHRAE, 2007).

There are various factors that affect the IEQ such as temperature, moisture, precipitation, amount of chemicals and pollutants in the air and the quality of outdoor air imported to the indoor environment. On the other hand, carbon dioxide (CO_2) is the basic indicator for building ventilation rates (Bakó-Biró et al., 2012; Ng et al., 2011; Turanjanin et al., 2014). Its affect is such that CO_2 levels can negatively affect the human decision-making capabilities; at 2500 ppm or lower, this performance becomes marginal and in some cases even dysfunctional (Satish et al., 2011). Thus, these IEQ factors directly affect the occupants of a healthcare facility and are a measure of their satisfaction. Therefore, they should be controlled and monitored as a priority (El-Sharkawy and Noweir, 2014).

1.2 LEVEL OF RESEARCH OUT ON THE TOPIC:

There exists a sizeable research on building IEQ (Chao and Hu, 2004b); indoor air quality of educational institutes has been broadly measured and analyzed (Cartieaux et al., 2011; de Gennaro et al., 2014; Asif et al., 2018b; Branco et al., 2015; Annesi-Maesano et al., 2013) and the acceptable thermal comfort level has been established (Lomas and Giridharan, 2012; Khodakarami and Nasrollahi, 2012; Pourshaghaghy and Omidvari, 2012)). Also, most studies are carried out in cold climatic regions like USA, Canada, UK and other European countries (Candanedo and Feldheim, 2016; Wei et al., 2015; St-Jean et al., 2012). But there are limited studies on the collective and comparative analysis of thermal comfort and ventilation rates. It is quite rare to find a study comprehensively covering the aspects of indoor temperature, relative humidity and CO_2 concentration in a complex facility like a hospital located in hot and humid climate (Pourshaghaghy and Omidvari, 2012).

1.3 RELEVANCE TO NATIONAL NEEDS:

The context of investigation for the current study is Pakistan which is a developing country and does not have proper air quality management schemes. This causes grave problems in the local healthcare sector. According to a local study, for healthcare and better environment, air quality can be determined by the particulate matter levels imparted by various indoor activities and infiltration from outdoor (Gulshan et al., 2015). A recent study shows that the quality of atmosphere in three local hospitals is affected by the visitors occupancy level. It is concluded that the importance of HAIs in Pakistan is progressivley increasing because of several reported cases of nosocomial infection caused by contaminated air (Ishtiaq et al., 2017). Another survey was conducted in local hospitals to evaluate the present hygiene and environmental conditions. The findings reveal lack in the practice of correct infection control. It is claimed that these findings are not particular to just the three surveyed hospitals, but the results can be generalized for almost all the hospitals of the country (Baqi et al., 2009).

1.4 OBJECTIVES:

In the light of existing appalling state of practice, the main objectives of current study are;

1. To identify and analyze the present condition of IEQ in local healthcare facilities
2. To identify the retrofitting techniques to improve IEQ through better ventilation
3. To simulate the current conditions on the basis of required ventilation
4. To design retrofit intervention for IEQ improvement

1.5 ADVANTAGES OF RESEARCH:

At the end, suggestions for retrofitting techniques are given. Improved air quality in a healthcare facility reduces the energy use. Improving airflow and ventilation, maintaining humidity and carbon dioxide levels can result into optimization of HVAC system and it also ensures that the load is reduced on the equipment. Efficiency certainly leads to reduced costs on electricity bills. Better IEQ is achieved after removing the harmful and toxic agents from the ambiance. These particles/agents can cause allergies, sneezing, congestion, an itchy throat, and irritated eyes. Improved IEQ helps get rid of these possibilities of discomfort. It can help reduce the odors, especially in hospitals, as there are pungent smells of various drugs and medicines. Humidity is also a factor that affects the IEQ. Hospital being the populated facility faces the problem of humidity in hot climate. Moisture level in air can be the cause of mold growth and increased dust mite population. That can also generate bacteria and attract pests. Similarly, low level of moisture can be the reason for skin irritation, nose bleed and dryness. This study can benefit the hospital management to pay attention to the IEQ which will ensure a comfortable atmosphere to the patients.

CHAPTER 2

LITRETURE REVIEW

2.1 IEQ FACTORS

The reason that the patient should not stay longer in a hospital is not only to reduce the hospitalization expenditure but also to avoid unnecessary exposure to HAIs (Graves et al., 2007; Capolongo et al., 2017). Since patients are already in a delicate condition due to suffering from ailment, the chances of getting affected by more infections increase. Likewise other occupants and users of healthcare facilities such as doctors, nurses, visitors and hospital staff are also exposed to the risk of developing life threatening diseases (Capolongo et al., 2017). And since poor environmental conditions can lead to high cost of energy consumption and low productivity, it is essential to provide comfortable conditions to the occupants to ensure health and sustainability (Asadi et al., 2017; Schellen et al., 2010). The role of design and operations of the built environment, where these individuals spend considerable amount of time, in addressing health issues has been duly noted (Lee and Kim, 2008). In this regard, China has since long moved its legislation to maintain the indoor environmental quality of the buildings (Lai and Yik, 2007).

Researchers have highlighted the role of healthy buildings and their effectiveness towards better IEQ. In a study on residential buildings, the results show that certain measures can be taken to improve IEQ along with reducing the energy consumption (Noris et al., 2013). Also, it was shown in a thermo-graphic investigation that considerable amount of energy can be saved by the improvement of building envelop and effective insulation (Buonomano et al., 2014). Further, three healthcare buildings were selected to enable a detailed review of current retrofit approaches in the healthcare industry, with particular attention to provisions for patient safety and energy efficiency. It was found that some of the construction activities had a direct impact on patients and their wellbeing during the retrofit projects (Mohammadpour et al., 2017).

Indoor environment comprises of five main factors which are comfortable temperature, indoor air quality, acoustic control, odor control and optical comfort (Abbaszadeh et al., 2006; Asadi et al., 2017; Angelova, 2016). These factors are both compound in their nature and interconnected in their function. For example, the compounding is such that comfortable temperature consists of temperature and relative humidity. And the interconnectedness is such that temperature, relative humidity, CO_2 and number of occupants significantly influence the indoor air quality of a healthcare facility (Wan et al., 2011). Further, fungal particles are also considered as a vigorous contaminant in healthcare environment, and their concentration is found to increase mostly during the construction or restoration works (Sautour et al., 2007). Lastly, the interconnected factor of indoor air quality is assessed through various other factors such as carbon monoxide (CO), total volatile compounds (TVOCs), aldehydes (-CHO), ozone (O_3), particulate matters (PM 1, PM 2.5,PM 10), radon gas (Rn), nitrous oxide (N_2O) and airborne microbial contaminants (Michael Leung, 2006).

However, the entire assessment of IEQ is based on direct measurements of its factors and parameters (ASHRAE). This task can become exceedingly daunting with many factors and parameters due to constraints of time and resources. Therefore, to reach to the most significant and contributing factors, a detailed desk exercise was carried out. In this process, following the methodology of a similar research, literature was retrieved using keywords such as ‘indoor environmental quality’, ‘indoor air quality’, ‘healthcare buildings and indoor environment’ (Ullah et al., 2016). As a result, 18 research papers were retrieved and used for identifying and synthesizing the IEQ factors. A total of 18 factors were identified from the selected papers and then a two-step content analysis methodology was adopted for shortlisting. In the first step, frequency of appearance of a factor in all the papers under consideration was counted and accumulated. In the second step, the qualitative score in terms of high (H), medium (M) and low (L) was allotted to each factor after carefully reading its significance in each paper it has appeared in. This qualitative score was then converted into a semi quantitative scale (H=5, M=3 and L=1). Finally, as shown in Table 2-1, literature score was calculated using Equation 1 which was then normalized and used to highlight the significance of all identified factors and shortlist the most significance ones.

$$Literature\ Score = Qualitative\ Score\ \ x\ \left(\frac{Frequency}{Total\ No. of\ \ Papers\ x\ 5}\right) \qquad Equation\ 1$$

As a result, three top factors, accounting for 40% of overall score, are selected: temperature (T), relative humidity (RH) and carbon dioxide (CO_2). These factors are considered for data collection and analysis.

Table 2-1 Literature analysis of IEQ factors

#	Parameter	Frequency	Qualitative Score	Literature Score
1	Relative humidity	13	3	0.139
2	Temperature	12	3	0.129
3	Carbon dioxide	12	3	0.129
4	Total volatile organic compounds	10	3	0.107
5	Particulate matter 10	8	3	0.086
6	Aldehydes	7	3	0.075
7	Airborne bacteria count	6	3	0.064
8	Particulate matter 2.5	6	3	0.064
9	Fungi	3	5	0.054
10	Ozone	3	3	0.032
11	Nitrogen dioxide	7	1	0.025
12	Carbon monoxide	6	1	0.021
13	Particulate matter 1	2	3	0.021
14	Radon	2	3	0.021
15	Sulphur dioxide	4	1	0.014

16	Nitric Oxide	1	3	0.011
17	Bio aerosols contaminants	1	1	0.004
18	Lead	1	1	0.004

2.2 VENTILATION RATES AND INDOOR ENVIRONMENT

It is recognized that ventilation design is a vital component in the architectural design that impact the productivity and health of occupants (Meadow et al., 2014). Similarly, in 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 i.e. temperature difference between outdoor and indoor environment which will create buoyancy effect (Saadatjoo et al., 2018). Natural ventilation is considered as an energy efficient strategy which also increase 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 the excessive energy consumption, 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 substitutes the concentration of indoor CO_2 (Bhattacharya et al., 2012; Seppänen et al., 1999). Overall, there is inconstant 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 a sizeable research on the importance of ventilation requirement and strategies for indoor environmental control. For example, a study was conducted on the operation and maintenance of HVAC system in a healthcare facility because it has strict ventilation requirement. It was found that the capacity of the HVAC system must be in accordance with 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 office building to study 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 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, there was a research in the neighboring country; India, on the similar matter. It was 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 HVAC system. That results into notable effect of outdoor air in the quality of 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, it states two methods to improve IEQ in breathing area without altering the energy consumption of ventilation. First is to control operation of ventilation system and second is to modify arrangement of building internal layout (Zhuang et al., 2014). In the context of healthcare facilities, a study validated the fact that naturally ventilated wards have more comfortable indoor environment at night-time. Also these would be stronger design with respect to 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 prominent effect on the indoor environmental quality and its components i.e. T, RH & CO_2 (Ramachandran et al., 2005; Korjenic et al., 2010; Branco et al., 2015). These ventilation rates can be improved by suitable retrofitting techniques (Santamouris and Dascalaki, 2002).

2.3 WHAT IS RETROFITTING?

Retrofitting is *"a set of interventions, dictated by a coherent architectural attitude and technically optimized, in particular through a full coordination of the interventions on the sheathing surfaces and the technical installations"*. When a building is retrofitted, the design and operations of the facility is taken into account for the modification and improvement of a specific field (Rey, 2004). It denotes to all actions and suggestion of efficient technology, systems and services which helps in reducing the utilization of energy (Gholami et al., 2015). It varies from the concept of renovation and uplifting on any facility as it is not applied for the aesthetics and practical aspect, it mainly aims to reduce the energy consumption (Baeli, 2013). Even if the reduction of CO_2 from indoor air is critical but during the process, thermal and functional comfort matters should be considered (Suhr et al., 2013).

2.4 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 research purpose we have simulated the results with the given inputs values related to human beings (Blanes and Pedersen, 2005).

2.4.1 Heat balance

The heat balance is stated by the following equation 2:

$$V = \frac{S_b - AU\Delta t}{c\Delta t} \qquad Equation\ 2$$

While S_b is the sensible heat per person ‘W’, Where A is the surface area of each selected location, m^2, heat transmission coefficient for building surfaces is donated by U, W/m^2 K, the difference of temperature in indoor and outdoor is expressed as Δt, K. the readings were collected in °C, so 273.15 was added in each value for the conversion in K. c is the specific heat of air, 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).

2.4.2 Moisture Balance

The ventilations rates calculated with related humidity are expressed as humidity balance equation 3. As¸ L=Δ *H V*680. Hence,

$$V = \frac{L}{\Delta H \times 680} \qquad Equation\ 3$$

The difference between indoor and outdoor humidity levels are shown by ΔH, kg/m^3.

While, L is the latent heat of 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.

2.4.3 Carbon dioxide balance

It is already known that the ratio of concentration of indoor and outdoor CO_2 indicates the ventilation rates in the building (Zhuang et al., 2014). Alike the mentioned two equations, ventilations rates can also be determined by indoor and outdoor CO_2 levels. The formula for this is expressed as equation 4.

$$V = \frac{C}{\Delta C\ \times\ 10^{-6}} \qquad Equation\ 4$$

2.5 MODELING AND SIMULATION

Modeling and Simulation is a technique which is very effective in the fields of academics, decision making, feasibility reports and analysis. It has been used as the recent emerging technology tool and attained a position in various domains e.g. industries, defence departments and healthcare facilities. Consequently, the vast utility of the technique, wide range of simulation and modeling tools are required in 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 as the simplest of form of computing data and getting required outputs. Data needs to be entered in one cell and output is shown in another one. But the limitation always remain that there is no visual representation or any inflow out flow diagram. It also has 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, dynamic behavior of any model is also need to be described. Therefore, alternative modeling tool is required to analyze dynamic systems(Grigoryev, 2015). AnyLogic is a known complex system analysis tool for the simulation and modeling, considered amongst the best for agent based modeling, discrete events and system dynamics (Garifullin et al., 2007; Borshchev and Filippov, 2004; Hu, 2017). While having broad graphical abilities, AnyLogic allows pre-developed theories to define agent behavior, connections and environmental linkages (Borshchev and Filippov, 2004). A simulation model is a continuously running program which operates on the trajectory provided by the programmer. Like other programing methods, these models have own set of rules which are in the form of analytical equations, Flow charts, timelines and system dependent diagrams. As the model executes, the outputs are established and observed. Data entry and model formation is not difficult for the spreadsheet user because both process are relatable (Grigoryev, 2015).

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

CHAPTER 3

RESEARCH METHODOLOGY

This study is conducted following a structured and formal research methodology as shown in Figure 3-1. The entire process is divided into three stages which are explained in the subsequent sections.

3.1 STAGE I

This stage outlines the genesis of the entire study and deals with some fundamental aspects that include the selection of topic along with the formulation of problem statement and research objectives. Background knowledge was gathered in the light of published articles to identify the gap in the current research. Different questions pertaining to requirement, basic advantages, application and reasons for selection of this topic were answered at this stage.

After the completion of introduction phase, a detailed literature review was conducted to reveal the importance of IEQ especially in the healthcare facilities and how they can be improved. Through the detailed study of articles published between the years 2000-2017, 18 factors of IEQ were identified (Hasnain et al., 2018). The identified factors were evaluated through a content analysis and the top three factors were selected, as previously explained (Siddiqui et al., 2016).

