Patient Room Design that Integrates the Personalized Ventilation System for Cross-Infection Control

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Abstract

Many airborne diseases such as Coronavirus variants are spread from person to person by indoor air movement. This is of particular concern in healthcare environments such as hospitals. There is a significant body of research that suggests that indoor ventilation strategies such as personalized ventilation systems my help reduce the spread of these viruses. While there are studies related to the efficacy of air movement from personalized ventilation, there are very few studies that explore how best to integrate these systems into the design process for hospital patient rooms. This study focuses on how to integrate personalized ventilation (PV) and displacement ventilation (DPV) systems into patient room design. The aims of this study are to first, develop a procedure using the Choosing By Advantages approach to make design decisions related to the implementation for personalized ventilation and displacement ventilation in private and semi-private patient rooms to prevent cross-infection. Secondly, using this approach, design solutions are proposed for patient room layouts with PV and DPV in different locations. The study proposes the best locations and components of the PV and DPV ventilation air supply and exhaust. Further practical models/simulation rooms are required to test the impact of PV systems on patients' and nurses' daily activities.

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General Audience Abstract

Many airborne diseases such as Coronavirus variants are spread from person to person by indoor air movement. This is of particular concern in healthcare environments such as hospitals. New personalized ventilation systems place ventilation air directly at the patient bed and consequently can reduce the spread of these viruses by effectively managing in-room air movement. This study explores how best to make design decisions for the implementation of personalized ventilation systems into hospital patient rooms. Applying this decision-making approach, design solutions are proposed that integrate personalized ventilation with commonly used displacement ventilation in patient rooms.

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1. Chapter 1: Introduction

1.1 Background

1.1.1 The development of infection control

In the 19th century, ventilators were invented and were developed by Peter Lord into ventilator rooms (Slutsky, 2015). Mechanical ventilation, originally for patients with lung diseases, was applied to buildings. In the same century, Florence Nightingale emphasized the importance of hygiene and hospital management for patient treatment and advocated the reform of hospital design. In the book *Notes on Hospitals (1863)*, she recorded that sunlight and ventilation were important factors for infection control. Deficient ventilation in hospitals could result in the spreading of disease (Nightingale, 1863). Healthcare facility design had higher standards and requirements than civil and commercial building designs, especially for ventilation. Heating, ventilation, and air conditioning (HVAC) systems were developed and assisted infection control in healthcare facility design due to the development of technology. The HVAC systems improved ventilation quality and efficiency in controlling the spread of the viruses in healthcare facilities. In recent years, due to the emergence of pandemics such as SARS and H1N1, people have realized the importance of considering infection control in the schematic design phase of healthcare facilities(Lateef, 2009). As the world grapples with an increase in pandemics, like Covid-19, it is highly important for designers and engineers to improve ventilation and consider HVAC systems in the schematic design phase for infection control.

1.1.2 COVID-19

In 2019, a new highly contagious widespread disease, COVID-19, has emerged and impacted our lives. COVID-19 has impacted people's daily lives through the way people work, activities, and health. It forces us to integrate epidemic prevention into our daily lives and requires architects to pay more attention to infection control in healthcare facility designs. According to the CDC (n.d.), people of all ages may be infected, but elderly people and people with certain underlying medical conditions are at an increased risk of contracting severe illnesses from COVID-19. This virus is carried by patients and spreads widely. Healthcare facilities with a mixing of vulnerable people and potential virus carriers are dangerous environments.

1.1.3 The importance of HVAC for infection control

Influenza virus, rhinoviruses, adenoviruses, and respiratory syncytial virus spread through the air, and so does the COVID-19 virus. Li et al., studied the role of ventilation in preventing airborne transmission. They found that ventilation can decrease the virus concentration in rooms and restrict virus transmission. Even though the minimum ventilation rate to control the spread of airborne infection was unknown, the role of ventilation in removing airborne viruses was well known (Li et al., 2007). According to the Centers for Disease Control (*Guidelines for Environmental Infection Control in Health-Care Facilities*, 2003), "Heating, ventilation, and air conditioning (HVAC) systems in health-care facilities are designed to ... remove contaminated air, facilitate air-handling requirements to protect susceptible staff and patients from airborne healthcare-associated pathogens, and minimize the risk for transmission of airborne pathogens from infected patients." Therefore, having an effective HVAC system is highly important for airborne infection control in healthcare facilities. While improper architectural design weakens the ventilation and results in poor infection control, proper building layouts achieve ventilation efficiency. For projects with high ventilation requirements, it is important to consider the HVAC system at an early stage of building design.

1.1.4 Considering HVAC systems in the early stages

HVAC systems play an important role in infection control. They affect the design of the building interior, while building design impacts the performance of the HVAC system. Therefore, it is necessary to consider HVAC systems in the early design stage for healthcare facilities to achieve good interior designs and efficient ventilations.

Building design and ventilation systems can cooperate to enhance infection control. In healthcare facilities, based on the function and ventilation requirement, spaces are defined as clean zones and dirty zones. The size and airflow rate are different in each zone. For infection control, air should flow from clean zone to dirty zone (Atkinson & World Health Organization, 2009). In particular rooms, architects should consider the location of the air inlet and outlet since there are clean and dirty zones within a single room. Besides single rooms, in buildings, architects should arrange floor plans and ventilation systems based on the ventilation requirements of the clean and dirty zones. Considering these zones and air inlet and outlet locations at the early stage of healthcare facility design can assist the ventilation system for better infection control.

On the other hand, improper building design can have negative impacts on the effectiveness of ventilation systems on infection control. According to Copeland, locating the bathroom outward in a patient room would decrease the air change rate at the back of the patient room and result in a high risk of cross-infection (Copeland, 2016). Also, Méndez et al., in their paper *Optimization of a hospital room by means of CFD* stated that “the geometry of enclosed spaces and the presence of furniture modifies the airflow pattern as well as the mean age of air" (Méndez et al., 2008). The wrong room design will weaken the ventilation system's ability to remove the contaminated air, thereby increasing the possibility of cross-infection. Therefore, architects should analyze the airflow patterns of the ventilation systems and design hospital rooms with the analysis results in mind if they pursue high ventilation efficiency.

1.1.5 Ventilation systems for infection control

Natural ventilation, mixing ventilation, and displacement ventilation are commonly used in buildings. All of these ventilation systems help with infection control, but with different effects. Natural ventilation, driven by natural forces, is the most popular way to ventilate buildings such as schools, offices, and homes. It can achieve a high ventilation rate but is not ideal for infection control because it is very susceptible to external factors. Displacement ventilation normally supplies cool fresh air at a low velocity from below. Due to the thermal buoyancy, fresh air would slowly move up and fill the room. This type of ventilation is considered to prevent cross-infection in hospital facilities effectively and is applied in some hospitals. Mixing ventilation is the most used ventilation system in public buildings. It mixes air in rooms and performs well for good indoor air quality by diluting the contaminant concentration. However, the drawback of the mixing ventilation for infection control is the spreading of contaminants in rooms and resulting in cross-infection.

People have been looking for alternative ventilation systems for infection control. One example of a new ventilation system is the personalized ventilation system, which could release fresh air directly into people's breath zones and remove the exhaled contaminants from patients. It provides individual control and creates a microenvironment around individuals. There were many studies on the application of this ventilation system in different scenarios, such as an office building, a consultation room, and a patient room. Its ability to remove contaminants was proven by many researchers. Occupants were less exposed to airborne pathogens when both personalized ventilation and mixing ventilation were used in a room (Cermak & Melikov, 2007). The personalized system also performed better than the mixing ventilation system for infection control in the patient rooms (Zheng et al., 2011). This system, different from the mixing or displacement ventilation systems, needs to cooperate with a heating and cooling system. Therefore, there are two types of ventilation systems in a room: a room ventilation system and personalized ventilation systems. The author applies these two systems in this study and calls this combination the dual ventilation system. More information on the personalized ventilation system and the room ventilation system will be discussed in the literature review.

1.2 Problem statement

Practitioners in hospitals are at high risk of exposure to the COVID-19 virus. They may get infected because of contacting with the COVID-19 virus carriers. In healthcare facilities, the ventilation system is crucial to prevent cross-infection. Besides the traditional ventilation systems, a new personalized ventilation system was introduced for infection control after SARS appeared. There were numerous studies on the personalized ventilation (PV) system. However, there isn't architecture point of view on integrating PV systems in rooms and buildings. This research focuses on integrating PV systems into patient room design and how to promote the effectiveness of the ventilation system to prevent cross-infection when designing patient rooms.

This research is based on a series of assumptions on ventilation. In this research, the author assumes that the PV system is effective for infection control in the patient rooms. Other assumptions are made during the design process. CFD studies are required to prove some of the assumptions.

1.2.1 Research questions

1. How do PV systems work in private and semi-private patient rooms?
2. What is the cooling and heating system in the patient rooms?
3. What are the ideal locations of PV systems in the private and semi-private patient rooms?
4. How to keep patients comfortable when applying PV systems near them?
5. What challenges do architects face when applying the PV system to the patient rooms?

1.3 Research objectives

Even though there were many related documents that prove the feasibility of the personalized ventilation system for contaminants removal in healthcare facilities, the author has not found healthcare buildings that use this system, and PV systems' impact on building designs is unknown. Therefore, the author would like to focus on this research gap on the PV systems, and to study the PV system from the architectural point of view. The author is going to investigate the design of patient rooms that use PV systems.

The purpose of this study is to properly integrate the dual ventilation system into the private and semi-private patient rooms to provide a safe and comfortable environment for patients, practitioners, and visitors. The author studies this question through immersive case studies, which explores ways to integrate the personalized ventilation system and the room ventilation system into the private and semi-private patient rooms. The author creates and assesses patient rooms with ventilation systems in different locations. In the end, the outcomes are private and semi-private patient rooms with dual ventilation systems that prevent cross-infection in the rooms.

1.4 Research Methodology

Adding personalized ventilation (PV) systems to patient rooms impacts the comfort of patients and the interior of patient rooms. The author studied this problem in three phases. In the first phase, the author gained more knowledge on the operation and style of the PV system through literature reviews. In this phase, she found a room ventilation system that can properly cooperate with the PV system. In the second phase, the author studied ways to integrate the PV supply and exhaust near patients in a qualitative approach through immersive case studies. The author complied with codes and considered patients' comfort when evaluating each alternative. In the third phase, the author designed private and semi-private patient rooms that integrate the PV and room ventilation system in different locations. The author complied with FGI guidelines, ASHRAE standards, and the hospital and health care facilities code by AIA when designing the patient rooms. In this process, the author analyzed each alternative based on the cooperation of two ventilation systems. The author used Choosing by Advantages as the decision-making system. In the end, private and semi-private patient rooms that rationally integrate the dual ventilation system for cross-infection control were designed.

2. Chapter 2 Literature review

The literature review assesses the different types of ventilation systems used for airborne infection control. This section also provides information on the application of personalized ventilation systems in architectural designs.

2.1 The assessment of ventilation systems for infection control

2.1.1 Natural ventilation

Natural ventilation has a high ventilation rate and requires little maintenance. However, it is largely influenced by external factors, such as site selection, climate, microclimate, and building design, all of which make the ventilation unpredictable (Atkinson & World Health Organization, 2009). Hua Qian et al., (2010) studied the performance of natural ventilation in infection control in the wards in Hong Kong. The results indicated that the larger the opening the higher the ventilation rate, but the more unstable the ventilation. The researchers concluded that "compared with mechanical ventilation, natural ventilation is difficult to control and predict... the pathogen-containing droplet residues are possible to escape from the ward to the corridor"(Qian et al., 2010). Therefore, it is not ideal for healthcare facilities to have high ventilation requirements for infection control.

2.1.2 Mixing ventilation

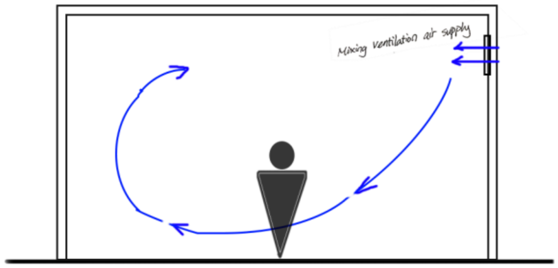

Figure 1 mixing ventilation airflow

Mixing ventilation is commonly used for infection control. This system creates air turbulence in the room when mixing the clean air with contaminated air. It controls cross-infection by supplying clean air into the room to dilute the contaminants in the room. The cleaner air is supplied, the less contaminants remain in the room. However, the personalized ventilation (PV) system performs better than the mixing ventilation system. According to Schiavon et al., using personalized ventilation can reduce energy consumption up to a maximum of 51% compared with mixing ventilation (Schiavon et al., 2010). The personalized ventilation system was also more efficient than the mixing ventilation system. Melikov pointed out that "PV combined with mixing ventilation is always superior to mixing ventilation alone in regard to both occupants' comfort and protection from infectious agents" (Melikov, 2004).

2.1.3 Displacement ventilation

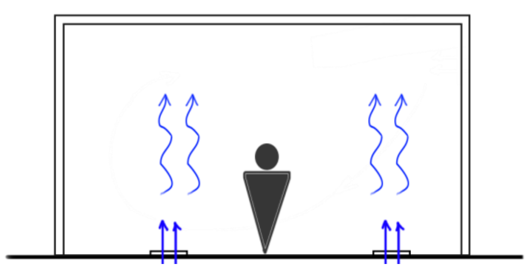

Figure 2 displacement ventilation airflow

Displacement ventilation (DPV) normally supplies clean air cooler than the surroundings from below. Because of the convection, cool air fills the lower part of the room, while warm air moves upward and escapes from the exhaust above. This air movement is called the piston flow. Unlike mixing ventilation, which mixes clean and polluted air in the room, or piston flow uses clean cool air to move contaminated room air up above the occupied zone.

In the paper "*Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method,"* Zhao et al. proposed that displacement ventilation, compared with mixing ventilation, had fewer contaminants deposited in the room. They established a full-scale room with same air supply and similar heat sources using two different ventilation methods: a displacement and a mixing. They tracked the particles (represent contaminants) in both cases to figure out the air movement, velocity, and temperature distribution. The figure of the velocity distribution for displacement ventilation showed that "the displacement ventilation produced thermal plume in the room and stratified temperature distribution" and some air particles migrated upward for a short distance when they hit the wall (Zhao et al., 2004). The result showed that under displacement ventilation, large number of particles escaped from the exhaust. The displacement ventilation was more efficient than the mixing ventilation in contaminants removal because fewer particles remained in the displacement ventilated room (Zhao et al., 2004).

According to Atkinson, displacement ventilation, piston-type ventilation, had an air change efficiency of 100% (Atkinson & World Health Organization, 2009). Many researchers have studied the performance of displacement ventilation systems in hospitals for infection control. Qian et al. (2006) studied the displacement ventilation system in a 4.2m (13.8ft) x 3.6m (11.8ft) x 2.5m (8.2ft) hospital ward. The result indicated that the displacement ventilation "could effectively remove the exhaled gaseous or fine particles if the source patient was facing up. Moreover, a high concentration zone of exhaled droplet nuclei due to thermal stratification locking was also observed in displacement ventilation" (Qian et al., 2006). Due to the research result, Qian et al. did not recommend using displacement ventilation in the patient rooms. However, in this study, Qian et al. neglected the impact of room height on the contaminants concentration for the displacement ventilation system. It was unknown whether the concentration zone could be eliminated by increasing the room height.

Villafruela et al. (2019) further studied displacement ventilation for airborne infection control in private patient rooms. The contaminants concentration zone also appeared in their 2.8m (9.2ft) study models. Besides this lockup phenomenon, they also found out that the position of a solar radiated exterior wall relative to the patient and nurse had an impact on contaminant distribution: the contaminant cloud moved toward the exterior wall when the nurse faced the exterior wall. The contaminant cloud was distributed evenly if the heated wall was behind the nurse (Villafruela et al., 2019). In general, the use of displacement ventilation for infection control requires further study.

2.1.4 Personalized ventilation system (PV system)

Personalized ventilation system supplies air to individuals and allows them to control airflow direction and the amount of air.

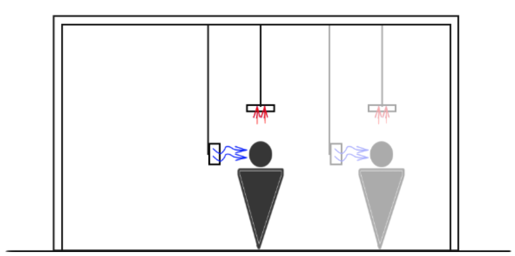

Figure 3 personalized ventilation airflow

2.1.4.1 The PV system for infection control

Xiao-hong Zheng, Hua Qian, and Li Liu (2011) proposed that the mixing ventilation system couldn't decrease the risk of airborne infections such as SARS and H1N1 effectively in hospitals. To solve this problem, their study focused on a new personalized ventilation system that contained an air supply system and an air exhaust system for controlling cross-infection in the patient rooms.

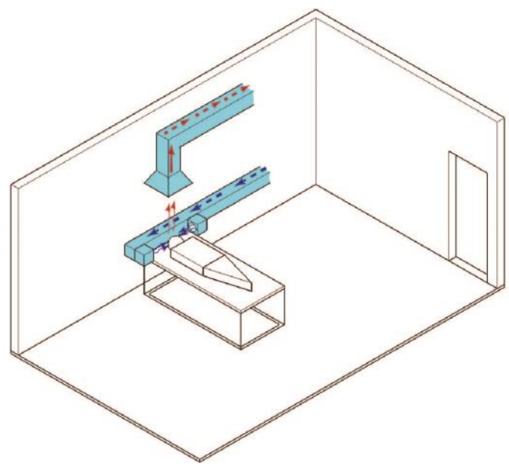

Figure 4 Adopted from Zheng et al.'s personalized ventilation system model (Zheng et al., 2011)

Zheng et al. (2011) simulated a typical 4m x 3m x 3m two-bed patient room with two personalized air supply outlets at the head of each bed and a personalized air exhaust device at the top of each bed. The mixing ventilation system was the background ventilation system, and its vent was located at the top of a wall. Two manikins, one simulating a susceptible person and another one simulating an infected person, were placed on the beds with 1m in distance between them. Four scenarios were simulated. Case 1 only used the mixing ventilation system with a ventilation rate of 450m^3/h. Case 2 used the mixing ventilation system with a ventilation rate of 306m^3/h and a personalized ventilation system with a ventilation rate of 143m^3/h. Case 3 used the mixing ventilation system with a ventilation rate of 90m^3/h and a personalized ventilation system with the ventilation rate of $144m^3/h$. Case 4 used the personalized ventilation system with a ventilation rate of $450m^3/h$ (Zheng et al., 2011). Computational fluid dynamics (CFD) was used to calculate the airflow pattern and dispersion of contaminants. Inhaled local air quality index was used to calculate the amount of contaminated air the susceptible person inhaled.

Based on the data collected, Zheng et al. (2011) found that there was higher indoor contaminant concentration when the mixing ventilation system was used (Case 1). In Case 2, the mixing ventilation system disturbed the airflow of the personalized ventilation system and resulted in poor contaminant exhaust. In Case 3, the background mixing ventilation system had low air velocity, so the ventilation system performed better than case1 and Case 2 in terms of contaminants exhaust. In Case 4, when only using the personalized ventilation system, the number of contaminants in the susceptible person's breath zone was the lowest.

The results indicated that the personalized ventilation system, utilizing the breathing direction and human thermal buoyancy, effectively decreased the possibility of cross-infection by controlling the airborne virus from spreading at the source and supplying fresh air to patients. If the background ventilation system interrupted the airflow pattern of the personalized ventilation system, the effectiveness would be weakened (Zheng et al., 2011).

Zheng et al. (2011) assessed the personalized ventilation system on airborne infection control between two patients in a patient room, but there were limitations. The study didn't evaluate the performance of the personalized ventilation system under the influence of the displacement ventilation system. Also, it didn't consider the influence of equipment and practitioners' movement on the airflow patterns in a patient room.

Regarding the personalized ventilation system's ability to control the airborne transmission, Pantelic et al. assessed the PV in the case of coughing. A coughing machine was placed facing a healthy manikin. Comparing the use of ceiling supply mixing ventilation (MV) and the combination of PV and ceiling supply MV, the results showed that personalized ventilation flow "was able to re-establish itself quickly and rapidly reduce the concentration of the droplets in the inhalation zone"(Pantelic et al., 2009). The healthy manikin not only had a short exposure time to the virus but also exposed to a lower virus concentration level environment. The combination of PV and ceiling supply MV was more effective than using ceiling supply MV alone.

Overall, these researchers proved the effectiveness of personalized ventilation systems in infection control. The personalized ventilation systems effectively removed the contaminants and reduced the possibility of cross-infection. Adding a personalized ventilation system to a regular ventilation system was better than using a regular ventilation system alone.

2.1.4.2 PV with MV vs. PV with DPV

According to A. K. Melikov in the article "*Personalized Ventilation*," personalized ventilation should cooperate with a room ventilation system such as a mixing ventilation system or a displacement ventilation system (Melikov, 2004). However, from the literature review above, the room ventilation system affects the performance of the personalized ventilation system. Therefore, I further studied the influence of two common ventilation systems, the mixing ventilation (MV) and the displacement ventilation (DPV), on the PV system in order to find the best room ventilation system to cooperate with the PV system.

J. Yang, S. C. Sekhar, K. W. D. Cheong, and B. Raphael (2015) studied the personalized air supply and personalized exhaust in their paper "*Performance Evaluation of A Novel*

Personalized Ventilation – Personalized Exhaust System for Airborne Infection Control." They compared the performance of the PV-PE system under the following cases: using top-exhaust or shoulder-exhaust devices, 3 types of manikin positions, 5l/s and 10l/s air supply speed, and using a mixing or displacement ventilation system in the background.