3.2 STAGE II

This stage involves planning, preparing and collecting primary data to achieve the study objectives. As reported in past studies, researchers have collected data through interviews and questionnaire surveys from the hospital occupants to evaluate the comfort conditions (Hellgren et al., 2011). But to enhance the reliability of findings, this study used primary data for which a two-step collection process was designed. In the first step, the most suitable

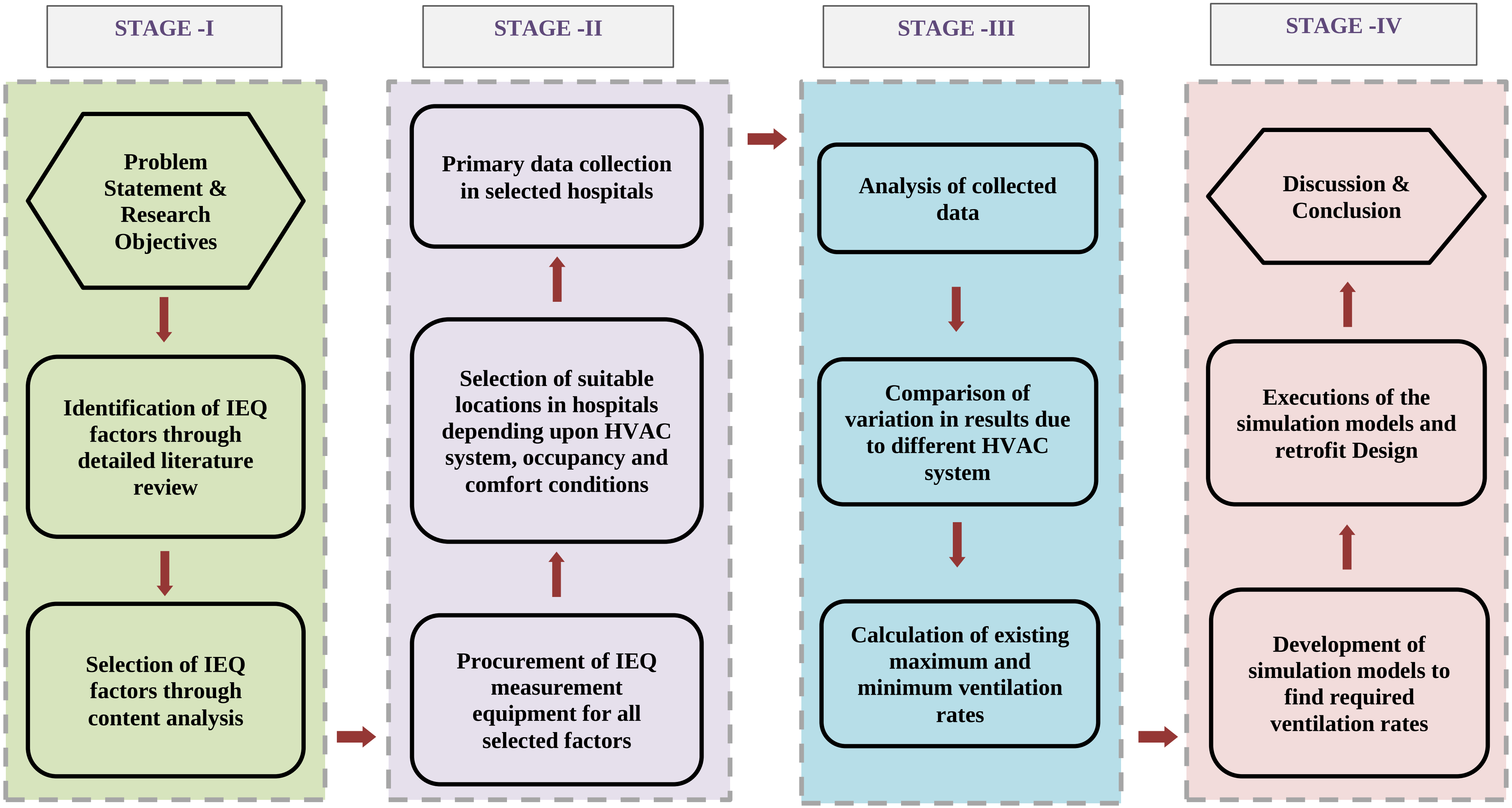

Figure 3-1 Research Methodology

equipment for the measurement of selected IEQ factors was identified. As part of this, various IEQ meters were reviewed after market survey and specification evaluation. Their technical details are given in Table 3-1. It is important to note that to avoid any commercial conflict, the brand names are not specified and instead code names are given. Commercial information can be provided by the authors on request. Additionally, along with a mention in the local currency (PKR), prices are also specified in US $ for better understanding by the international readers. After considering the quality, price and accessibility of the available options, Equipment 1 was found suitable and thus procured.

Table 3-1 Technical specifications of IEQ meters

Code	Parameter	Measuring Range	Accuracy	Made	Price Range (PKR)
Equipment 1	T	0ºC to 50º C	±0.8 ºC	USA	45,000-50,000 (US $ 365-405)
	RH	10 to 90 %	±4% RH		
	CO_2	0 to 4000 ppm	±40 ppm(<1000ppm)		
Equipment 2	T	-10 ºC to 60 ºC	±0.6 ºC to ±0.9 ºC	Taiwan	30,000-35,000 (US $ 245-285)
	RH	10 to 99.9 %	±3% RH		
	CO_2	0 to 9000ppm	± 5% Reading		
Equipment 3	T	-10 ºC to 70 ºC	±1.2 ºC	China	10,000-15000 (US $ 80-120)
	RH	0.1% to 99.9%	±3% RH		
	CO_2	0 to 9999pm	± 5% Reading		

The second step was the assessment of existing condition of the three selected IEQ factors. For this purpose, keeping in view the convenience of data collection and possible variety of results, four different hospital facilities were selected. Three of them were semi-government hospitals with reserved rights of service while one was a public hospital. The number of hospitals were selected based on the sample size used in past research (Hellgren et al., 2011; Ishtiaq et al.). Details of the selected hospitals for data collection are given in Table 3-2. To avoid any bias and unnecessary disclosure, hospital names are encoded.

All the selected hospitals are located at two major cities; the three semi-government hospitals (H2, H3 and H4) are situated in the subtropical climatic area of twin cities of Islamabad-Rawalpindi, consisting of the capital of the country. The forth hospital (H1) is in Lahore, the second largest city of the country and capital of Punjab province. The climatic conditions for H1 were different from the rest as it is located in a semi-arid climatic zone (Sarfaraz et al., 2014; Mazhar et al., 2015). After the selection of hospitals, for installation of IEQ meters, four locations inside each hospital were indicated depending upon the occupancy, existing HVAC systems and current comfort (Branco et al., 2015; Asif et al., 2018a; Jung et al., 2015). These locations were:

1. Emergency room (ER) which is the most crowded and frequently used area.
2. Operation theater (OT) which is a highly sterilized and isolated area.
3. Intensive care unit (ICU) which is a highly monitored and controlled area.
4. Medical ward (MW) where patients are kept for a relatively longer period and attendants are allowed to visit.

The data was collected for a period of 6 days at each location, day and night, with data logging at an interval of 5 minutes (Asif et al., 2018b; Ferdyn-Grygierek, 2016). To represent the location according to their timeframe, suffixes ‘N’ and ‘D’ are used for night and day respectively. For example, H1L1N represents night-time of Location 1 in Hospital 1. To formalize the process, prior approvals were sought from the authorities at each hospital before installation of meters. IEQ data was recorded in the months of September, October and November of 2017 during which there is a pleasant weather in the region and does not require substantial use of air conditioning. This was done particularly to avoid variation in data due to extreme weather conditions which warrant a substantial use of cooling or heating (Guerra-Santin and Tweed, 2015).

Table 3-2 Description of location of data collection

Hospital Code	Total Beds	Department Name	Coordinates	AC type	Location	Location Codes
Hospital 1 (H1)	3000	Accident and Emergency Department	31.57N,74.31E	Fans and natural ventilation	ER (L1)	H1L1
					OT (L2)	H1L2
					ICU (L3)	H1L3
					MW (L4)	H1L4
Hospital 2 (H2)	800	Institute of Cardiology	33.59N,73.04E	Split units, exhaust and ceiling fans	ER (L1)	H2L1
					OT (L2)	H2L2
					ICU (L3)	H2L3
					MW (L4)	H2L4
Hospital 3 (H3)	2500	Accident and Emergency Department	33.58N,73.04E	Split units, exhaust and ceiling fans	ER (L1)	H3L1
					OT (L2)	H3L2
					ICU (L3)	H3L3
		OT Complex			MW (L4)	H3L4
Hospital 4 (H4)	1200	Accident and Emergency Department	33.59N,73.04E	Central air conditioning system	ER (L1)	H4L1
					OT (L2)	H4L2
					ICU (L3)	H4L3
					MW (L4)	H4L4

3.3 STAGE III

This stage deals with individual and comparative analysis of gathered data. In doing so, several analyses were performed to determine the variation in the raw data. MS Excel was used to take the mean hourly values which were then generalized to an entire day, giving only one day data for each location (Branco et al., 2015). The result of this study is divided in three parts. Firstly, the variation in day and night conditions is analyzed. Secondly, a comparison is made between the hourly means of same locations in all hospitals extended to 24 hours for all the three factors separately. For this purpose, Wilcoxon sign test has been performed using SPSS for both of the comparisons (Asif et al., 2018b). Thirdly, the percentage of exceedance from international standards is determined. Based on the collected data and information collected from the literature review, minimum and maximum ventilation rates for each location is calculated using MS Excel spreadsheet. These ventilation rates helped determining the allowable values of corresponding selected IEQ parameters.

3.4 STAGE IV

At the last stage, using AnyLogic 8, three different simulation models are developed based on three balance equations identified from the literature review (Pedersen et al., 1998; Borshchev and Filippov, 2004). The models are then executed by altering the inputs values, keeping the minimum and maximum ventilation rates in consideration, to determine the variation in selected IEQ parameter .These allowable values are compared to the given standards to validate the simulation model. Suitable retrofitting techniques are suggested in accordance with the range of required ventilation rates. . At the end, findings are discussed and conclusions are inferred to reach to practical implications and recommendations for practitioners as well as researchers.

CHAPTER 4

RESULT AND DISCUSSION

4.1 DESCRIPTIVE DATA RESULTS

The minimum and maximum values of the parameters for each location have been summarized in Table 4-1 for day- and night-time. The least indoor temperature (T) is recorded in H2L1N (21.5°C) and H3L3D (21.6°C) while the highest is recorded in H1L4N (27.7°C) and H1L4D (27.7°C). Similarly, minimum value of relative humidity is observed in H1L4D and H2L2D (34.4%), while the maximum value is observed in H2L4N (58.4%). The minimum CO_2 level is measured in H2L2N (386ppm) and maximum is observed in H1L4D (2042ppm).

Table 4-1 Descriptive Analysis of Recorded Data

Location	No. of Hours	T		RH		CO_2	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
H1L1N	12	25.9	26.7	36.5	43.2	1102	1601
H1L2N	12	25.1	25.6	49.7	55.4	1430	1991
H1L3N	12	26.5	26.8	45.3	48.1	1402	1794
H1L4N	12	26.8	**27.7**	34.7	43.8	919	1872
H2L1N	12	**21.5**	22.4	51.0	55.3	725	1210
H2L2N	12	23.7	25.4	35.5	47.4	**386**	445
H2L3N	12	24.3	26.3	49.3	55.6	620	821
H2L4N	12	24.7	25.5	51.3	**58.4**	815	1125
H3L1N	12	22.9	23.4	45.8	48.6	785	1090
H3L2N	12	24.4	24.7	45.6	47.3	869	945
H3L3N	12	22.2	23.8	48.2	53.4	770	830
H3L4N	12	22.9	23.7	46.1	49.4	519	798
H4L1N	12	23.7	24.2	39.3	44.6	470	636
H4L2N	12	23.5	25.5	41.3	47.1	466	499
H4L3N	12	23.9	24.2	43.9	47.9	488	553

H4L4N	12	23.8	24.0	41.3	47.1	476	537
H1L1D	12	25.5	26.9	36.5	44.4	1019	1976
H1L2D	12	24.6	25.1	50.4	53.2	1028	1744
H1L3D	12	26.5	26.7	43.6	47.0	1305	1629
H1L4D	12	26.6	**27.7**	**34.4**	46.5	933	**2042**
H2L1D	12	22.2	23.4	49.7	57.6	715	1223
H2L2D	12	23.5	25.4	**34.4**	42.7	407	518
H2L3D	12	24.5	25.7	46.5	51.2	608	836
H2L4D	12	25.2	26.2	50.8	57.2	786	1151
H3L1D	12	22.9	23.6	45.5	48.5	783	1021
H3L2D	12	22.6	24.9	45.5	54.4	855	1145
H3L3D	12	**21.6**	23.2	45.6	54.0	790	889
H3L4D	12	22.9	23.7	46.1	49.5	528	732
H4L1D	12	23.4	24.1	37.1	42.6	478	558
H4L2D	12	23.4	25.8	40.5	45.9	461	575
H4L3D	12	23.6	23.9	41.4	44.8	465	532
H4L4D	12	23.1	24.0	40.5	45.9	457	522

4.2 GRAPHS AND TRENDS

To illustrate the difference in day and night values of the measured parameters, the 24-hour data is divided into 12 hours. First 12 hours after sunset i.e. 6:00pm to 6:00am are considered as night-time, while other 12 hours i.e. 6:00 am to 6:00pm are considered as day-time. The 12-hourly data of each parameter is plotted for each selected location and variations are observed. The difference in the values of T, RH and CO_2 is because of type of human activity, orientation of building, ambient temperature, occupancy level and type of HVAC system (Asif et al., 2018b; Jung et al., 2015). Although there is no fixed time of occupancy level in hospital as it is a public place and data is recorded particularly in the emergency departments where occupancy level varies every hour, a peak time of 12:00pm is indicated by the hospital authorities. Therefore, 12:00pm is considered as the peak occupancy hour as reflected in the analysis.

4.3 TEMPERATURE

A graph is plotted between emergency rooms of each hospital with respect to day- and night-time. It can be observed in Figure 4-1 that H1L1N and H1L1D have the highest plotted values for T while H2L1D and H2L1N have the lowest values. It is seen that there is more fluctuation in the graph of H2L1, which indicates the instability in the temperature. Similarly, Figure 4-2 shows the variation of temperature in the OTs during day- and night-time. H3L2D has the lowest temperature at the start of the day, but it gradually increases as the day progresses. The same trend is seen in other locations as well. H1L2N, H1L2D and H3L2N do not show any sudden change in the temperature throughout the observation period.

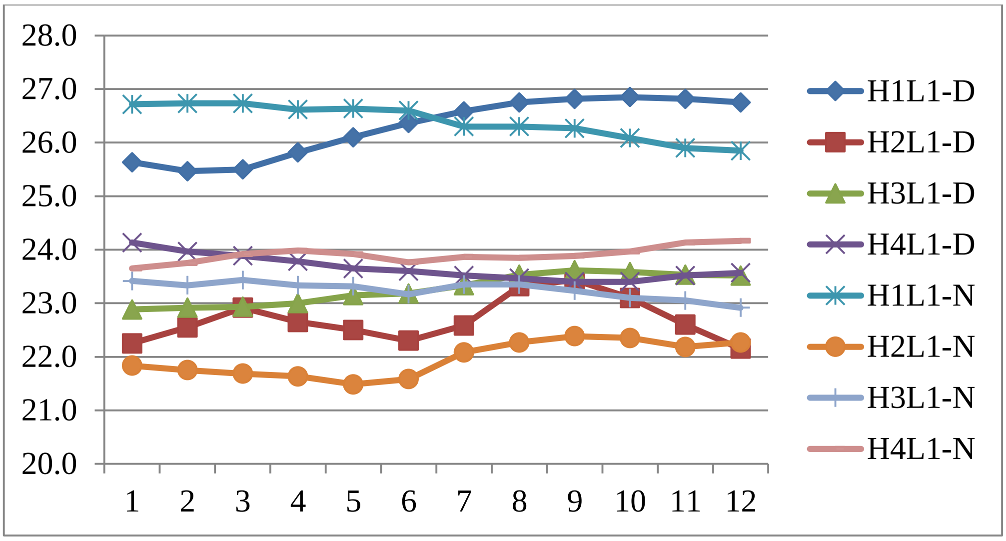

Figure 4-1 Indoor temperature in ERs

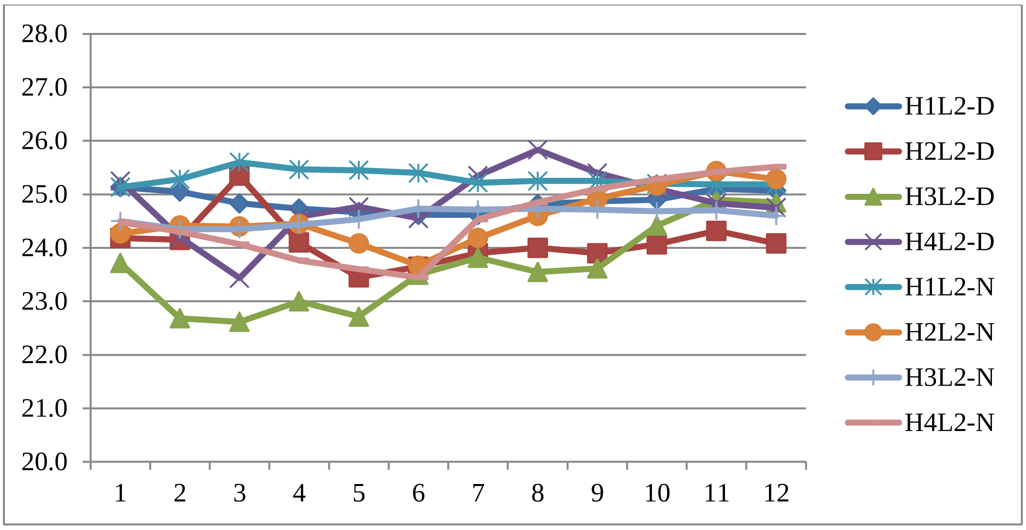

Figure 4-2 Indoor temperature in OTs

The temperature trend in ICUs is shown in Figure 4-3. As the area remains isolated, consistent trend is noticed in all the ICUs. The temperature remains constant for 24 hours in H1L3 and H4L3. However, H3L3 shows a little decrease in the temperature during the early hours. H2L3D and H2L3N also show an increase of temperature around peak time. In Figure 4-4, mostly linear temperature trend is noticed in medical wards. H1L1D and H1L1N show an increased curve at the peak hours of the day. On the other hand, H2L4D and H2L4N show a slight diversity in the day-time but the overall temperature remains linear in other locations. This study shows that the temperature has not much diversity in other locations but only in OTs. The reason behind these fluctuating values is the unplanned, abrupt and large occupancy levels.

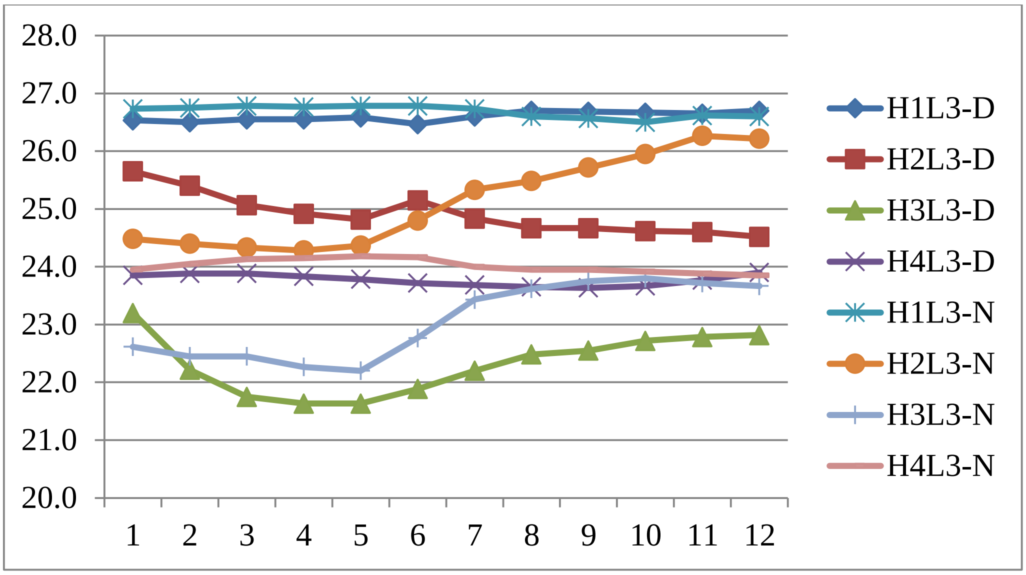

Figure 4-3 Indoor temperature in ICUs

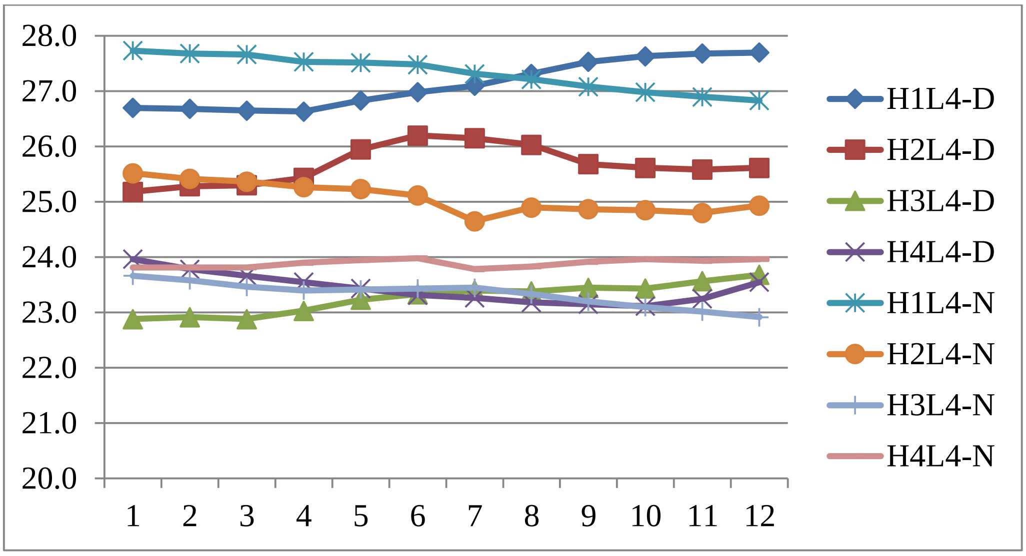

Figure 4-4 Indoor temperature in MWs

4.3.1 Day and night comparison (T)

Table 4-2 indicates the results of Wilcoxon sign test performed to determine the variation in day- and night-time temperature values in all the locations. H1L1 shows no significant deviation (p>0.05) during day- and night-time. Similarly, H1L3 and H1L4 also do not show any notable variation throughout the period. However, H1L2 shows a significant variation (p<0.05) which tells that there was a prominent difference in day- and night-time temperatures in OTs. Similarly, H2L1, H2L2 and H2L4 show a significant difference

($p<0.05$) while H2L3 has no difference in day and night readings of temperature. In H3, only H3L2 shows a significant difference ($p<0.05$) while other locations indicate a similar behavior throughout the time. An opposite trend is noticed in H4 where only H4L2 has no significant difference ($p>0.05$) and the overnight trend in all other locations in H4 is different. It is observed that L3 has the least variation in day- and night-time that implies it has a consistent atmosphere.

Table 4-2 Wilcoxon sign test statistics for T

	H1L1D - H1L1N	H1L2D - H1L2N	H1L3D - H1L3N	H1L4D - H1L4N
Asymp. Sig. (2-tailed)	.665	**.003**	.130	.254
	H2L1D - H2L1N	H2L2D - H2L2N	H2L3D - H2L3N	H2L4D - H2L4N
Asymp. Sig. (2-tailed)	**.003**	**.023**	.432	**.015**
	H3L1D - H3L1N	H3L2D - H3L2N	H3L3D - H3L3N	H3L4D - H3L4N
Asymp. Sig. (2-tailed)	.929	**.005**	.004	.637
	H4L1D - H4L1N	H4L2D - H4L2N	H4L3D - H4L3N	H4L4D - H4L4N
Asymp. Sig. (2-tailed)	**.028**	.099	**.003**	**.006**

4.4 RELATIVE HUMIDITY

The trend of relative humidity is directly related to the indoor occupancy rates and ventilation system of a building (Asif et al., 2018b).It is observed in Figure 4-5 that the highest value of relative humidity is observed in H2L1, where there is a notable increase during the peak time. This increment starts early in the morning and continues till the evening. It shows a slight raise in H3L1 during the night-time and the start of day. H4L1N and H1L1D share almost the same type of graph, and similar is the case with H4L1D and H1L1N.

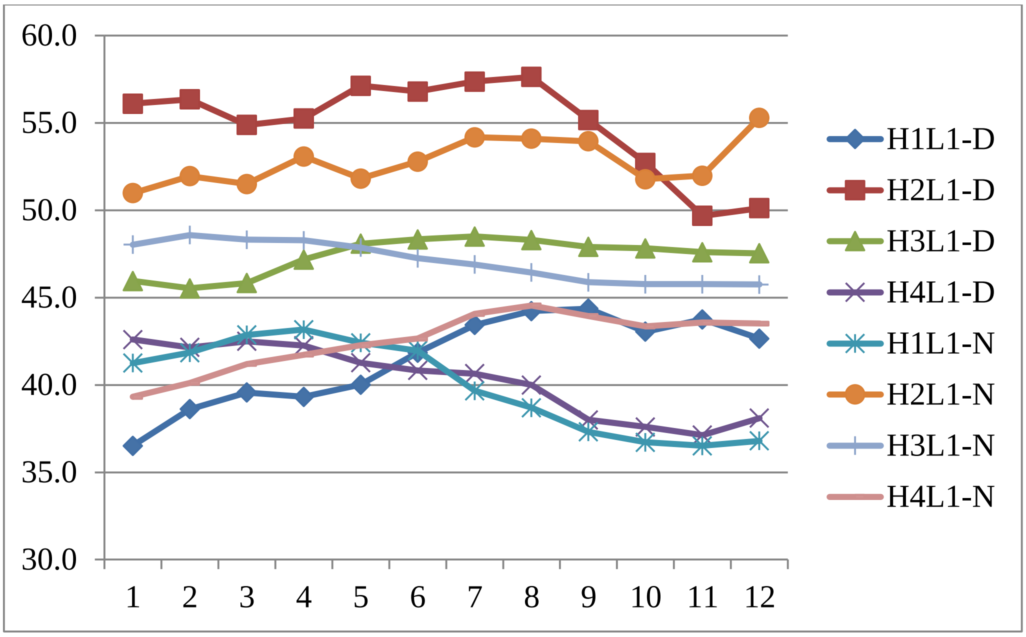

Figure 4-5 RH in ERs

In Figure 4-6, OTs in all the hospitals shows a random trend. For example, H2L2N has a sharp raise of relative humidity. It indicates the maximum number of occupancy during the night-time. H4L2D, H2L2D, H4L2D, H1L2N and H3L2D also have fluctuating graphs. Only H3L2 shows a linear graph at night because it was a scheduled OT room while others are casualty OTs with a mandate to operate on patients as and when required. It is evident from Figure 4-7 that ICUs also show an overall abrupt change of relative humidity levels; the most visible change is noticed in H3L3D and H3L3N. H2L3 shows increased relative humidity levels between the early morning and afternoon span. The graph of relative humidity levels in medical wards is vertically spread, which means there is a wide range of measured values.

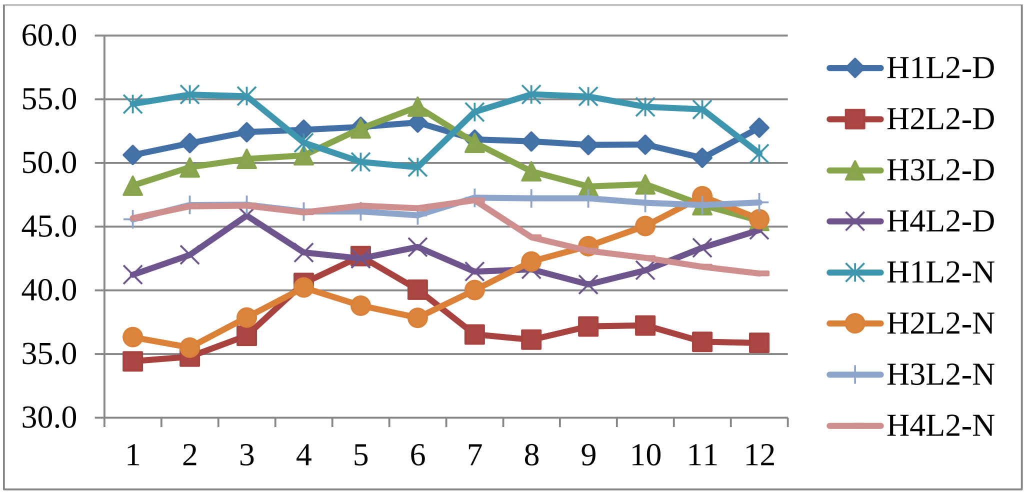

Figure 4-6 RH in OTs

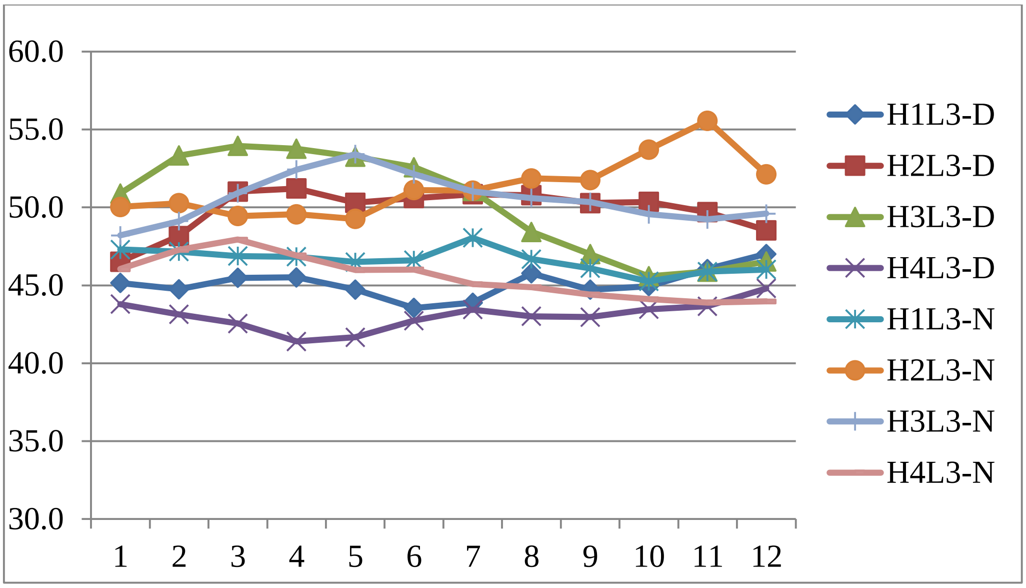

Figure 4-7 RH in ICUs

Finally, in Figure 4-8 , H1L4D and H1L4N show a single peak graph. H3L4N and H3L4D also have a consistent graph with a slight raise at 12:00pm. H2L4D, H2L4N and H4L4N have random values in the graphs. The graphs of OTs are the most converged and relative humidity is most controlled there.