To simulate the possible conditions in the consultation rooms, Yang et al. placed a healthy manikin and an infected manikin in chairs in 3 different arrangements: manikins were placed at 45° to each other, 90° to each other, and facing each other. They used NO2 to simulate contaminants exhaled by the infected person. 3 types of evaluation indexes were used: intake fraction, exposure reduction, and personal exposure effectiveness (Yang et al., 2015). Although Yang et al. (2015) studied different positions of exhaust devices, different manikin positions, different background ventilation systems, and different airspeeds, I only focused on their results regarding the background ventilation system.

Based on the data they collected, Yang et al. pointed out that "compared with the cases when personal exhaust (PE) is working together with PV, the PV airflow rate has a stronger effect on the Personalized Exposure Effectiveness with displacement ventilation," which means that the DPV facilitated the effect of the PV air supply (Yang et al., 2015). Furthermore, by comparing the data, Yang et al. found out that MV didn't help with the PV because "the mixing effect of MV disturbs the pulling effect of the Personalized Ventilation–Personalized Exhaust system"(Yang et al., 2015). Overall, the displacement ventilation system was a better system to corporate than the mixing ventilation in the consultation room in health centers.

In summary, this paper evaluates the effectiveness of the personalized ventilation system (PV and PE) in consultation rooms with mixing and displacement ventilation systems. Even though patients' activities and positions in the patient rooms were different in the consultation room, the impact of DPV and MV on the airflow of PV should be the same. DPV should improve the effectiveness of PV, while MV should have less benefit on PV due to its impact on the airflow pattern.

2.1.5 Ventilation system conclusion

In summary, from the research on ventilation systems, I understood the importance of a ventilation system for infection control. The new personalized ventilation system controls airborne infections effectively. It exhausted the contaminants from the source, supplied fresh air directly to patients' breath zones, and created a cocoon of air around each patient to create a controllable environment around patients. The personalized ventilation system performs the best when cooperating with the displacement ventilation system. In the research, I assumed that the PV system has benefits in cross-infection control and assume that the DPV system is the preferred system to couple with the PV based on the literature review. This collaboration of the PV and DPV systems is called the Dual-Ventilation system. The airflow pattern of this Dual Ventilation system is: the PV system supplies warm fresh air near patients, and the DPV system supplies cool air into the room. Due to thermal buoyancy, the cool air slowly moves up, picks up the PV fresh air, and brings it to patients. The air continues to go up and removes the exhaled polluted air from the PV exhaust above patients' heads.

After a basic understanding of the ventilation system in the patient rooms, I also studied patient room designs before integrating the dual-ventilation system into patient rooms.

2.2 Patient Room Design

2.2.1 Patient room and airflow

Alexa Copeland (2016) addressed the impact of the layout, the location of the air supply and return, and the air change rate of patient rooms on hospital-acquired infections. This research concentrated on the impact of the room size and locations of bathroom entrances on the performance and effectiveness of the air ventilation system.

Copeland (2016) simulated single-patient room models in different sizes (21.4 m^2, 27.9 m^2, and 34.8 m^2) with different bathroom locations (inboard and outboard). The ventilation system supplied air at 360 cfm (6ACH) above the bed and returned air near the patient room entrance. For Computational Fluid Dynamics (CFD) modeling, Integrated Environment Solutions Limited © Virtual Environment was used to observe the airflow pattern, local mean age air, and CO_2 concentration. Risk assessment equations were also used to evaluate the possibility of infection in the patient rooms. An educational nursing simulation room was used to verify the accuracy of data collected by the CFD.

Based on the results, Copeland pointed out that “the size did not have a large impact on velocity and air age, rather design had an impact on the local mean age of air at different areas within the room” (Copeland, 2016). The inboard patient room had an even air circulation. The air would stay longer in the bathroom if the door was open, but it was still 6ACH per hour (Copeland, 2016). Bathrooms located outboard influenced ventilation and resulted in poor air circulation compared with the inboard patient room. Even though the air change around the patient’s bed was at 6ACH, the air stayed longer at the back of the room and increased the risk of infection. If the air was well circulated, 6 ACH could reduce the risk of airborne infection when healthy people stayed in the patient room with an infected person for an hour. However, if there were distractions such as the outboard bathroom, 6 ACH air supply was not enough and contaminants might concentrate longer in the room (Copeland, 2016).

Although Copeland did comprehensive research on the topic, it still had limitations. Copeland did not consider the impact of different locations of supply air and return registers on air movement. Also, it's unknown whether the results were constant when using different air ventilation systems. In this paper, I understood that poor room design would result in uneven air ventilation and increase infection risks of healthy people. I also learned that the inboard bathroom had the least impact on air ventilation in the patient rooms.

2.2.2 Patient room and personalized ventilation

Zulfikar A. Adamu and Andrew Price (2015) studied proper ways to integrate natural personalized ventilation in multi-bed patient rooms. Natural personalized ventilation (NPV) was different from the personalized ventilation system because it was a natural ventilation system driven by buoyancy instead of mechanics. Based on the study of NPV in the two-bed patient rooms, Zulfikar A. Adamu and Andrew Price (2015) found out that when discharging air over patients, vertical air channels could largely eliminate the lateral spread of airflow. For the arrangement of two supply ducts, Zulfikar A. Adamu and Andrew Price tested both top-bottom and side-side duct arrangements. The result showed that duct arrangement didn’t have a large influence on NPV system efficiency. For the four-bed Nightingale Cruciform Ward, the researchers found that: under the influence of a window, “the lateral spread is restricted to one side due to the presence of partitions” (Zulfikar A. Adamu & Andrew Price, 2015). Without windows, NPV Significantly reduces the particle concentration in the source location and the center of the patient room (Zulfikar A. Adamu & Andrew Price, 2015).

Although NPV used natural air movement instead of mechanical, it addressed the lateral spreading and impact of windows on airflow in the multi-patient rooms. I understood that extending the supply duct downwards could reduce the lateral force. Even though NPV air was intended to migrate toward windows due to convection, a partition that separated windows from the room could minimize the impact of windows on airflow.

2.2.3 Mental health

Besides considering the spatial impact of patient rooms on the ventilation system, it is important to consider patients' mental health influenced by patient room design. In the book *Designing the Patient Room: A New Approach to Healthcare Interiors*, Sylvia Leydecker discussed interior elements in hospitals that may influence the well-being of patients. The location of the beds "should be placed so that they can be reached from three sides, so staff has direct access, especially in the case of an emergency. Medical and nursing staff should be able to see the patient from the door to assess the momentary situation on entering the room" (Leydecker, 2017, p. 27). Walls should block the noise to provide a pleasant environment for patients. The ceiling concealed artificial lighting equipment and cables and avoided dazzling patients who laid on the bed (Leydecker, 2017, pp. 35-36). The use of natural light and artificial materials such as imitation wood floors could create a sense of home. Natural wood was not recommended due to the requirement of hygiene (Leydecker, 2017, p. 48). The ventilation system should be designed to avoid causing noise or mental stress to patients.

2.2.4 Patient room design conclusion

Out of the consideration for the patient room design and the presence of a dual-ventilation system, the placement of the ventilation devices would influence patients' experience in the patient rooms. The layout of the room also had impacts on the ventilation systems. So, I further studied the dual-ventilation system in the patient rooms concerning the application of the system and the patient room designs.

2.3 Design guidelines

2.3.1 FGI guidelines for design and construction of hospitals, 2018

The FGI guidelines regulated the minimum design requirements for patient rooms and other healthcare facilities. For private patient room designs, there should be a minimum clearance of 3 feet between the sides and foot of the bed and any wall or fixed obstruction. Multiple-patient rooms should have a minimum clearance of 4 feet between the foot of each bed. For family zones, patient rooms should provide a minimum clear floor area of 30 square feet per family member (FGI Guidelines, 2018).

2.3.2 American Society of Heating and Air-Conditioning Engineers

ASHRAE Standard 170 offers guidance, regulation, and mandates to designers of health care facilities. It provides guidance on ventilation requirements for healthcare facilities. ASHRAE recommended a minimum of 6 ACH, 2 outdoor ACH and a design temperature of 70°F to 75°F for regular patient rooms ("ASHRAE 170 Ventilation Of Healthcare Facilities," 2017).

2.4 Literature Review Conclusion

Considering the high contagiousness and rapid spread of COVID-19, the efficiency of the ventilation systems should be improved in healthcare facilities. From the literature review, I understood that the personalized ventilation and displacement ventilation system can improve the ventilation efficiency effectively. I also got information regarding patient room design. The literature review chapter provided primary information for the subsequent application of PV systems in inpatient facilities or other healthcare facilities.

3. Chapter 3 Methodology

In this section, the author studied the application of the PV ventilation system and displacement ventilation system in private and semi-private patient rooms. She also considered the design of the patient rooms with this dual ventilation system. The author studied this through immersive case studies in a qualitative approach. The author focused on the design of the private and semi-private patient rooms with the dual-ventilation system. During this process, the author complied with the hospital and healthcare facilities design code by AIA and ASHRAE.

The decision-making system was Choosing by Advantages. In this process, the author compared the alternatives based on experience, knowledge about ventilation systems, and healthcare facility design requirements. The total importance of advantages helps researchers to make a judgment. In the end, private and semi-private patient rooms that rationally integrate the dual ventilation system will be designed.

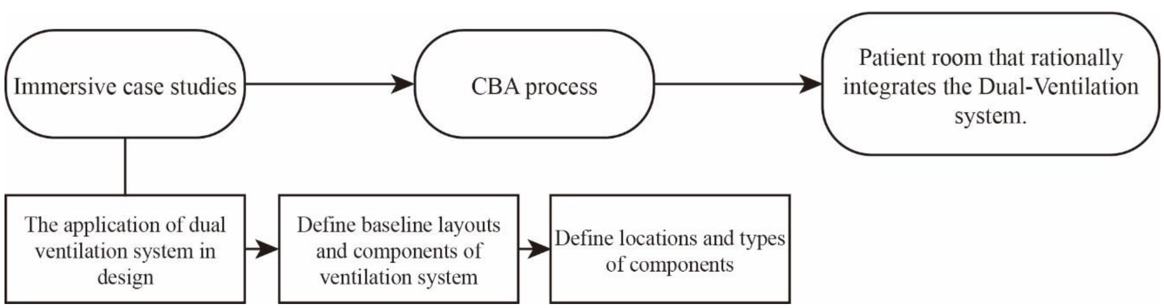

Figure 5 Research methods flow chart

3.1 Immersive case study

The author immersed herself into private and semi-private patient room designs that integrate the personalized ventilation system and displacement ventilation system to provide a safe and comfortable environment for patients, visitors, and practitioners. During the design process, the author used the information from the literature review to apply the dual ventilation system into the patient rooms. The author applied the PV, DPV, and patient room design knowledge into case studies. The goal was to discover the proper position of the dual-ventilation system in private and semi-private patient rooms, and to provide an elementary design for further and deeper research in the future.