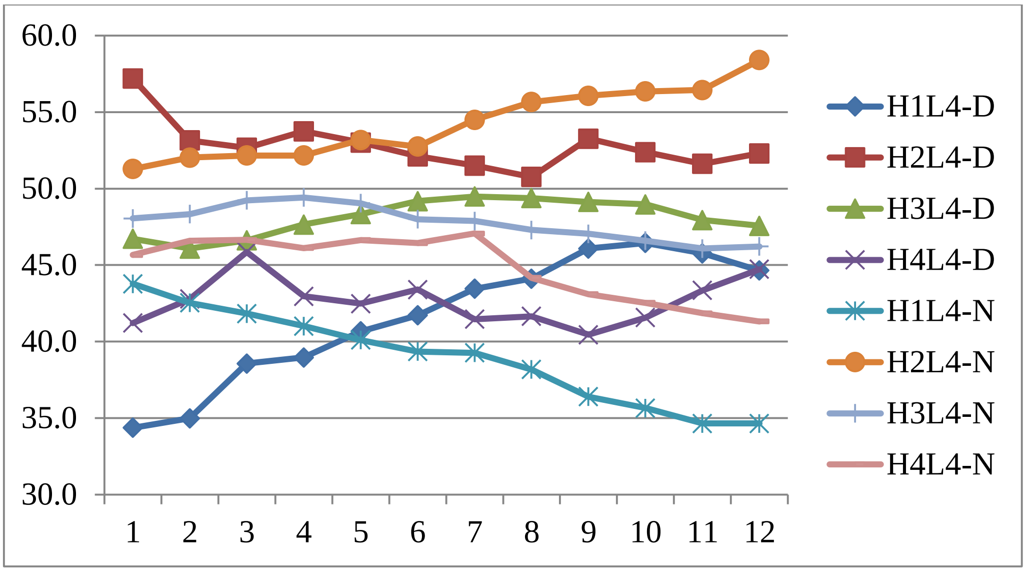

Figure 4-8 RH in MWs

4.4.1 Day and night comparison (RH)

It is seen in Table 4-3 that a significant difference ($p<0.05$) is noted in H1L3D and H1L3N, other locations in H1 show similar trends in values. In H2 and H3, only OTs indicate a significant difference ($p<0.05$) in night and day values. In H4, only H4L1 has no significant difference ($p>0.05$) while for all other locations, night-time values are different than those of day-time. An overall trend indicates that there is no difference observed in the emergency room in any of the hospitals.

Table 4-3 Wilcoxon sign test statistics for RH

	H1L1D - H1L1N	H1L2D - H1L2N	H1L3D - H1L3N	H1L4D - H1L4N
Asymp. Sig. (2-tailed)	.209	.050	**.008**	.158
	H2L1D - H2L1N	H2L2D - H2L2N	H2L3D - H2L3N	H2L4D - H2L4N
Asymp. Sig. (2-tailed)	.060	**.041**	.065	.182
	H3L1D - H3L1N	H3L2D - H3L2N	H3L3D - H3L3N	H3L4D - H3L4N
Asymp. Sig. (2-tailed)	.753	**.007**	.695	.610

	H4L1D - H4L1N	H4L2D - H4L2N	H4L3D - H4L3N	H4L4D - H4L4N
Asymp. Sig. (2-tailed)	.060	**.028**	**.005**	**.028**

4.5 CARBON DIOXIDE

As a universal indicator of indoor air quality, CO_2 indicates the presence of other indoor air pollutants and contaminants which lead to several signs of health risk (Branco et al., 2015). Hospitals are already full of health threats because most number of unhealthy and airborne diseases affected patients are present in the building (Capolongo et al., 2017). Like other parameters, CO_2 concentration graphs are drawn for each location in the hospitals. Figure 4-9 shows that there is a visible change in CO_2 levels of H1L1D and H1L1N. Emergency rooms have the most unplanned occupant density as the flow of people is dependent upon the casualty ratio. A high occupant density is observed at the late hours of night while morning is not so crowded. H4L1 shows almost linear graph of CO_2 with a slight raise in the evening time. As the OTs of H1 is utilized at maximum, the CO_2 concentration is highest, particularly during day-time and it is observed to be lowered in night-time.

In Figure 4-10 , H4L2N, H4L2D, H2L2N and H2L2D share a similar consistent trend with the lowest recorded CO_2 concentration. Figure 4-11 show that ICUs has a very stable CO2 levels in all the locations other than H1L3D and H1L3N. The CO_2 levels are highest during the morning time. It is visible in Figure 4-12 that medical wards are not monitored and controlled like ICUs, and the movement and occupancy are not regular. H1L4N and H1L4D have the highest CO_2 concentrations especially in evenings. Similarly, H2L4 and H3L4 show a comparable trend in days and nights. One the contrary, H4L4 was the lowest and most stable location in the observed medical wards.

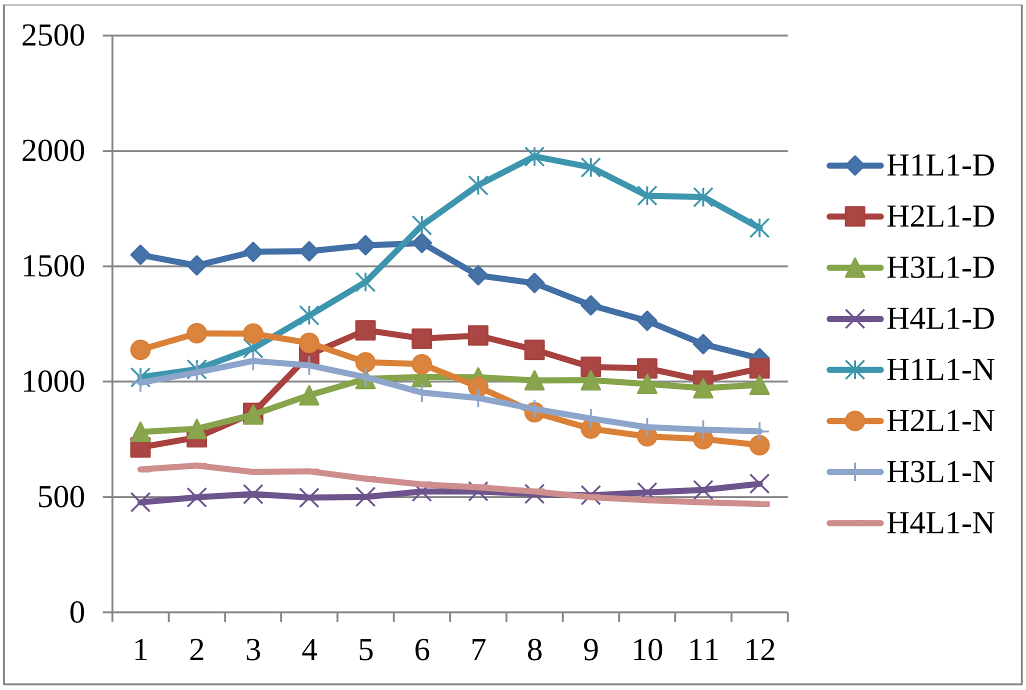

Figure 4-9 CO_2 in ERs

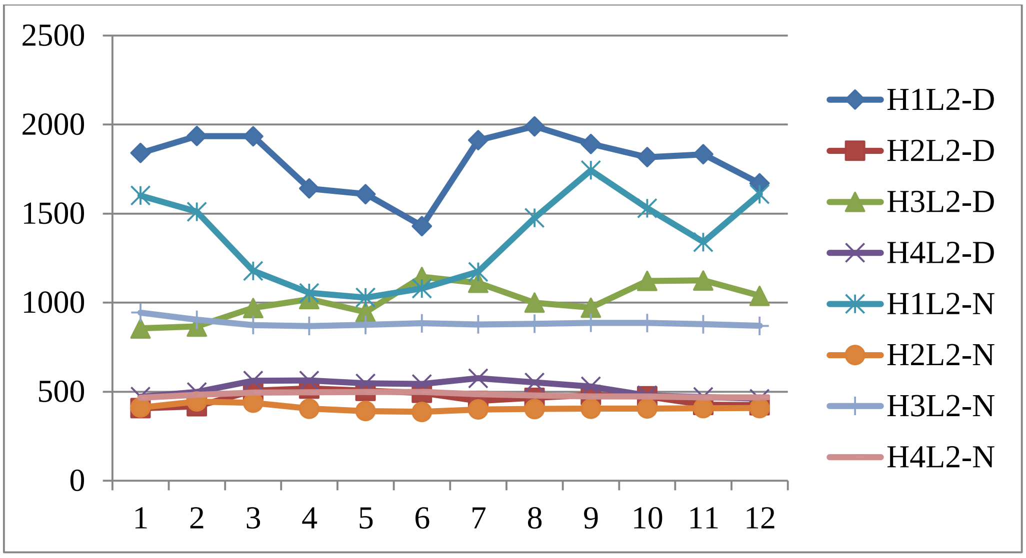

Figure 4-10 CO_2 in OTs

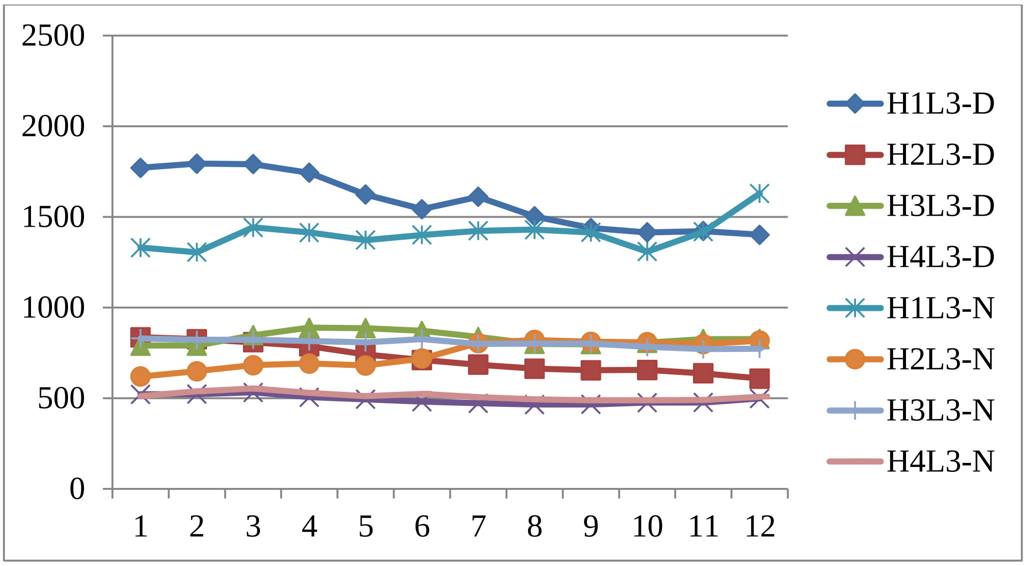

Figure 4-11 CO_2 in ICUs

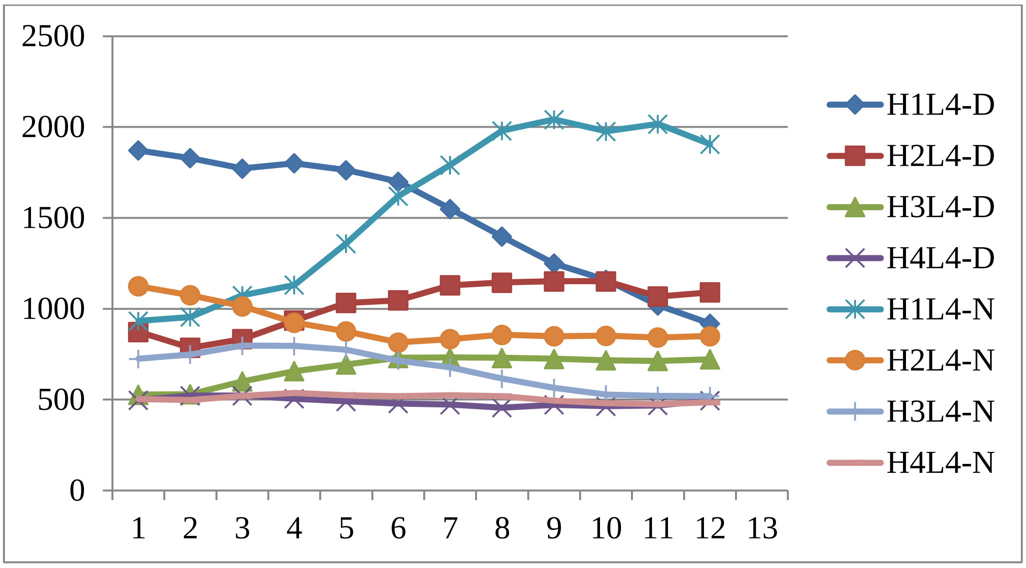

Figure 4-12 CO_2 in MWs

4.5.1 Day and night comparison (CO_2)

It can be noticed in Table 4-4 , there is no significant difference ($p>0.05$) in the day and night-time observations of emergency rooms in all the hospitals. Contrary to that, OTs have the most irregular trends in night and days as it is seen in all the hospitals. This indicates that the occupancy level and ventilation system have no prominent effect over 24 hours on CO_2

concentration. Only H4L4 shows a significance difference ($p<0.05$) and all other medical wards have similar trends for day- and night-time values.

Table 4-4 Wilcoxon sign test statistics for CO2

	H1L1D - H1L1N	H1L2D - H1L2N	H1L3D - H1L3N	H1L4D - H1L4N
Asymp. Sig. (2-tailed)	.209	**.002**	**.012**	.695
	H2L1D - H2L1N	H2L2D - H2L2N	H2L3D - H2L3N	H2L4D - H2L4N
Asymp. Sig. (2-tailed)	.695	**.008**	.583	.117
	H3L1D - H3L1N	H3L2D - H3L2N	H3L3D - H3L3N	H3L4D - H3L4N
Asymp. Sig. (2-tailed)	1.000	**.008**	.060	1.000
	H4L1D - H4L1N	H4L2D - H4L2N	H4L3D - H4L3N	H4L4D - H4L4N
Asymp. Sig. (2-tailed)	.136	**.006**	**.004**	**.034**

4.6 PERCENTAGE EXCEEDANCE FROM STANDARDS

To ensure maximum accuracy in measuring the percentage exceedance from the standards, three standards for each selected parameter are 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 (Lee and Chang, 2000; ASHRAE, 2007). The closest value available in any of the selected standards is considered for comparison. This is done to observe the minimum level of exceedance which is already alarming enough. The larger values can also be used but they would amount to unnecessary huge exceedance which is not the purpose of any scientific study. 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., 2018b).