Patient room design has high standards and many requirements. The author maximized the effectiveness of the dual ventilation system without making big changes on regular patient room design, thereby making it more convenient for ordinary patient rooms to add PV systems. With less impact on the architectural design, this new PV system could be more acceptable for designers and owners to improve the building ventilation.

Even if the author did not want to impact the basic design of the patient rooms, there were still many factors to consider when adding new ventilation systems in the patient rooms. Through the immersive case study process, the author designed private and semi-private patient room models with different device locations of the air supply, return, and exhaust of the displacement and personalized ventilation systems. The author also discussed different types of air supply devices on their influence on patients and the performance of the ventilation system.

3.1.1 Choosing by Advantages

Choosing By Advantages (CBA) is a collaborative and transparent decision-making system and a decision-making process. According to Jim Suhr, "CBA is a set of concepts and methods designed to make decision making more effective for organizations, communities, and individuals." It enhances decision maker's intuition and judgement by "simplifying, clarifying, and unifying the art of decision making" (Suhr, 1999). The principle of sound decision making is the core. Decisions must be made based on the importance of advantages (Suhr, 1999). It took quantitative valuations and allowed researchers to make a qualitative judgment with them. The decision making phase includes four steps (Suhr, 1999):

1. Summarize the attributes of each alternative
2. Decide the advantages of each alternative
3. Decide the importance of each advantage
4. Choose the alternative with the greatest total importance of advantages.

The author applied CBA throughout the immersive case study. CBA was needed to determine the diffuser types, system locations, room layout, etc. In this process, the author first defined the alternatives for each aspect by looking for relevant information. Then the author defined factors considering the comfort of patients and visitors, the effectiveness of the two ventilation systems, and other factors. After summarizing the attributes of each alternative based on the knowledge and information gathered, the author determined the advantages of each alternative, and assigned an importance value to each of these advantages. Finally, the author evaluated the alternatives based on the total importance of advantages each alternative had and chose the one with the highest number.

Limitations of CBA in this research:

In this study, the CBA system the author used had limitations. The author defined factors based on the information she read from relevant books and literatures. She made assessments based on her experience, the literatures, and common knowledges. The CBA process the author used was following her own judgements. The involvement of patients, practitioners, and stakeholders in the future to refine the elements in the CBA process. Further and deeper CBA studies were needed.

3.1.2 Assumptions in the research

- However, regarding the PV local exhausts extracting a small volume of air (equal to the volume of PV supply air), the author assumed that PV local exhausts have minimal impact on the air stratification and low noise. More information regarding this assumption requires further study using CFD (Computational fluid dynamics) models. The author also assumed that PV controlled cross-infection effectively even circulating small amount of air around patients.
- When studying the locations of DPV systems, the author assumed that the cool air moved upward when meeting heat sources and walls based on particle movement pattern of displacement ventilation traced by Zhao et al., (2004) in "*Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method.*"

3.2 Define baseline layouts and components of ventilation system

Each semi-private patient room contained two beds, two PV systems, one DPV system, two family zones, and one bathroom. Each private patient room contained one bed, one PV system, one DPV system, a family zone, and one bathroom.

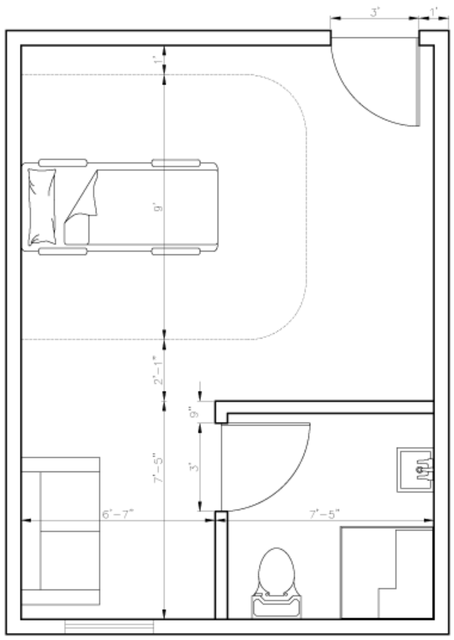

Figure 6 Private patient room baseline layout

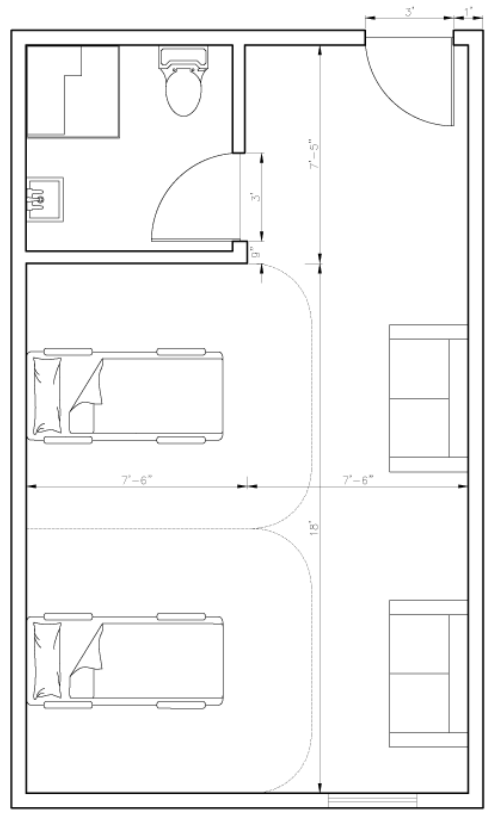

Figure 7 Semi-private patient room baseline layout

For each PV system, there were two supply outlets on each side of the patient and one local exhaust. Based on the study of the PV in the literature review, the author put the personal air supply devices near each patient to discharge fresh air directly to people's breath zone and put one local exhaust device above each patient to exhaust the exhaled contaminants by the patient. Since patients spent most of their time laying on the beds, they preferred a warmer temperature than the practitioners and visitors. Due to this different temperature requirement between regular people and patients, the PV provided a comfortable microenvironment around the patients by supplying air at a higher temperature than the DPV.

The DPV system serviced the cooling of the room. One air diffuser was placed in the room to cascade cool air. There was also an air return and an exhaust in the room. The return was in the upper part of the room. The exhaust was located on the ceiling to discharge the heated stale air. The heating method of the room is discussed below considering the system corporation.

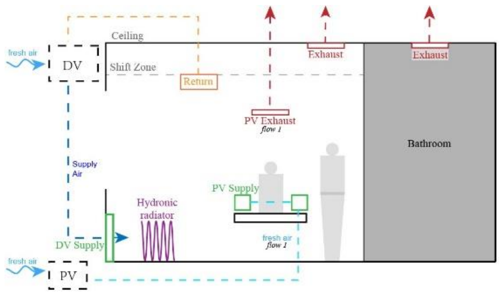

Figure 8 Dual-ventilation system in private patient rooms

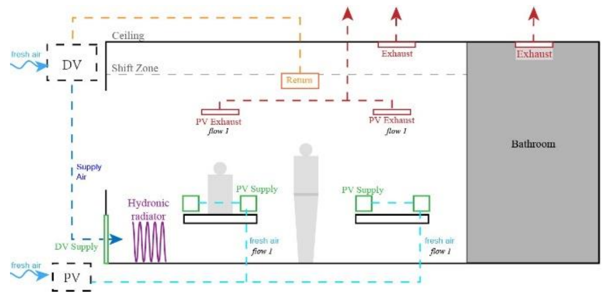

Figure 9 Dual-ventilation system in semi-private patient rooms

3.2.1 Room Heating

The Displacement Ventilation relies on thermal buoyancy, which makes it incapable of heating. There are many strategies on the market for room heating when using a displacement ventilation system: using heaters, using fan coil units, and adding hydronic systems. The mixing air pattern disturbs the airflow pattern of PV and weakens the performance of the PV system, so the author excludes the fan coil units. The heater and the hydronic system are both radiant heating. The author selected the hydronic heating system because using water is more energy-efficient than using electricity.

3.3 The application of dual ventilation system in design

In this phase, the author studied the proper locations of the PV supply diffuser, PV local exhaust devices, the DPV supply diffuser, the air return, and the air exhaust in both private and semi-private patient rooms. The author also discussed the proper layouts of patient rooms to integrate the dual ventilation system in this section.

3.3.1 Semi-private patient room

Although semi-private patient rooms are not commonly used as private rooms in the US, there are many countries, such as China, that have semi-private patient and multi-bed patient rooms. Therefore, the author discussed the semi-private patient rooms design in this study.

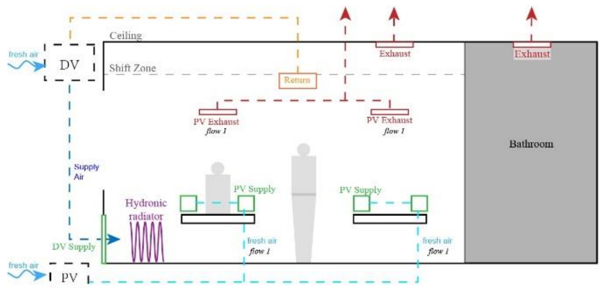

Figure 10 Dual-ventilation system concept drawing (not the final location of the system)

3.3.1.1 PV location

PV Supply

Step 1: Identify alternatives:

The PV system supplied fresh air directly to patients' breath zones near their heads. Considering PV supply's impact on patients' comfort, PV effectiveness, and patient room design, the author evaluated three locations of PV supply diffusers near patient beds: above the bed, aligned with the bed, and under the bed. In these three alternatives, the locations of the PV diffusers were gradually moved away from the patient because patients' comfort was the main concern and putting the PV diffusers away could avoid the airflow affecting patients.

Since the height of patient beds is adjustable and typically beds on the market range from 20 inches to 30 inches, the author selected the middle number 25 inches for all the alternatives.

Putting the PV supply diffusers outside the wall as separate devices was not considered, since they might block the movement of the beds, patients, and practitioners.

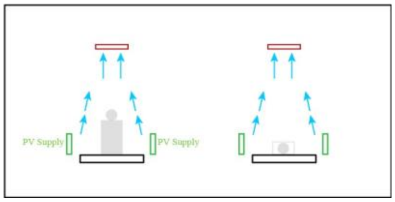

Figure 11 Above the bed

The top of the diffuser is 30 inches or more above the floor

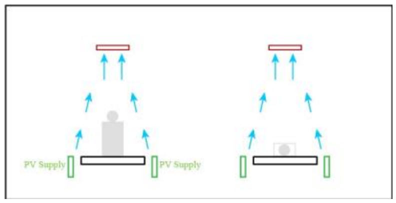

Figure 12 Align with the bed

The top of the diffuser is about 20 inches above the floor

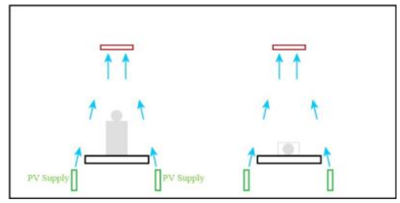

Figure 13 Under the bed

The top of the diffuser is less than 20 inches above the floor

Step 2: Define factors:

PV system is close to patients. Therefore, patients' comfort, and ventilation efficiency must be considered when deciding the PV supply locations. For considered ventilation efficiency, both PV and DPV should be considered since air streams impact each other. When adding new systems to rooms, the change on the existing design should also be considered. PV supply's impact on the headwall system should also be included. For patients' comfort, the author focused on the airflow that patients might feel when supply air. Other factors that had small impact on patients' comfort and ventilation efficiency were not considered. For example, noise was not considered since the author assumed that less noise was generated because the PV system supplied small amount of air near patients.

Step 3: Define the must/want to have criteria for each factor:

- Factor 1: patient comfort: This factor considered the patient's comfort on the bed since blowing air directly on patients on bed for a long time may cause dry skin and sore muscles (Advisor, 2020). Criteria: less air blow directly on patient is better.

- Factor 2: PV effectiveness: having an effective PV system for cross-infection control is the main goal of this research. To allow patients to have fresh air intake, the distance between the human and air outlet is important. Criteria: the closer the PV supply to the patient's face, and more amount of fresh air the patient can get, the better the effect.
- Factor 3: PV+DPV effectiveness: When having two ventilation systems in a room, it is important to consider the cooperation of the two systems. According to Kosonen et al., “in rooms with displacement air distribution the highest velocity typically occurs below 0.1 m (4 inches)”(Kosonen et al., n.d.). Even though the cool room air from the DPV diffuser can pick up the PV fresh warm air and bring the fresh air to patients’ breath zones, there is a possibility of mixing the two air streams. Therefore, the criterion of this factor is: the farther the PV diffuser is from the DPV jet near the floor, the better.
- Factor 4: Impact on the headwalls: The PV air supply can be incorporated into the headwall system in the patient rooms. The headwall system is a wall that contains medical gas tubes and electronic wires, located at the head of each patient bed. Most of the wires and tubes gather in the upper part of the headwall. Criteria: To avoid the clutter in the headwall and give space to the PV ductwork, putting the PV supply in the lower part of the headwall is better.

Step 4: Summarize the attributes of each alternative:

The attributes of each alternative were based on author’s common knowledge and information relative to DPV and PV ventilation systems in the literature review chapter.

Table 1 PV air supply diffuser location CBA

Factors	Above the bed		Align with the bed		Under the bed	
Patient comfort Attributes: Advantages:	Patients feel and hear the air movement		may feel little airflow		cannot feel the airflow	
			more comfortable	80	much more comfortable	90
PV effectiveness Attributes: Advantages:	blow next to patients		blow around patients		blow air away from patients	
	Easiest to be inhaled by patients	100	Easier to be inhaled by patients	80		
PV+DPV effectiveness Attributes: Advantages:	not meet the DPV jet		not meet the DPV jet		May cross-mix with DPV jet	
	less air turbulence	50	less air turbulence	50		
Impact on the headwalls Attributes: Advantages:	locates with the clutter		locates away from the clutter		locates away from the clutter	
			less impact on the headwall system	10	less impact on the headwall system	10
Total importance of advantages		150		220		95

Step 5 Decide the advantages of each alternative:

Criteria were applied in this step. The least preferred attributes were underlined, the most important advantage for each factor was circled.

Step 6 Decide the importance of each advantage:

The researcher assigned a score to each advantage in a scale from 1 to 100. The author decided that easiest to be inhaled by patients was the paramount advantage (100 IofAs). Patients feel much more comfortable was the most important advantage (90 IofAs). Patients feel more comfortable and PV easier to be inhaled by patients were important advantages (80 IofAs). The total importance of advantages was calculated. Aligning the PV supply grille with the bed had the highest total importance of advantages (IofAs), so the author selected this alternative for the patient room design.

Local Exhaust

The local exhausts were above patient beds. It exhausted the contaminated air and created negative pressure on the upper part of the patient beds. The local exhaust could control cross-infection by preventing the contaminants from spreading in the room.

To balance the load of the total air supply and total air exhaust in each patient room, the local exhaust should be small-scale local exhaust devices that have little impact on the total air change of the room. The amount of air the local exhaust extracts requires further study. In this study, the total air supply should balance with the total air extracted from the patient room.

Since there was no study to prove the effectiveness of PV-exhaust grilles facing forward, the author did not consider this PV-exhaust design in the case studies. Adopted from Zheng's PV model (Figure 3), the author discussed the conditions when the PV-exhaust grilles face downward. The author evaluated three alternatives with the local-exhaust heights at 6ft, 6.5ft, and 7ft above the floor. For all the three alternatives, the patient bed height was set to a maximum height of 30 inches, and the patient and nurse are 5 feet 6 inches tall.

Step 1: Identify alternatives:

- Case 1: The exhaust grille was located 6ft above the ground.

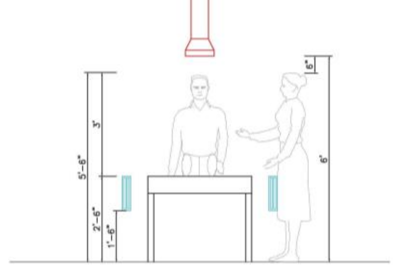

Figure 14 Front and side views of 6ft PV exhaust with a patient sitting or lying on the bed

- Case 2: The exhaust grille was located 6.5ft above the ground.

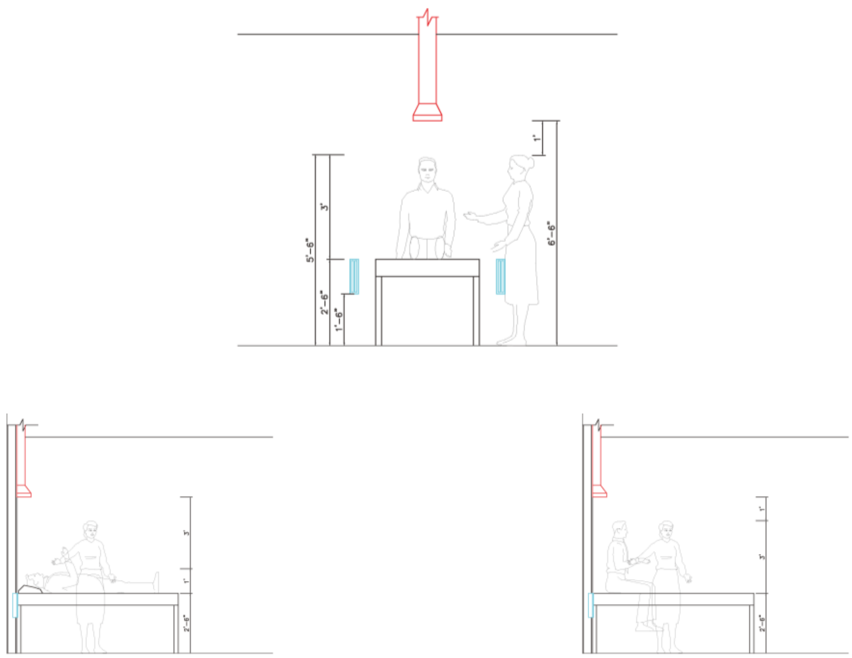

Figure 15 Front and side views of 6.5ft PV exhaust with a patient sitting or lying on the bed

- Case 3: The exhaust grille was located 7ft above the ground.

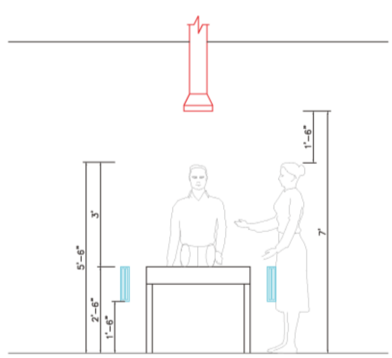

Figure 16 Front and side views of 7ft PV exhaust with a patient sitting or lying on the bed

Step 2: Define factors:

In the patient rooms, nurses need to take care of patients and operate medical equipment, and patients may engage in activities. The author considered safety issue in this section since the DPV exhaust device is above patients' heads. Patients' comfort and exhaust effectiveness were also important to address in this research. The author discussed these aspects from an architectural point of view. For patients' comfort, the author didn't consider noise problem since the PV exhaust was low velocity. More scientific information required CBA studies and practical models to further research.

Step 3: Define the must/want to have criteria for each factor:

- Patient Comfort: For this factor, the author considered the mental stress the patient may feel when looking up. From the literature review section, the author realized that devices might cause mental stress to patients, so the criterion is: Higher exhaust grille is better.
- Safety: The safety factor was evaluated based on the possibility of the patient's and nurse's heads hitting the device. Criteria: Higher exhaust grille is better.
- Exhaust effectiveness: Based on common sense, the closer the exhaust grille is to the source, the less the pollutants escape. Criteria: Lower exhaust grille is better.

Step 4: Summarize the attributes of each alternative:

The attributes of each alternative were decided based on the common knowledge and author's architectural diagrams. More accurate data was required for further research.

Table 2 PV local exhaust location CBA

Factors	Case 1		Case 2		Case 3	
Patient comfort Attributes:	poor		good		best	
Advantages:			farther from patients' face	60	much farther from patients' face	100
Safety Attributes:	close		moderate		far	
Advantages:			farther from patients and nurses' heads	60	much farther from patients and nurses' heads	90
Exhaust effectiveness Attributes:	best		good		okay	
Advantages:	much closer to the source (patient)	40	closer to the source. (patient)	20		
Total importance of advantages		40		140		190

Step 5 Decide the advantages of each alternative:

Criteria were applied in this step. The least preferred attributes were underlined, the most important advantage for each factor was circled.

Step 6 Decide the importance of each advantage:

The researcher assigned a score to each advantage in a scale from 1 to 100. In this case, the author decided that PV exhaust much farther from patients and nurses' heads was the paramount advantage (100 IofAs). Much farther from patients' faces was the most important advantages. The author assigned 90 IofAs to these advantages. Then the author assigned points to other advantages. Finally, the total importance of advantages was computed. Case 3 had the highest

IofAs. Therefore, the minimum height of PV local exhausts was 7 feet above the floor. According to the *displacement ventilation engineering guide* published by Price Industries in 2016, “If the exhaust is located lower than 7 ft [2 m], some polluted/hot air may remain within the occupied zone”. However, regarding the PV local exhausts extracting a small volume of air (equal to the volume of PV supply air), the author assumed that PV local exhausts have minimal impact on the air stratification. More information regarding this assumption requires further study using Computational fluid dynamics (CFD) models.