Table 4-5 Exceedance from the standards

Hospital Code	**Location Code**	**Temperature (%)**				**RH (%)**				**CO_2 (%)**			
		Nights		**Days**		**Nights**		**Days**		**Nights**		**Days**	
		<20	**>24**	**<20**	**>24**	**<45**	**>55**	**<45**	**>55**	**<600**	**>1000**	**<600**	**>1000**
H1	**L1**	0	100	0	100	0	100	0	100	0	100	0	100
	L2	0	100	0	100	33.3	0	0	0	0	100	0	100
	L3	0	100	0	100	0	0	0	50	0	100	0	100
	L4	0	100	0	100	0	100	0	75	0	83.3	0	91.7
H2	**L1**	0	0	0	0	0	8.3	0	66.7	0	50	0	75
	L2	0	91.7	0	58.3	75	0	100	0	100	0	100	0
	L3	0	100	0	100	0	8.3	0	0	0	0	0	0
	L4	0	100	0	100	0	41.7	0	8.3	0	25	0	66.7
H3	**L1**	0	0	0	0	0	0	0	0	0	33.3	0	41.7
	L2	0	100	0	25	0	0	0	0	0	0	0	50
	L3	0	0	0	0	0	0	0	0	0	0	0	0
	L4	0	0	0	0	0	0	0	0	33.3	0	16.7	0
H4	**L1**	0	16.7	0	8.3	100	0	100	0	66.7	0	100	0
	L2	0	75	0	91.7	41.7	0	91.7	0	100	0	100	0
	L3	0	41.7	0	0	41.7	0	100	0	100	0	100	0
	L4	0	0	0	0	41.7	0	91.7	0	100	0	100	0

Is can be seen in Table 4-5 , that the observed data that none of the locations exceeds the lower limit of temperature during day- and night-times as per the standards. But in H1, all the locations exceed the upper limit of standards. Also, H2L3 and H2L4 cross the upper limits. But, H4 reports the minimum exceedance from the upper limit of temperature standards. Similarly, in days, none of the location has a lower value than the lower limit of standard indoor temperature values.

In terms of relative humidity, H3 does not show any exceedance during day- and night-times. However, H4 has crossed lower limits of relative humidity levels but not the upper limits. In H1, standard upper limit of indoor CO_2 concentrations is crossed in almost all the locations. Even after having centralized air conditioning system and controlled upper limit standards, the parameters do not observe the lower limits of standards. This indicates that balance in the occupancy and ventilation is also necessary. In case of observing standards, H3 has the most suitable values. This complies with the installed combination of exhaust fans and split air conditioners, and also shown that the movement of occupants is controlled.

4.7 HOSPITAL AREA PLANS

Figure 4-13 shows the architectural plans of hospital 1 and hospital 2. All the layouts of selected four locations from each hospital are given to visualize the space allocation with respect to the number of beds. Hospital 1 had a spacious ER with 4 different bays and 7 beds each bay, but being a central hospital for public, it was sometimes overcrowded. OT in H1 was not so spacious but was used frequently being an unscheduled OT in accident and emergency block. ICU and MW shared similar type of layout but different occupancy level as ICU was entry restricted area. ER in H2 was divided in male and female areas. Occupancy rate was high. The OT was situated in peads block and it was scheduled, thus occupancy levels were not inconsistent. Similarly ICU was also situated in peads block and it was slightly spacious then other ICUs. MW was normally ventilated and occupancy level was higher as compared to the number of beds.

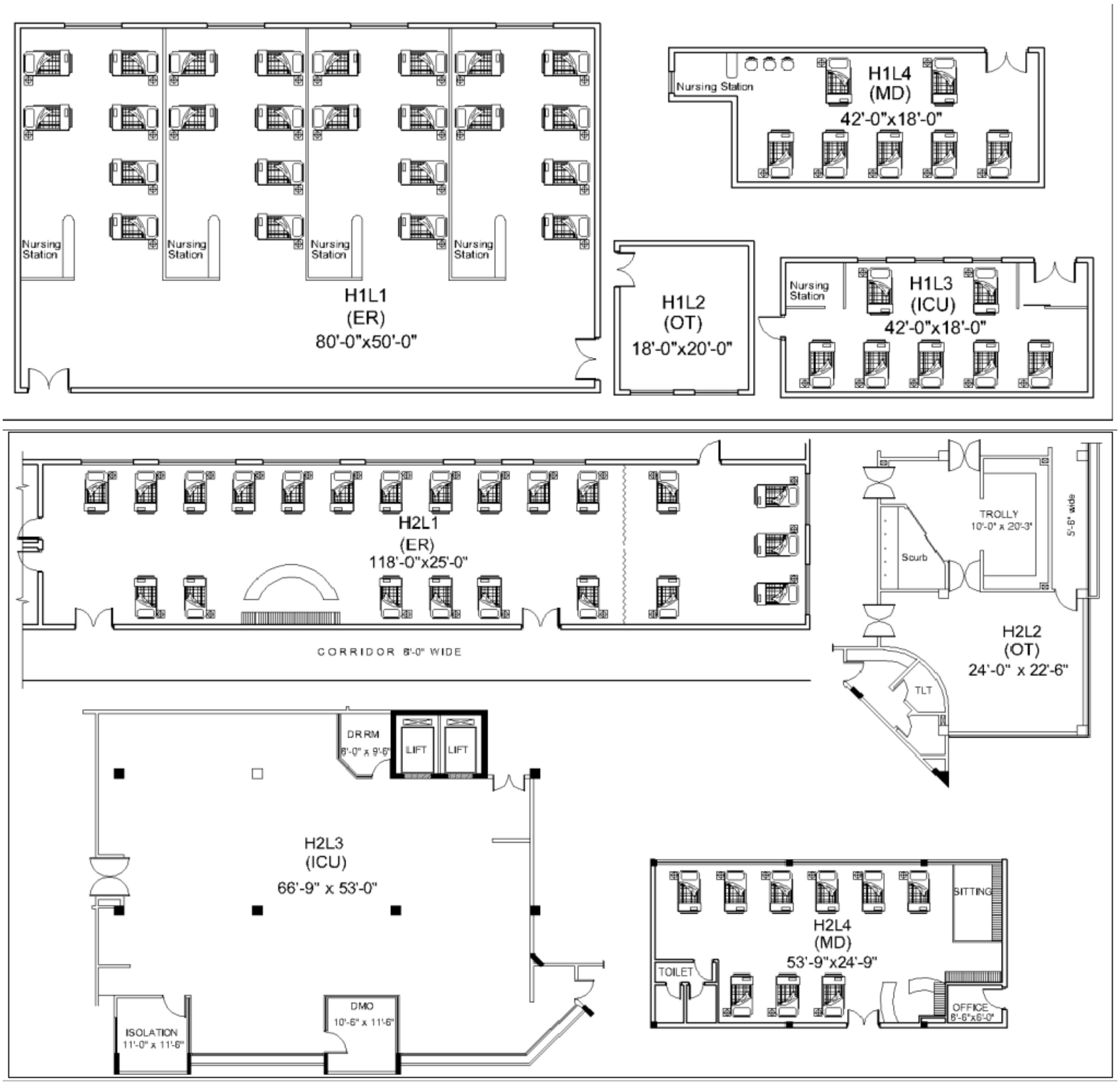

Figure 4-13 Architectural layout plans of H1 and H2

In Figure 4-14, the architectural plans of H3 and H4 can be seen. ER of H2 and H3 were almost similar in size and occupancy rates. The HVAC system was also similar. OT was spacious but not well ventilated. Occupancy rate was inconsistent due to random sessions with medical students. ICU was entry restricted with lock system. Only patients and staff were allowed. MW was very spacious with adequate occupancy level. In case of H4, it was noticed that the area of ER of H1 and H4 was almost same but there was a difference of occupancy level and HVAC system that caused higher CO_2 levels in ER of H1. OT was well ventilated, scheduled and spacious. ICU and MW were also spacious and well ventilated with sufficient occupancy level.

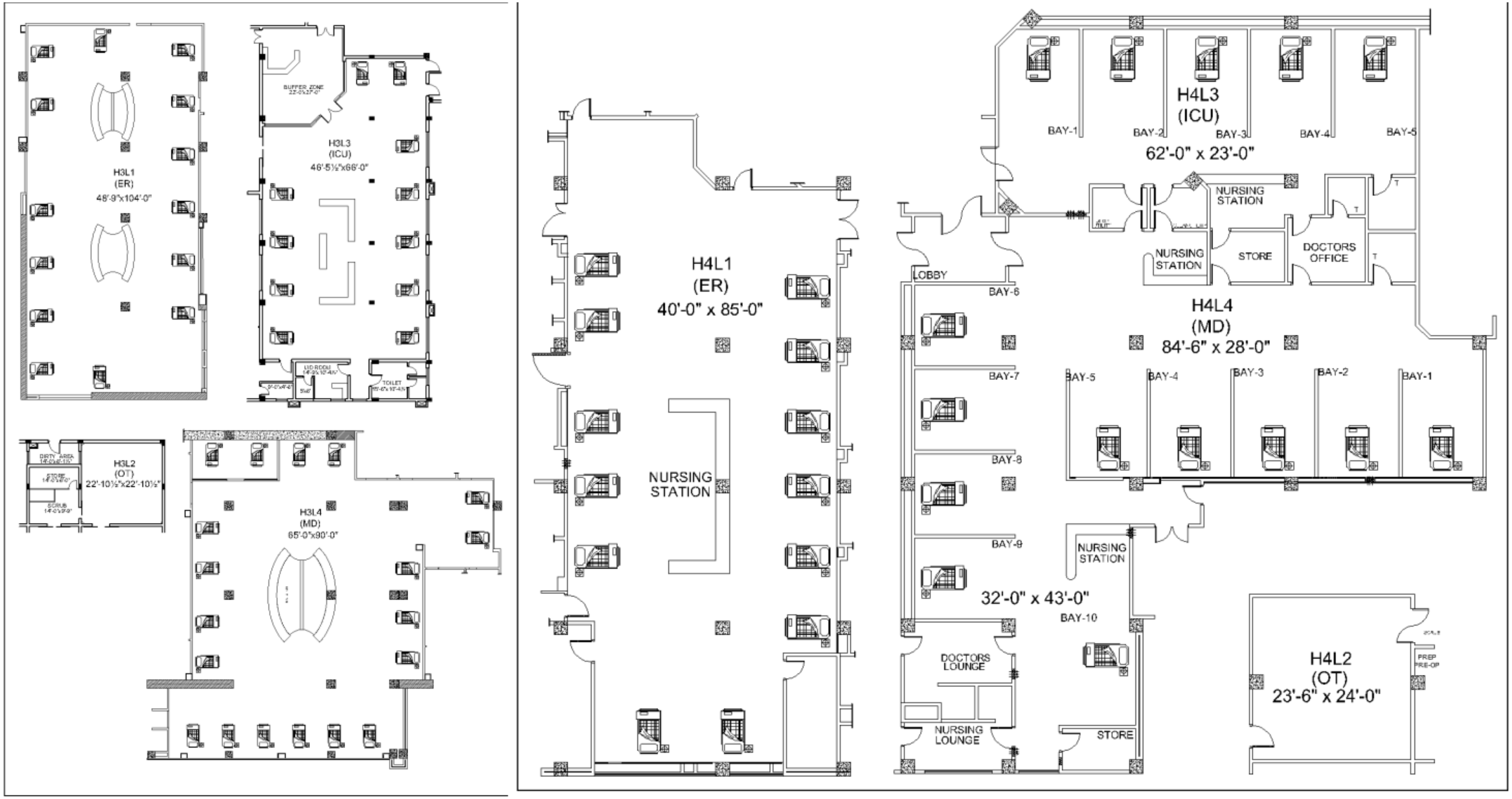

Figure 4-14 Architectural layout plans of H3 and H4

4.8 REQUIRED VENTILATION RATES:

Required ventilation rates are calculated through standard formula that is the Equation 5, shown below, provided by ASHRAE (Standard).

$$Vreq = (N * Rp) + (A * Ra) \qquad Equation\ 5$$

Where,

V_{req} = Required Ventilation rates
N = Number of Occupants
R_p = Perm person CFM required
A = Area of the room
R_a = Fresh air requirement per sft

Table 4-6 shows the input data used to determine the required ventilation rates in the selected locations. ASHRAE provides a standard formula to calculate the required ventilation based on the occupancy levels and area of the facility. These ventilation rates are verified using the simulation equations and afterwards used in the retrofit design.

Table 4-6 Required Ventilation rates using ASHRAE

Sr. No	Locations	Total Area (A) Sqft.	No. of Persons (N)	Cfm/Persons (Rp)	Cfm/Sft (Ra)	Fresh Air Requirement (Rp + Ra) Cfm	Fresh Air Requirement Cmh
1	H1L1	3998	90	25	0	2250	3803
2	H1L2	360	16	30	0.3	588	994
3	H1L3	780	20	15	0.3	534	902
4	H1L4	920	25	15	0	375	634
5	H2L1	2899	35	25	0	875	1479
6	H2L2	600	10	30	0.3	480	811
7	H2L3	3499	25	15	0.3	1425	2408
8	H2L4	1309	20	15	0	300	507
9	H3L1	4998	35	25	0	875	1479
10	H3L2	525	15	30	0.3	607	1027

11	H3L3	3499	20	15	0.3	1350	2281
12	H3L4	5998	35	15	0	525	887
13	H4L1	3798	25	25	0	625	1056
14	H4L2	560	10	30	0.3	468	791
15	H4L3	1599	8	15	0.3	600	1014
16	H4L4	4000	16	15	0	240	406

4.9 MODELING OF EQUATIONS IN ANYLOGIC 8:

Analytical models of the three given equations (2,3,4) is developed using MS Excel separately. The input values of the equations are related to human body. In the Equation 2, outdoor temperature is taken from the meteorologist department nearest to the selected location and is converted to Kelvins ‘K’ as the recorded values are in Celsius ‘°C’. Sensible heat of a human body at rested position is considered between 50W to 60W (Toolbox, 2004). Maximum occupancy level is observed and recorded while collecting the primary data. Floor area is also calculated by performing a survey with suitable laser meter and then it is drawn using AutoCAD 2014. The area is also converted from ft to m^2. U values are calculated for simple brick and cement plaster system, as all the 4 hospitals are constructed with local materials and common techniques. Using these values, maximum and minimum ventilation rates are calculated for each location.

4.9.1 Simulation model (T)

Figure 4-15 shows the model is developed in AnyLogic 8 using personal learning edition available on the website. Equation 2 is rearranged to the get the required minimum and maximum temperature as output by putting a range of suitable ventilation rates. The input ventilation rates were altered to using already calculated ventilation rates through ASHRAE guidelines as shown in Table 4-6. The new equation becomes:

$$T_i = T_o - \frac{S_b}{AU + Vc} \qquad Equation\ 6$$

Where T_i is the required indoor temperature, K, T_o is the outdoor temperature, K. S_b is the sensible heat of human body, multiplied with the number of persons 'n'. The equation is divided into two parts to simplify the model. First part is the calculation of area, U value and calculated ventilation rates and the results are collected as stock. This stock values is further used in main equation. It was notices that the range of temperature was maintained to the international standards by using these calculated values.