PV system location conclusion

In the studies of PV systems in semi-private patient rooms, the author studied the locations of PV supplies and local exhausts separately. In this process, she considered the effectiveness of the ventilation system, safety, and patient comfort. After using CBA to evaluate each alternative, the author decided to have the PV supply aligned with the patient bed and the PV local exhausts 7 feet above the floor. For the locations of the DPV system, the author changed her studying method. Instead of discussing the exhaust and supply separately, the author studied the locations of DPV supply, return, and exhaust together. In addition to the factors considered above, the author also considered the mutual influence between room layout and DPV system location. This change was due to the complexity of the DPV system. Different from PV, the DPV system controlled the cooling of the room, which made the air pattern more changeable and mutable than the PV air pattern.

3.3.1.2 DPV location

The diagram below showed the dual ventilation system airflow in a semi-private patient room.

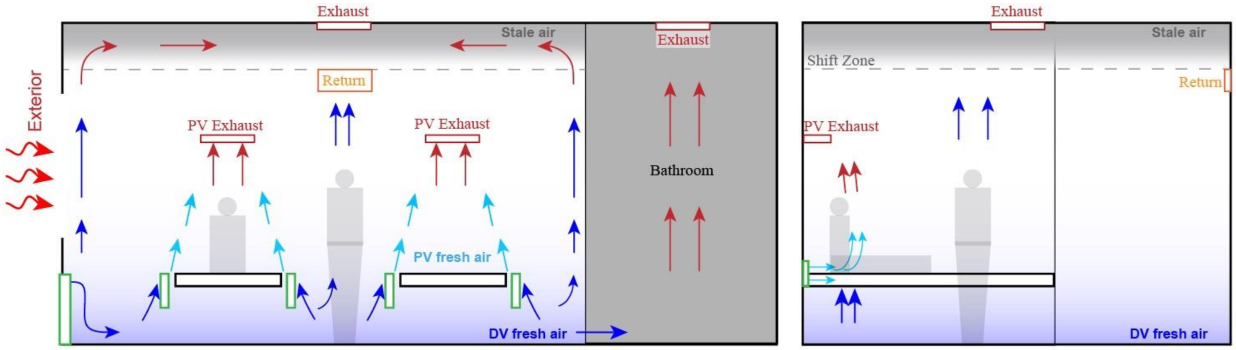

Figure 17 Dual-ventilation system airflow concept drawing (not the final locations of the system)

Step 1: Identify alternatives:

The author studied three different locations of DPV supply diffusers in the semi-private patient rooms because different locations of the supply diffusers had different impacts on the performance of ventilation systems, and room layouts might change due to the location of DPV supply diffusers. The author assessed these three locations of DPV supply diffusers to find the alternative that performs well.

To ensure the performance of the displacement ventilation system, the length of all the patient rooms was less than 30 feet. The ceiling height of the patient rooms was 10 feet. For all the alternatives, the author located the room exhaust at the center of the room on the ceiling to get an even air distribution. The return grille was located at 8 ft above the floor to form the air stratification so that the shift zone happened at 8ft. Also, to avoid air mixing, the room return and exhaust grilles were located away from the PV-exhaust, so that the low pressure near the return and exhaust grilles did not affect the PV airflow.

- Case 1: For this case, the author put DPV supply in the north because she assumed that airstreams had less influence on each other if the DPV supply was on the same side with the PV supply.

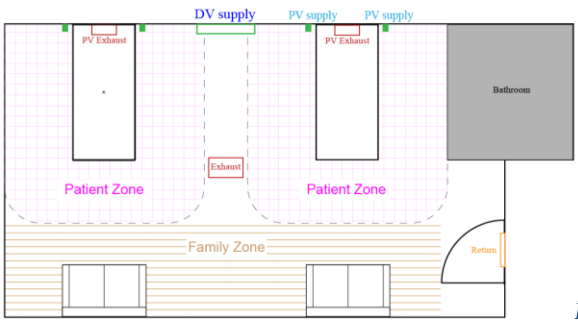

Figure 18 Semi-private patient room with DPV diffuser in the North

- Case 2: For this case, the author put DPV supply in the south at the center of the room because it could facilitate the air distribution in the room and less equipment was placed in the patient zone.

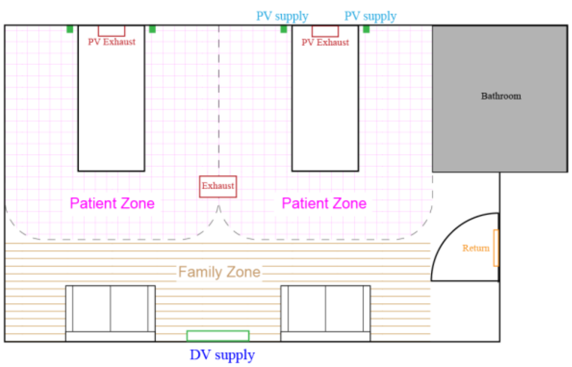

Figure 19 Semi-private patient room with DPV diffuser in the South

- Case 3 DPV supply in the west so that less equipment was placed in the patient zone, and it was energy efficient to put the cool air supply on the exterior side.

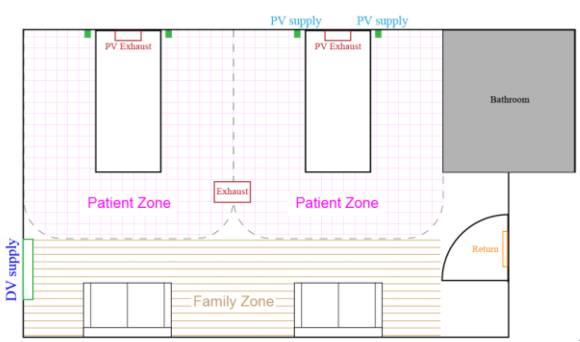

Figure 20 Semi-private patient room with DPV diffuser in the West

- The author did not study the case with DPV supply in the east side of the room because she did not want to place the diffuser near the room entrance, where frequent human activities happened in this area.

Step 2: Define factors:

Based on the literature review, the author selected factors that had large impact on ventilation efficiency for infection control. The author also considered the interaction between PV and DPV system since it might cause cross-mixing. Factors that had similar attributes were not considered such as air return locations. More thorough CBA study need to be addressed in the future.

Step 3: Define the must/want to have criteria for each factor:

- Airflow: The PV system created a micro air-circulation zone around each patient, and the DPV system overseed the infection control of the whole room while facilitating the PV system. One goal of this dual ventilation system was to avoid cross-infection by avoiding air mixing. Therefore, less air mixing is better. The diagrams below showed the air movement in semi-private patient rooms based on the information about displacement ventilation and personalized ventilation in the literature review.
- Temperature distribution: according to Zhao et al., (2004) in "*Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method*," the temperature distribution was uneven in the room with a displacement ventilation system. However, in summer, the exterior side has lots of heat transfer through the window. From the literature review, the author understood that uneven heat distribution might impact the distribution of the contaminants in the rooms. Contaminants were dragged toward the heated side (Villafruela et al., 2019). Therefore, the author

assumed that by putting the DPV diffuser near the window, it could lower the temperature near the windows, thereby cooled the heated area to alleviate the uneven distribution that contaminate the spaces near windows. This assumption requires further study. For this factor, the DPV diffuser closer to the exterior side is better.

- Comfort: For patients, since the uneven temperature or cool air is uncomfortable, the DPV air diffuser should not be placed too close to patient. For visitors, they prefer cool air, but uneven temperature is uncomfortable. Therefore, with DPV air diffuser cools the family zone, the more evenly cool air distributed around visitors, the better.
- People's movement: frequent activities may disturb the air convection. Even though the patient, practitioner, and visitor flow in the patient room were unclear, the author intended to reduce activities' impact on the airflow by carefully placing the diffuser in the room. Criteria for this factor is: Less movement around the diffuser is better.
- Bathroom location: In the literature review, Copeland proposed that locations of bathrooms, inboard or outboard, have an impact on air movement. Inboard bathrooms have less impact on air ventilation in the patient rooms than outboard bathrooms. Criteria: the inboard bathroom is better.

Step 4: Summarize the attributes of each alternative:

When studying the airflow, the author found the attributes of each alternative based on the article "*Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method.*" Based on this article, the author assumed that the cool air moved upward when meeting heat sources and walls based on particle movement pattern of displacement ventilation traced by Zhao et al., (2004), and she drew diagrams for each alternative. Diagrams were based on the researchers' assumption, CFD study is required for further and more detailed research. For temperature distribution factor, the author also drew diagrams based on the information that temperature was lower near the air diffuser than in the rest of the room (Zhao et al., 2004). Attributes were found based on the diagrams. Other attributes were found based on the literature review and common knowledge.

Airflow:

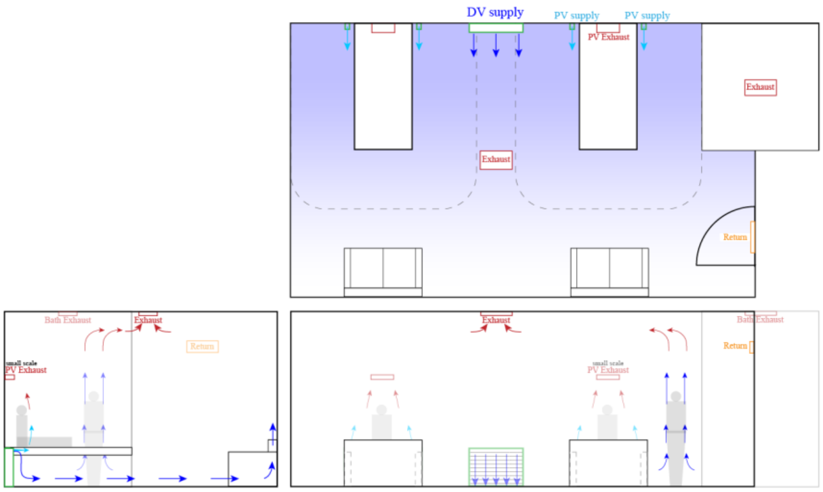

Figure 21 Semi-private Case 1 airflow

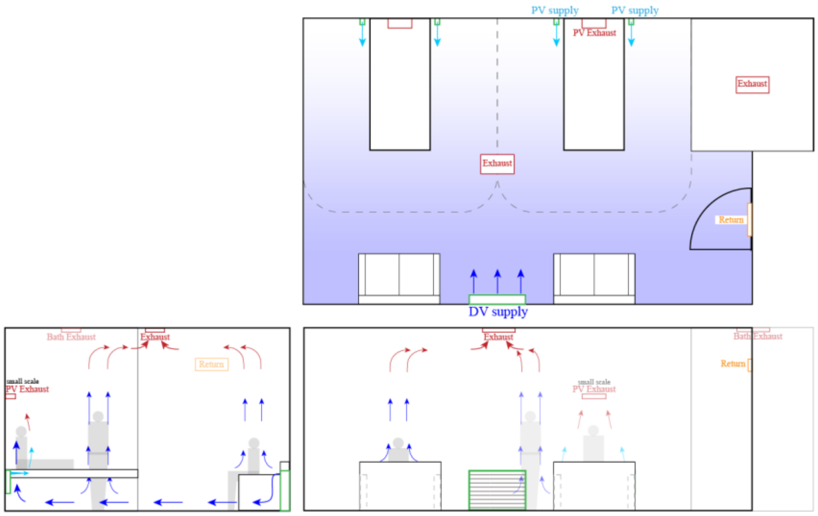

Figure 22 Semi-private Case 2 airflow

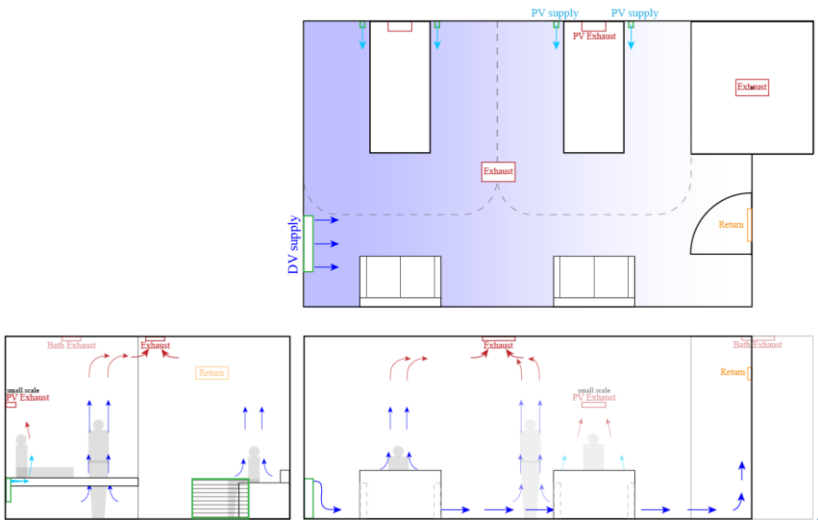

Figure 23 Semi-private Case 3 airflow

Temperature distribution:

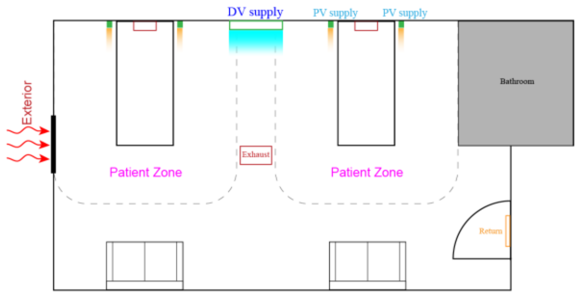

Figure 24 Semi-private Case 1 temperature distribution

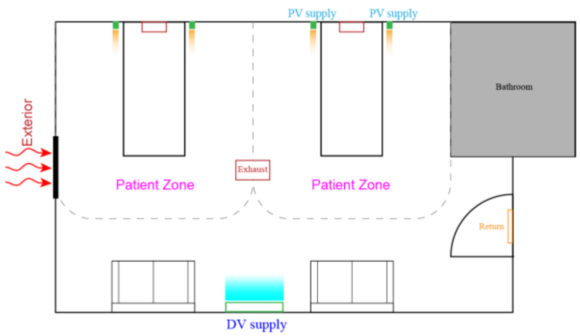

Figure 25 Semi-private Case 2 temperature distribution

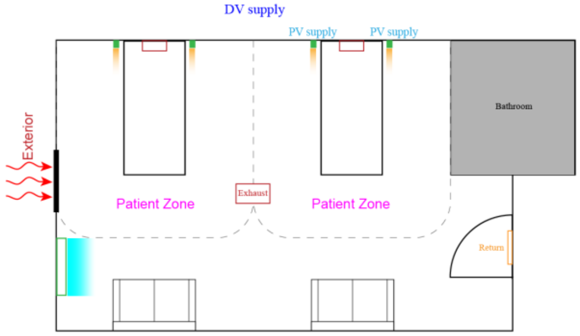

Figure 26 Semi-private Case 3 temperature distribution

Table 3 Semi-private patient room dual-ventilation system layouts CBA

	Semi-private patient room					
Factors	Case 1		Case 2		Case 3	
Dual-Ventilation Airflow	DPV and PV diffusers on the same side		DPV and PV diffusers on the opposite sides		DPV and PV diffusers perpendicular to each other	
Attributes:	less air mixing	100			less air mixing	100
Temperature Distribution attributes:	between two patient zones		in the family zone		on the exterior side	
advantages:			closer to windows	30	closest to windows	40
Comfort Attributes:	away from visitors		between two family zones		in one side of the family zone	
Advantages:	cooler air evenly distirbuted in the room	40	much cooler air evenly distributed in family zone	60		
People Movement Attributes:	nurses walk around in patient zones		away from the walkway		at the corner	
Advantages:			less activity	10	less activity	10
Total importance of	140		100		150	

Step 5 Decide the advantages of each alternative:

Criteria were applied in this step. The least preferred attributes were underlined, the most important advantage for each factor was circled.

Step 6 Decide the importance of each advantage:

The researcher assigned a score to each advantage in a scale from 1 to 100. The author decided that less air mixing in the room was the paramount advantage and assigned 100 IofAs to this advantage. Much cooler air evenly distributed in family zone was an important factor (60 IofAs). Among these alternatives, Case 3 had the highest total IofAs. Therefore, locating the DPV diffuser on the exterior side of the semi-private patient room was the most ideal option considering dual-ventilation efficiency, people's comfort, the impact of human activities, and temperature distribution.

3.3.2 Private patient room

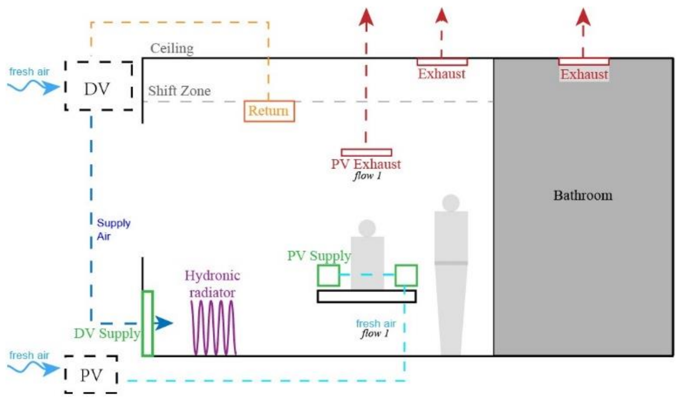

Figure 27 Dual-ventilation system concept drawing (not the final location of the system)

3.3.2.1 PV location

The locations of the PV supply and exhaust were relative to patients and beds. Therefore, in private and semi-private patient rooms, the location of the PV supplies and local exhausts were the same. The PV supply diffusers were located on both sides and aligned with the bed. The PV local exhaust was 6.5ft above the floor.

3.3.2.2 DPV location

The diagram below showed the dual ventilation system airflow in a private patient room.

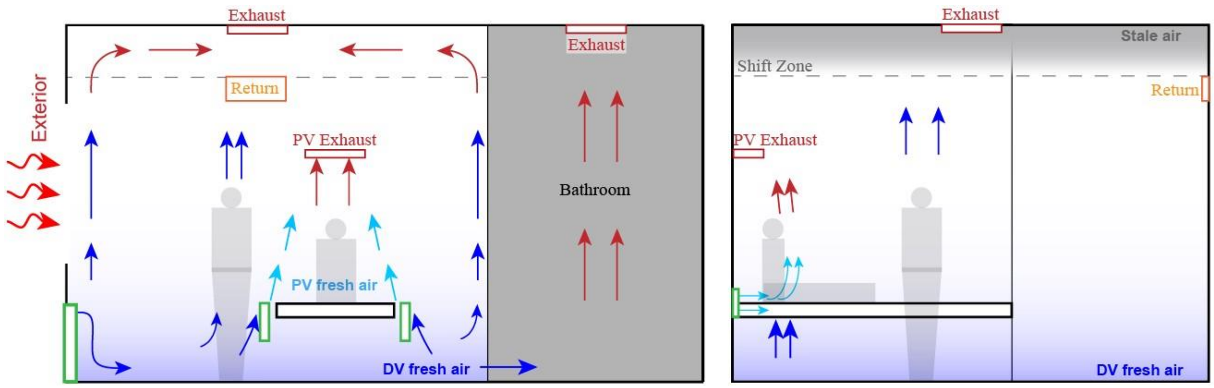

Figure 28 Dual-ventilation system airflow concept drawing (not the final locations of the system)

Step 1: Identify alternatives:

Alternatives: the author studied three different locations of DPV supply diffusers in both the inboard-bathroom and the outboard-bathroom private patient rooms.

- Case 1: Inboard bathroom with DPV supply in the North. In this case, air that discharged from DPV and PV supply diffusers flowed in the same direction.

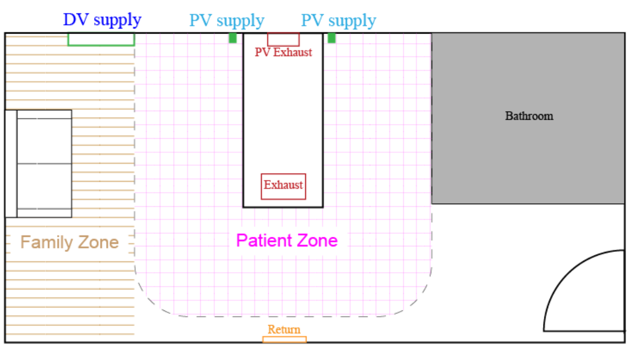

Figure 29 Inboard bathroom with DPV supply in the North

- Case 2: Inboard bathroom with DPV supply in the South. The DPV supply device was away from the clutter on the patient's side.

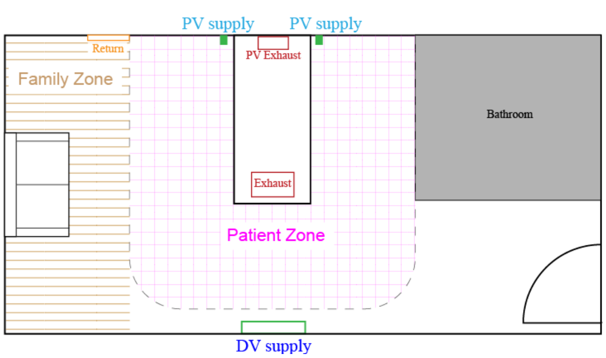

Figure 30 Inboard bathroom with DPV *supply in the South*

- Case 3: Inboard bathroom with DPV supply in the West. The DPV supply was away from the clutter and near the warm window.

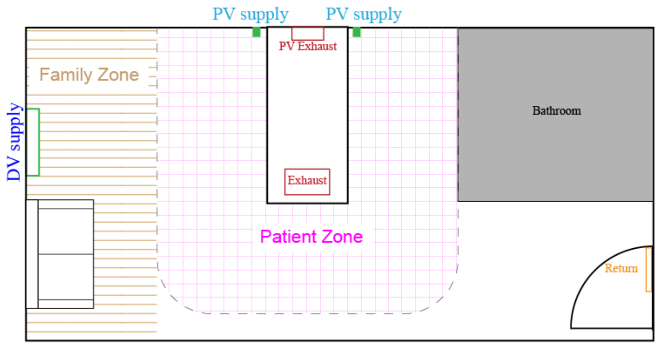

Figure 31 Inboard bathroom with DPV *supply in the West*

- Case 4: Outboard bathroom with DPV supply in the North.