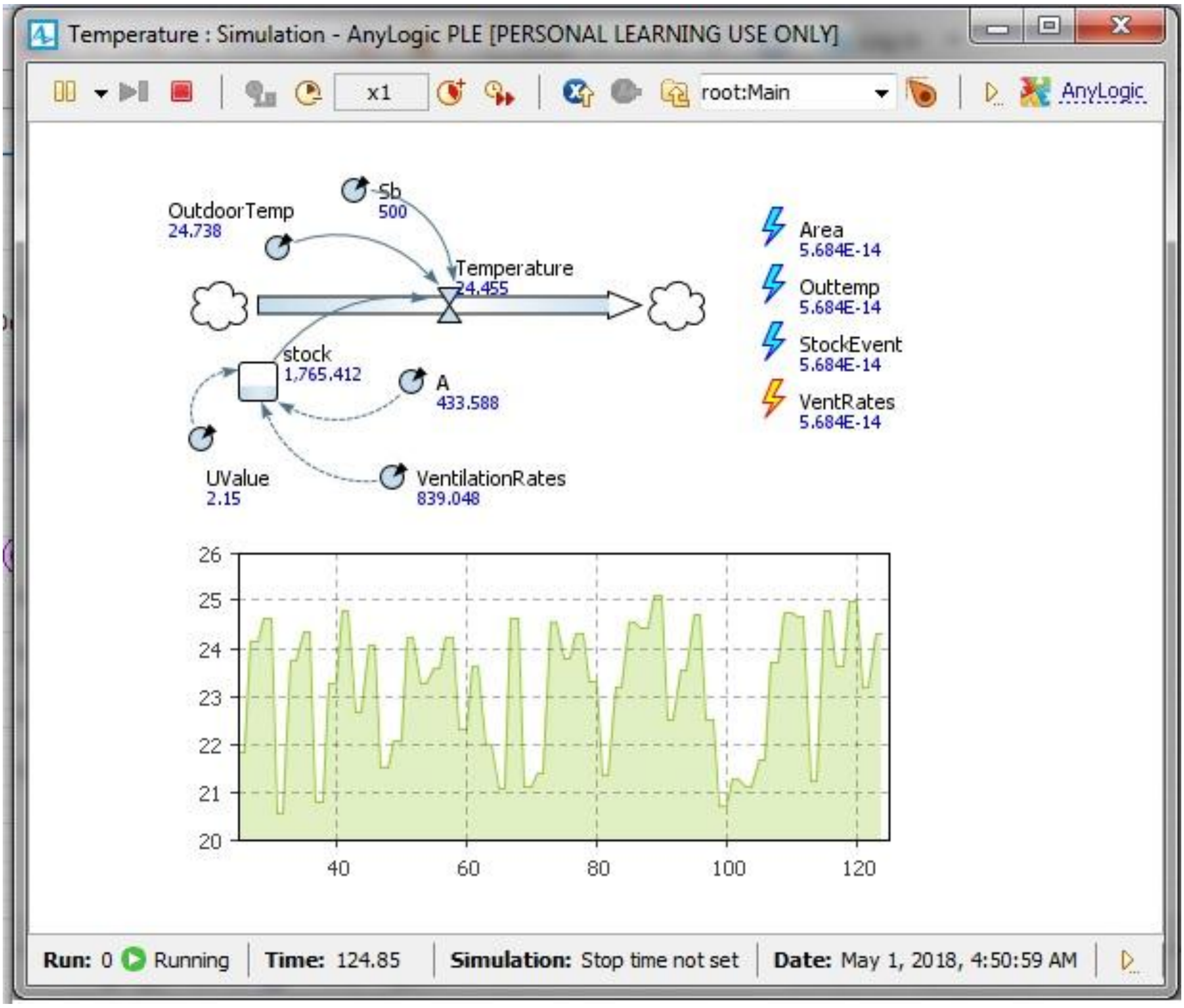

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Figure 4-15 Simulation model for indoor Temperature

4.9.2 Input data (T)

Corresponding input values for equation 6 are given in Table 4-7. The minimum and maximum ventilation rates in the table are calculated using recorded indoor temperature for each location.

Table 4-7 Input values for Equation 5

	Indoor Temperature (Ti)									
	Outdoor Temp (K)		Sensible Heat (W)	Maximum occupancy (No.)	Floor Area (m^2)	U Value (W/m2 K)	Observed Indoor Temp. (K)		Existing Ventilation Rates (m^3/h)	
	Min	Max	S	n	A	U	Min	Max	Vt-Max	Vt-min
H1L1	282.15	299.15	60	90	372	2.15	297.95	301.25	861	800
H1L2	282.15	299.15	60	16	33	2.15	296.95	300.95	83	73
H1L3	282.15	299.15	60	20	72	2.15	298.75	300.35	170	157
H1L4	282.15	299.15	60	25	85	2.15	299.35	302.05	201	184
H2L1	293.15	310.15	60	35	269	2.15	291.55	298.75	605	580
H2L2	290.15	309.15	60	10	56	2.15	294.55	302.45	127	121
H2L3	290.15	309.15	60	25	325	2.15	296.65	300.85	717	700
H2L4	293.15	310.15	60	20	122	2.15	294.95	301.75	276	262
H3L1	288.15	307.15	60	35	465	2.15	294.85	297.85	1024	999
H3L2	290.15	308.15	60	15	49	2.15	292.55	299.15	116	106
H3L3	290.15	308.15	60	20	325	2.15	293.05	298.15	714	700
H3L4	288.15	307.15	60	35	557	2.15	294.85	297.75	1223	1199
H4L1	286.15	307.15	60	25	353	2.15	295.45	298.25	777	760
H4L2	286.15	303.15	60	10	52	2.15	294.15	302.35	119	113
H4L3	286.15	303.15	60	8	149	2.15	294.85	297.95	325	320
H4L4	286.15	307.15	60	16	372	2.15	295.05	299.45	810	800

4.9.3 Simulation model (RH)

Similarly, a simulation model, shown in Figure 4-16, is developed using Equation 7, to get the required levels of suitable relative humidity. Equation 3 is rearranged for this purpose and Equation 6 is formed.

$$H_i = H_o - \frac{L}{V * 680} \qquad \text{Equation 7}$$

Where, H_i is indoor humidity level in kg/m^3, H_o is outdoor humidity level, kg/m^3 , V is the maximum or minimum ventilation rates, m^3/h. humidity levels are recorded in RH% levels, which are converted to kg/m^3 during the calculation.

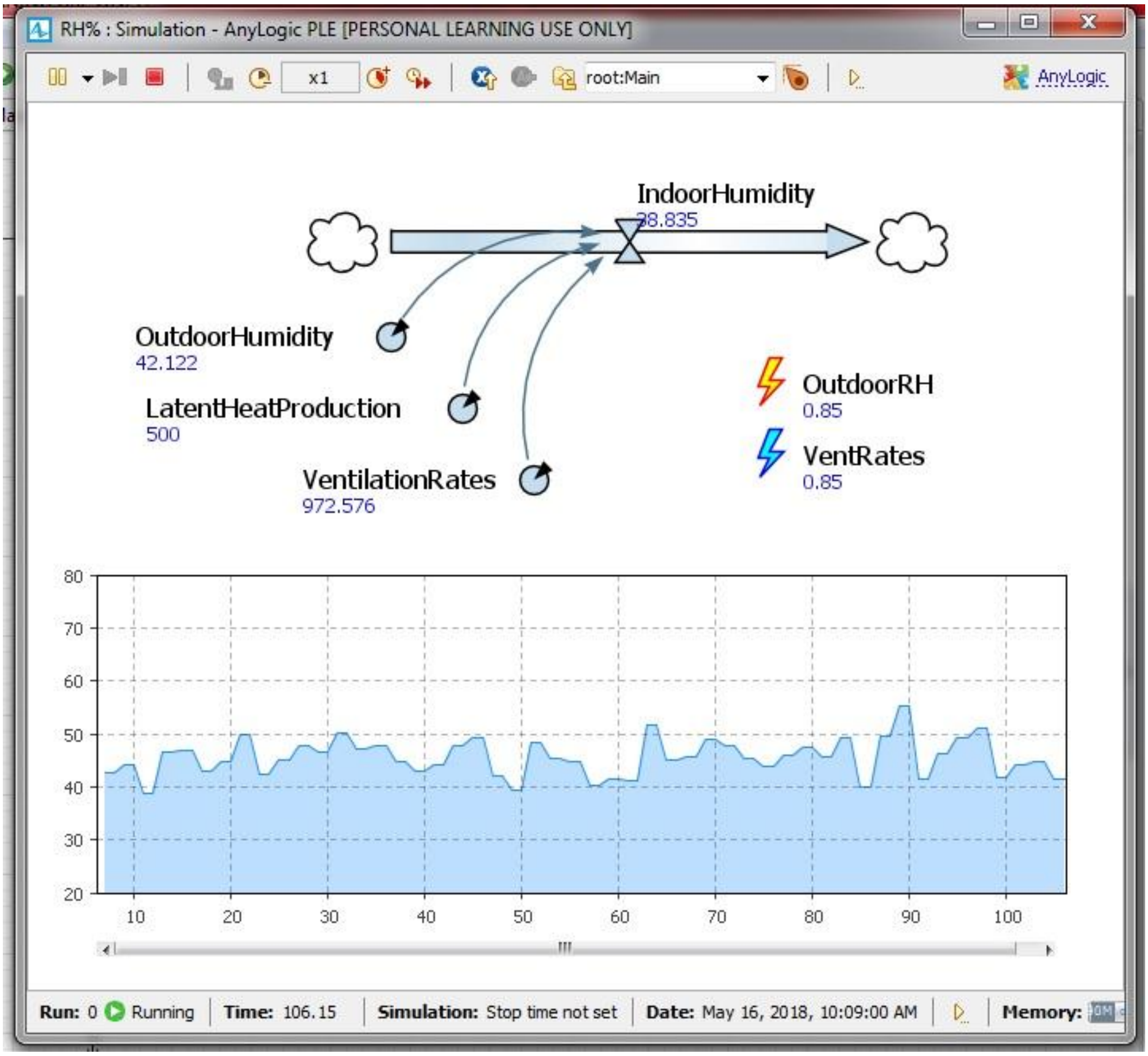

Figure 4-16 Simulation model for Relative Humidity

4.9.4 Input data (RH)

Corresponding input values for equation 7 are given in Table 4-8. The minimum and maximum ventilation rates in the table are calculated using recorded indoor relative humidity for each location.

Table 4-8 Input values for Equation 6

	Indoor Relative Humidity (RH%)							
	Outdoor Humidity Level (kg/m^3)		Maximum occupancy (No.)	Latent Heat (W)	Observed Indoor Humidity (kg/m^3)		Existing Ventilation Rates (m^3/h)	
	Min	Max	n	L	Min	Max	V RH-Max	V RH-Min
H1L1	16	75	90	50	30.9	52.8	1954	1311
H1L2	16	75	16	50	34.7	66.1	277	581
H1L3	16	75	20	50	35.9	52.9	325	293
H1L4	16	75	25	50	28	53.7	674	380
H2L1	22	85	35	50	44.1	70.5	512	781
H2L2	21	83	10	50	25.5	61.8	719	153
H2L3	21	83	25	50	39.1	62.9	447	402
H2L4	22	78	20	50	41.5	69.1	332	727
H3L1	19	77	35	50	39.2	53.9	560	490
H3L2	13	78	15	50	33.4	72.9	238	951
H3L3	13	78	20	50	34	62.4	308	415
H3L4	19	77	35	50	39.1	55.8	563	534
H4L1	18	82	25	50	27.9	55.4	817	304
H4L2	26	88	10	50	32.7	75.2	483	253
H4L3	26	88	8	50	34.1	53.1	319	74
H4L4	18	82	16	50	24.1	50	848	162

4.9.5 Simulation model (CO_2)

Likewise, third simulation model, shown in Figure 4-17, is prepared on the basis of Equation 8 to calculate the required range of indoor CO_2 concentration. Equation 4 was rearranged and the following equation was formed,

$$C_i = C_o + \frac{C}{V * 10^{-6}} \qquad Equation\ 8$$

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 production of carbon dioxide and V is the ventilation rates.

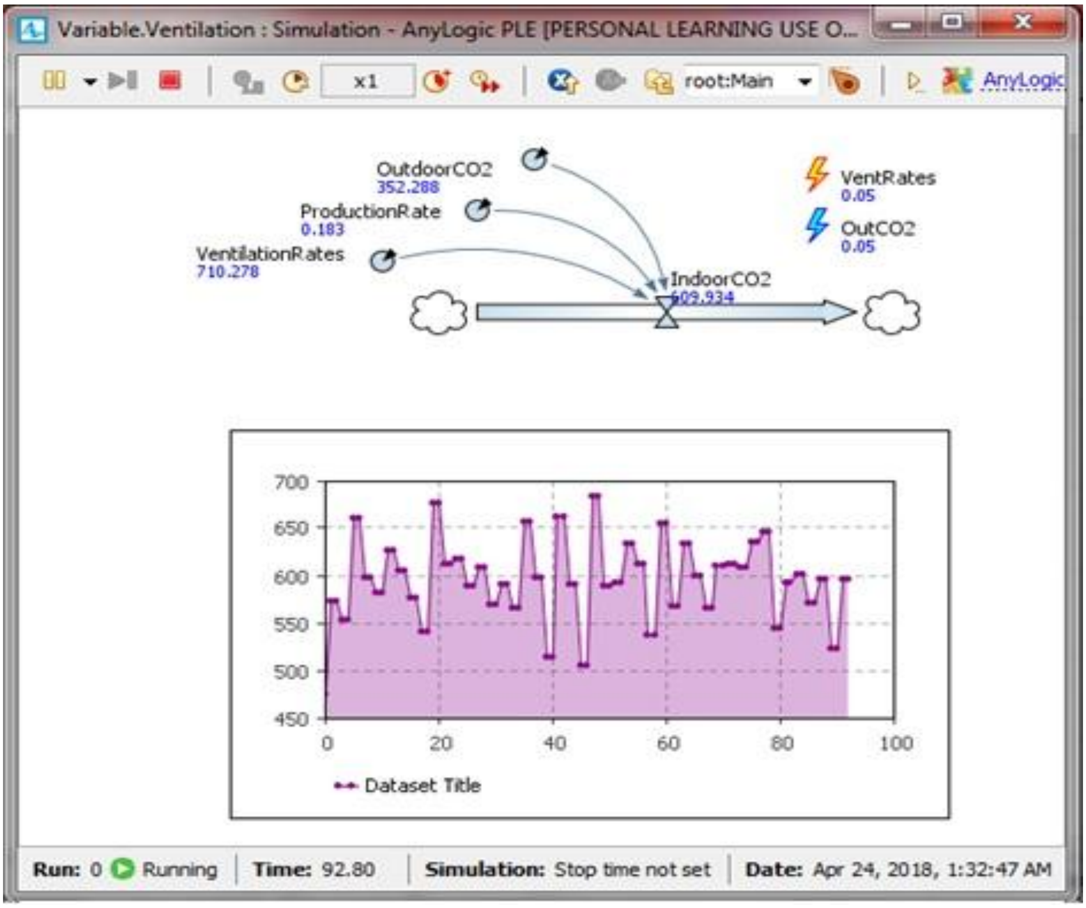

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Figure 4-17 Simulation model for indoor Carbon dioxide

4.9.6 Input data (CO_2)

Corresponding input values for equation 8 are given in Table 4-9. The minimum and maximum ventilation rates in the table are calculated using recorded indoor CO_2 concentration for each location.

Table 4-9 Input values for Equation 7

	Indoor Carbon Dioxide (Ci)						
	Production Rates (m^3/h)	Outdoor CO_2 (ppm)		Observed Indoor CO_2 (ppm)		Existing Ventilation Rates (m^3/h)	
	C	Min	Max	Min	Max	VCO_2-Max	VCO_2-Min
H1L1	0.183	300	450	683	2781	478	79
H1L2	0.183	300	450	589	2640	633	84
H1L3	0.183	300	450	847	2186	335	105
H1L4	0.183	300	450	627	2596	560	85

H2L1	0.183	300	450	609	1614	592	157
H2L2	0.183	300	450	452	806	1204	514
H2L3	0.183	300	450	525	1036	813	312
H2L4	0.183	300	450	441	1637	1298	154
H3L1	0.183	300	450	698	1308	460	213
H3L2	0.183	300	450	731	2256	425	101
H3L3	0.183	300	450	674	1082	489	290
H3L4	0.183	300	450	439	1237	1317	233
H4L1	0.183	300	450	399	749	1848	612
H4L2	0.183	300	450	389	738	2056	635
H4L3	0.183	300	450	422	649	1500	920
H4L4	0.183	300	450	410	956	1664	362

4.9.7 Comparison of the Three Balance Equations

A comparison was drawn between the minimum and maximum ventilation rates calculated using three equations from literature review and the required ventilation rates using ASHRAE equations. Three continuous lines show the existing ventilation rates in the selected locations. Figure 4-18 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 type of range of ventilation rates.

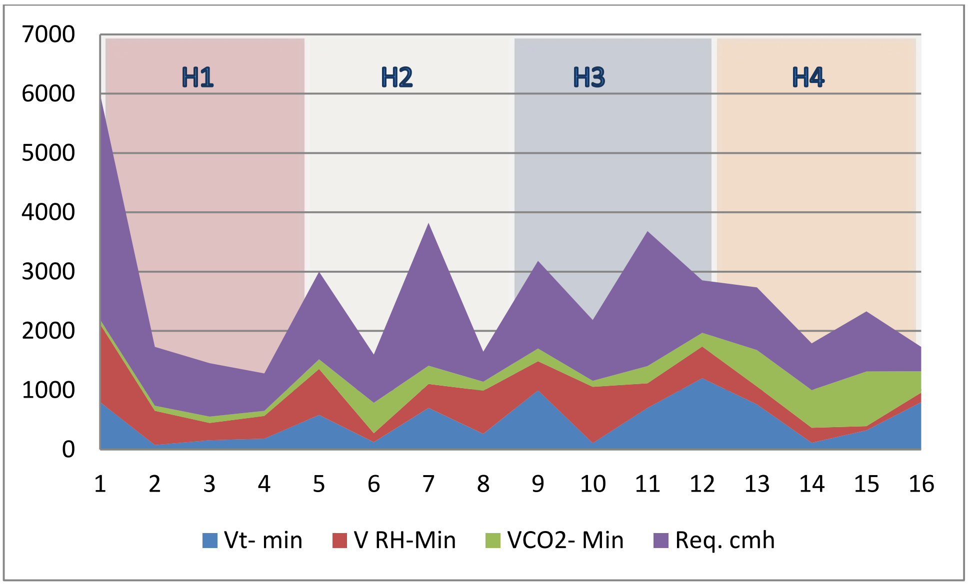


Figure 4-18 Minimum ventilation rates (T, RH, CO2)

Figure 4-19 shows the graph of maximum values of ventilation rates calculated through minimum values of T, RH and CO_2.Similar trend was noticed in the graph i.e. CO_2 shows the highest values of existing ventilation rates while temperatures shows the lowest. This trend can be because maximum exceedance in from standards in Table 8 is noticed in case CO_2 as compared to RH and T. Required ventilations rates, in both cases, have the highest values which will be incorporated in further simulation process.

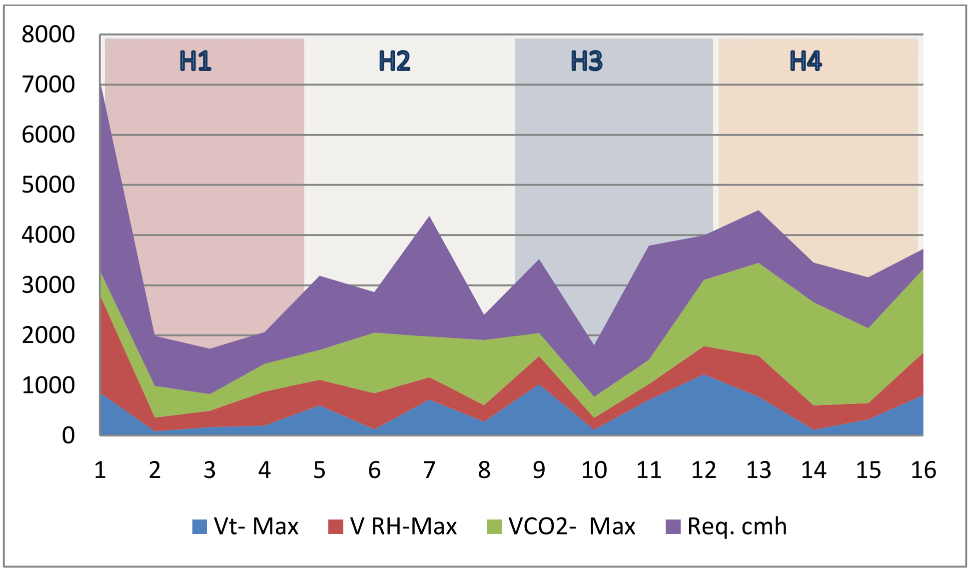


Figure 4-19 Maximum ventilation rates (T, RH, CO_2)

4.10 DISCUSSION

As it has been mentioned in Table 3-2 that H1 has no central air conditioning system, it is operated on fans and exhaust fans. So, it can be clearly seen in the graphs that H1 has the highest values of T, RH and CO_2 concentrations. Contrary to that, H4 has a centralized air conditioning system in L1, L3 and L4, and laminar airflow system in OTs. That is why it has the lowest and controlled values of all the three parameters. On the other hand, H2 and H3 have a mixed system of air conditioning with ceiling fans, exhaust fan and splits ACs being operated manually. Therefore, the graphs of H2 and H3 have comparable trends. It can be observed that HVAC is a significant driver of IEQ. A comparative study conducted in a Hong Kong school investigated two class rooms one with natural ventilation and the other with HVAC system. It was found that natural ventilation caused abrupt changes in the IEQ graphs, especially in the temperature readings, whereas there were comparatively lesser curves in the class room with HVAC system (Lee and Chang, 2000). Another study conducted in an educational institute of Pakistan was focused on the variation of T, RH and CO_2 measurements on weekdays and weekends. Again, there was a noticeable increase in the parameters on weekdays as compared to weekends (Asif et al., 2018b). A similar study conducted in children nurseries in Portugal found that the control in occupancy level and ventilation strategies can enhance the quality of indoor environment (Branco et al., 2015). The result validate that occupancy level is a major factor controlling the indoor temperature, humidity and CO_2 concentrations (Asif et al., 2018b).

The randomization in occupancy affects the sudden changes as observed for CO_2 in the OTs (L2). A similar trend was noticed in a study of three hospitals in Lahore (Ishtiaq et al., 2017). Random peaks in OTs graphs were observed because most of the time a group of medical students are summoned to practice and study a real-time case there. But emergency rooms (L1) in all the hospitals mostly show a single extensively risen graph which is mostly during the day-time. Similar peaks were noticed in the earlier studies when the occupancy was highest (Branco et al., 2015; Asif et al., 2018b). Such a phenomenon is observed either due to the flow of patients during day-time or a higher ambient temperature which causes a rise in the values of thermal comfort parameters. It has been mentioned that indoor temperature has a strong relationship with ambient temperature. This concept was endorsed by a study conducted in a UK hospital building. The values of thermal comfort parameters decreased as the sun set and was minimum during night-time (Khodakarami and Nasrollahi, 2012). Likewise, almost in all the locations, the average temperature during day-time was more than the average night-time temperature. And since H1 is located in a slightly warmer region of the country as compared to other three hospitals, its overall graph shows higher values even after continuous natural ventilation. In humid climates, excess ventilation can result in uncomfortable IAQ and can increase fungal growth. To provide adequate ventilation for an acceptable indoor air quality, ASHRAE standard 62-2001 requires that the outdoor air ventilation rate should be based on the occupancy of indoor space (Bhattacharya et al., 2012).

4.10.1 Proposed Retrofitting Techniques for the IEQ of Hospitals

With respect to the calculated ventilation rates, some retrofitting techniques were identified on the basis to improve the selected indoor environmental parameters, which were further shortlisted depending on their influence on the parameters. These selected techniques are then assessed on the basis of their cost effects. A short survey was performed with help of the 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 which is given in Table 4-10.

Table 4-10 Retrofitting Techniques with respect to cost ranks

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

4.10.1.1 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 there is no pollution outside, the fresh air supplied from ambient environment will more likely improve the indoor environmental quality (Chao and Hu, 2004b). To achieve the functional needs, operationally significant buildings such as hospitals and high performance laboratories should be adequately ventilated. An eminent way of maintaining the 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 purpose 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).

4.10.1.2 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, 2004a). Two main factors that influence the control strategies of HVAC system are temperature and CO_2 (Erickson and Cerpa, 2010). 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 (Fisk et al., 2010; Chao and Hu, 2004a; Nielsen and Drivsholm, 2010). It is verified that DCV is cost effective and energy efficient replacement to 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 level in the building. These sensor may include temperature sensor, infrared sensors, Carbon dioxide sensor and occupancy sensor (Norbäck et al., 2013).DCV should be preferred to improve air quality and lower the energy consumption (Nielsen and Drivsholm, 2010).

4.10.1.3 Energy Recovery Ventilator (ERV)

Recently, the concept of ERV is broadly used in industrial, commercial and residential facilities (Zhou et al., 2007; Liu et al., 2010). Energy recovery is an efficient method that is used for heat exchange between indoor and outdoor environment. It takes the exhaust air to the outdoor while supplying fresh air inside and also 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 air flows, and a connection of four pipes into a metallic frame with sufficient insulation (Zhang and Fung, 2015). Figure 4-20 shows the mechanism of air flow in an ERV, how energy recovery device comes in contact with the supply and return air.

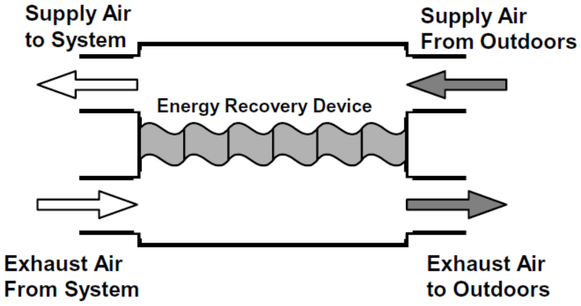


Figure 4-20 Counter-flow heat exchange pattern (Rabbia et al., 2000)

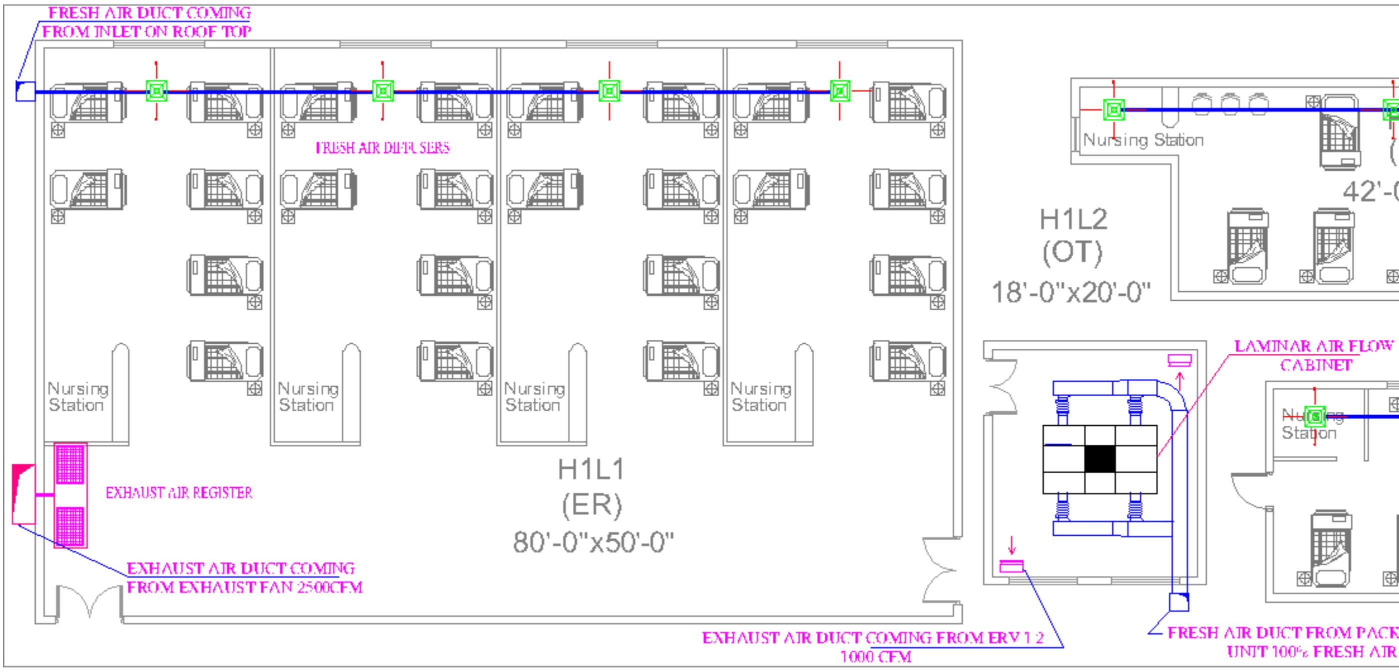
When it comes to comfort level, ERV operates in two dimensions which are shown in Figure 4-20. The first dimension is to transfer heat and moisture to the inside environment from the exhaust air flow to the incoming airflow in colder months and the second is to the inverse of the same operation in summer 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 frame on 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).

4.10.1.4 Laminar Airflow System:

It is also recommended in ASHRAE guidelines to use laminar airflow systems in Operartion rooms to prevent the airborne bacteria and particulate matters present in the air (Memarzadeh and Manning, 2002). Laminar airflow systems are used to reduce the infectious viruses on the operating room 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 systems are widely used and are considered most capable with respect to its influence on patient protection (Melhado et al., 2016). Its formation comprises on ceiling mounted HEPA filters. Vertical air passes and gets cleans through these HEPA filters which is thrown over to the operation area. The air flow is sometimes hindered with the positioning of scrub team but its 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 these are less likely to produce and sustain any bacterial colony in the indoor air. It is imperative to maintain the technical up gradation and cleaning of HEPA filters on regular basis for the optimized operations of the system otherwise minor failure in the maintenance can result into disastrous air contamination and endanger the health of the occupants (Andersson et al., 2014).

4.10.2 Proposed Retrofit Design:

The design for hospital 1 is given in the



. According to the proposed retrofitting design, exhaust fans are suggested in the emergency rooms 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 the better circulation of air. In Medical wards and ICUs, ERV systems are suggested because these places are mostly entry restricted and occupancy rates are controlled. While providing fresh air into the indoor environment, energy utilization is also possible in the said areas. Laminar airflow systems are proposed in the operation theater. Recent studies have validated the importance of laminar airflow systems to be used in operation theaters (Andersson et al., 2014). It is imperative to use the laminar airflow systems with proper AHU system as it is the basic requirement to control the CFM levels. VAV systems can also be used in order to maintain the required comfort levels.

The retrofit designs for all other hospitals i.e. Hospital 2, Hospital 3 and Hospital 4, are based on same retrofitting scheme and the drawings related to the retrofit design are attached as an Annexure- A.

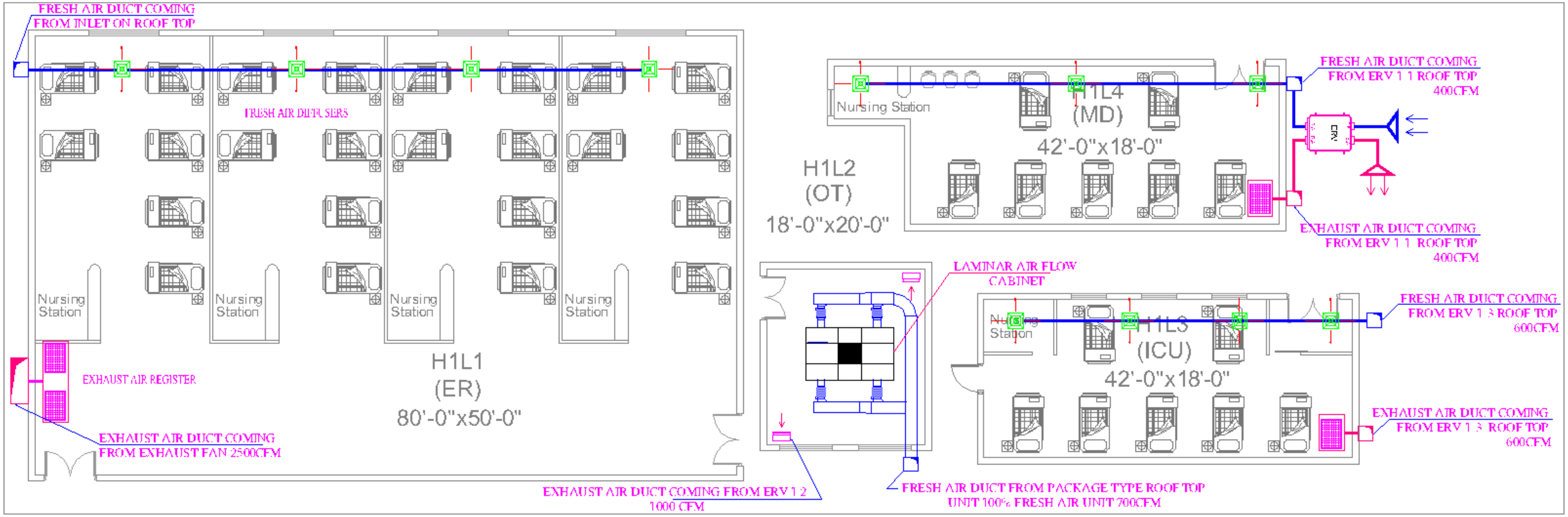


Figure 4-21 Retrofit design for Hospital 1

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

Comparative analysis of indoor environmental conditions including basic thermal comfort (T and RH) and CO_2 of four hospitals shows that occupancy level and ventilation rates are responsible for controlled IEQ. It is observed that ambient temperature and other parameters have a high effect on the indoor conditions especially when only natural ventilation is the source of air circulation. Due to better outside environmental conditions at night, IEQ is observed as closer to the standards. But random and undefined occupancy in hospitals accounts for the irregularity even in night-time environmental conditions. Centrally air-conditioned locations have linear and controlled trends in 24 hours indicating the best performance as compared to other ventilation strategies for this region. Splits ACs and exhaust fans also show a better performance in standardizing CO_2 concentrations.

These findings can help improve the strategies for indoor environmental quality especially in the hospitals and healthcare buildings. These strategies not only included design consideration at the beginning of hospital projects but also various retrofitting techniques are also proposed for the existing buildings to avoid uncomfortable conditions. It is recommended that buildings must be designed on maximum occupancy rates and these numbers should strictly be controlled during building operations. Along with mechanical ventilation, HVAC systems are necessary for crowded public places like hospitals. Also, improvements of ventilation rate changes with respect to these factors are recommended which will help in defining the optimum retrofits strategies.

A limitation of this study is that few hospitals for data collection were selected. But it is an established phenomenon that the process of acquiring permission from the authorities to place the equipment in hospitals is crucial due to privacy and reputation concerns, which is why there are limited environmental studies on hospitals. Therefore, it is recommended to perform the IEQ assessment in poorly governed local hospitals to reveal weak data which will not only help improve the design and retrofitting strategies but also highlight the IEQ issues to be resolved through better management.

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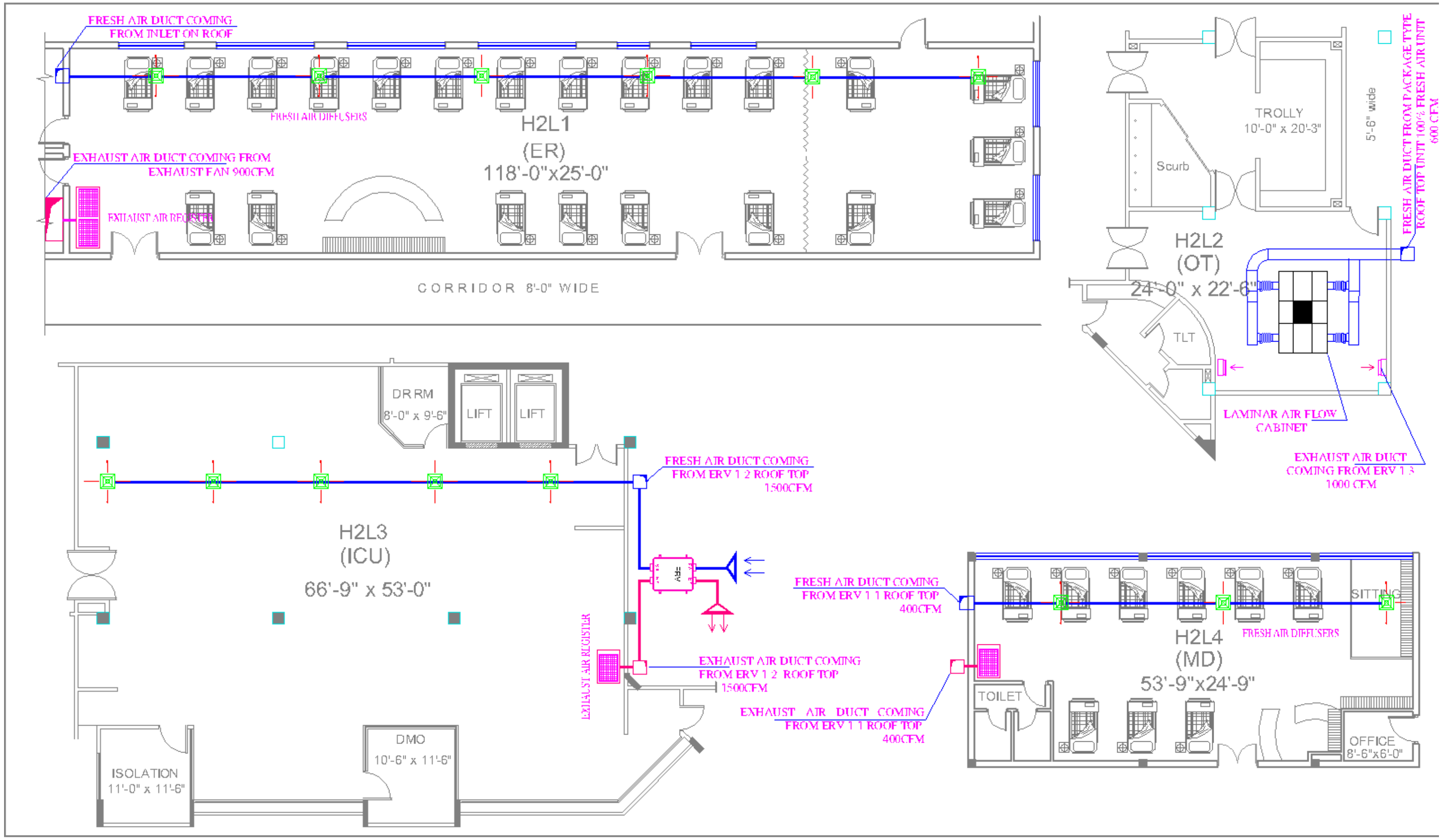
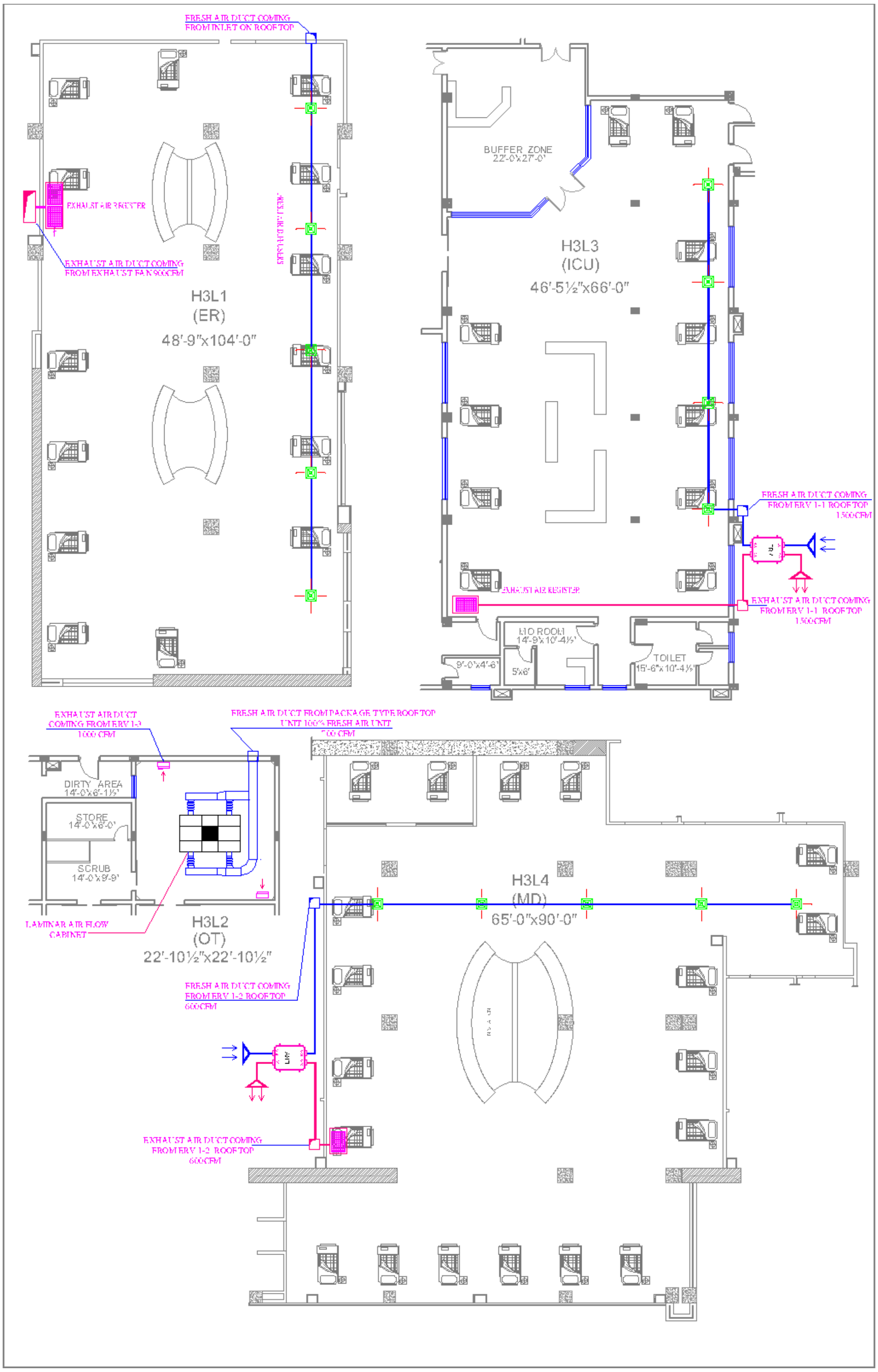
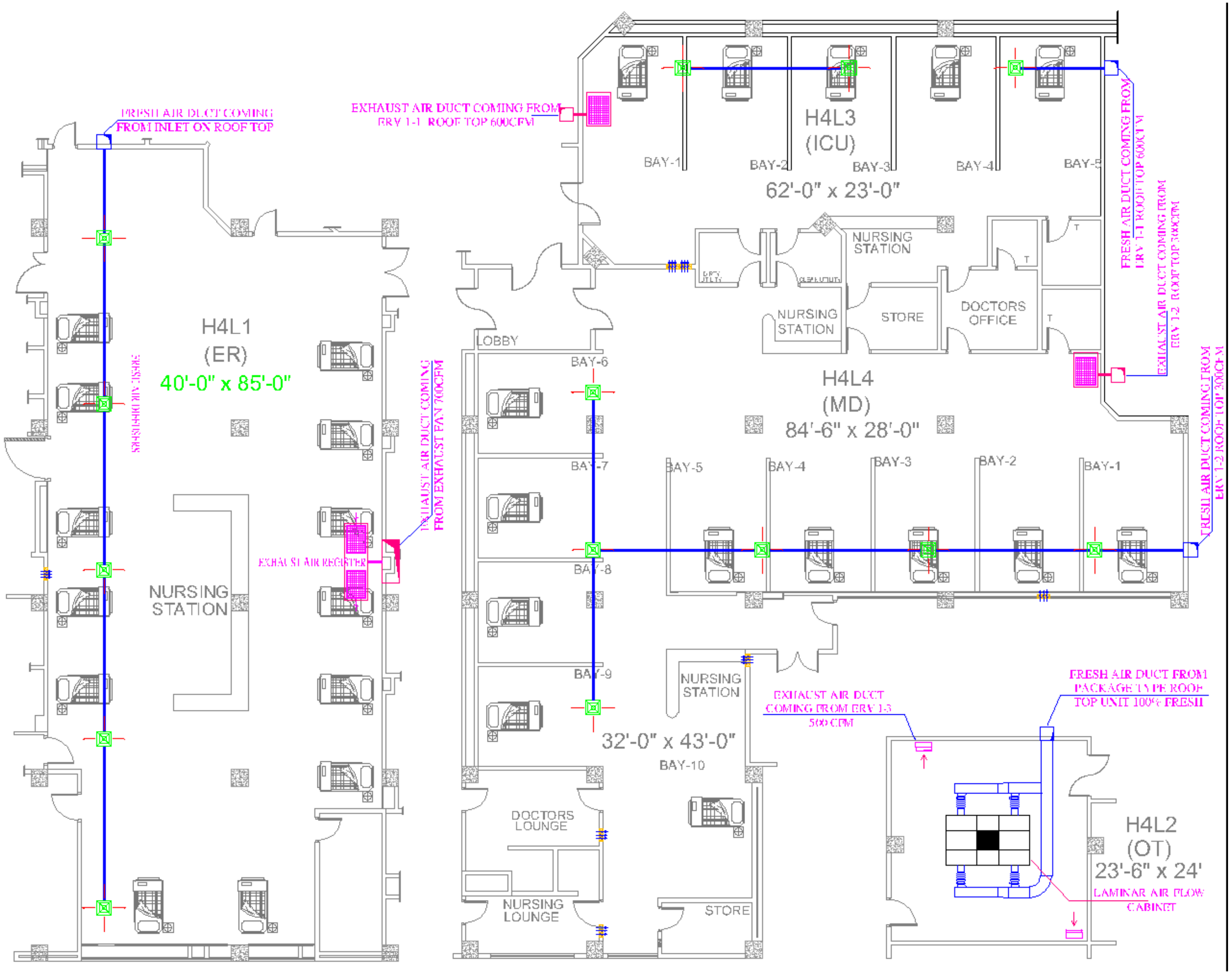
ANNEXURE- A



Retrofit Design for Hospital 2



Retrofit design for Hospital 3



Retrofit Design for Hospital 4