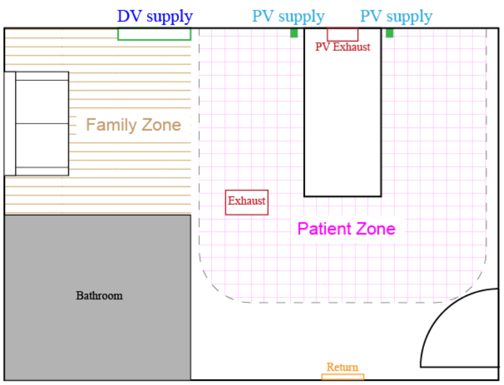

Figure 32 Outboard bathroom with DPV *supply in the North*

- Case 5: Outboard bathroom with DPV supply in the South

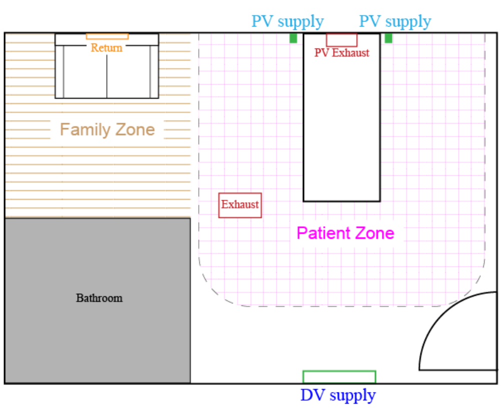

Figure 33 Outboard bathroom with DPV *supply in the South*

- Case 6: Outboard bathroom with DPV supply in the West

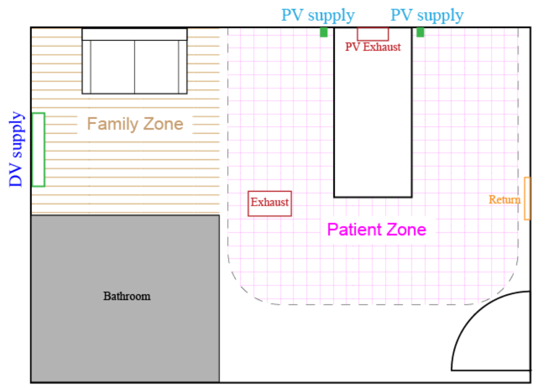

Figure 34 Outboard bathroom with DPV *supply in the West*

Step 2: Define factors: (same with the semi-private patient room DPV location's step 2)

Step 3: Define the must/want to have criteria for each factor (same with the semi-private patient room DPV location's step 3)

- Airflow: Less air mixing is better.
- Temperature distribution: The DPV diffuser closer to the exterior side is better.
- Comfort: The more evenly distributed air around people, the better.
- People's movement: Criteria for this factor is: Less movement around the diffuser is better.
- Bathroom location: In the literature review, the author found out that "the outboard patient room airflow was less effective for circulating fresh air than inboard patient room" (Copeland, 2016). Therefore, the inboard bathroom is better.

Step 4: Summarize the attributes of each alternative: (same with the semi-private patient room DPV location's step 4)

Diagrams of airflow and temperature distribution were shown below.

Airflow:

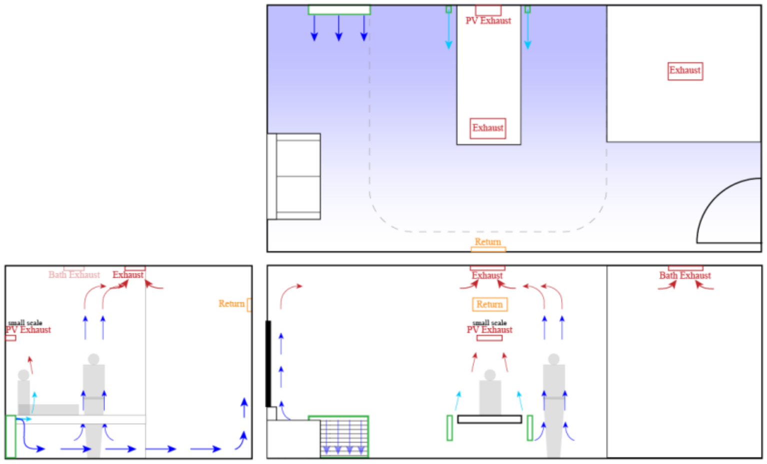

Figure 35 Private room case 1 airflow

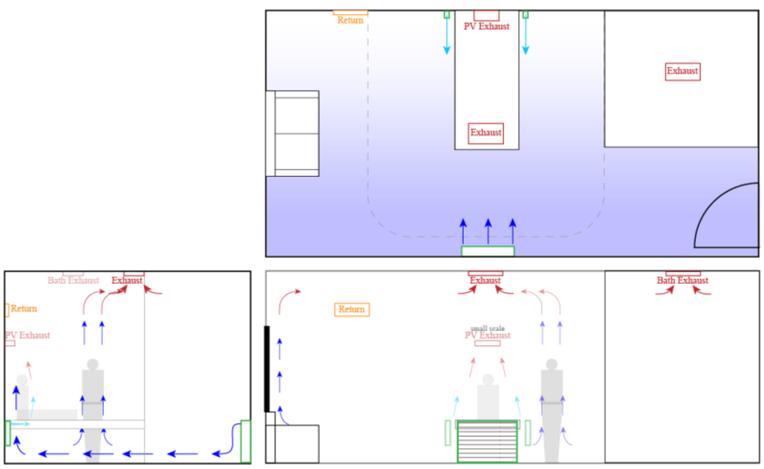

Figure 36 Private room case 2 airflow

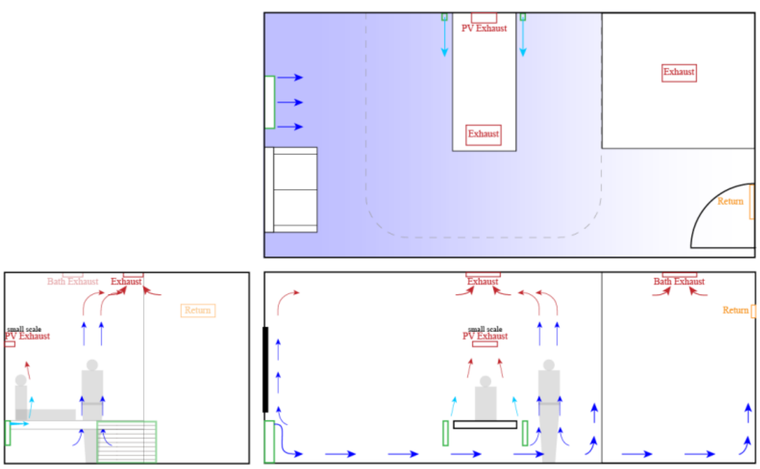

Figure 37 Private room case 3 airflow

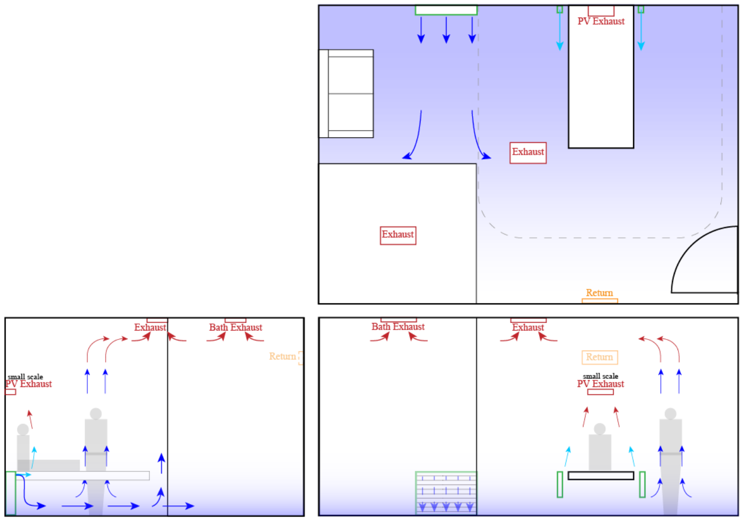

Figure 38 Private room case 4 airflow

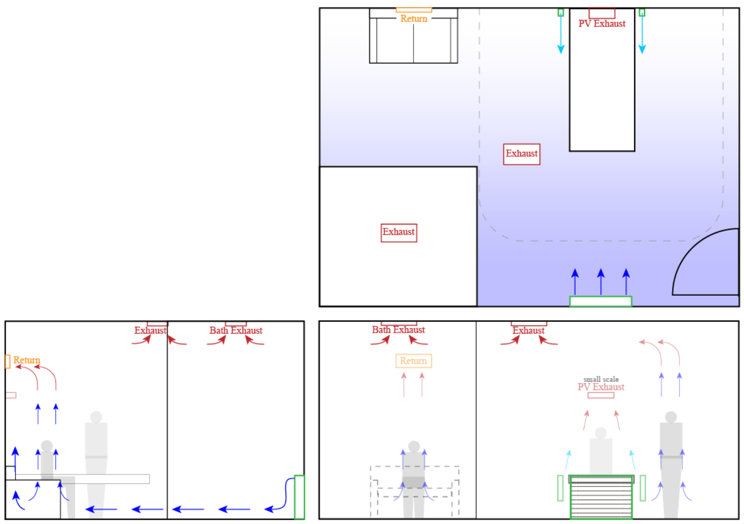

Figure 39 Private room case 5 airflow

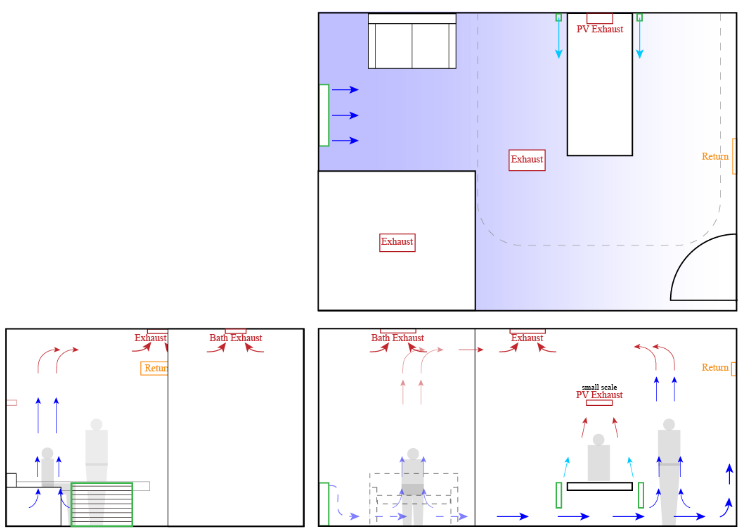

Figure 40 Private room case 6 airflow

Temperature distribution:

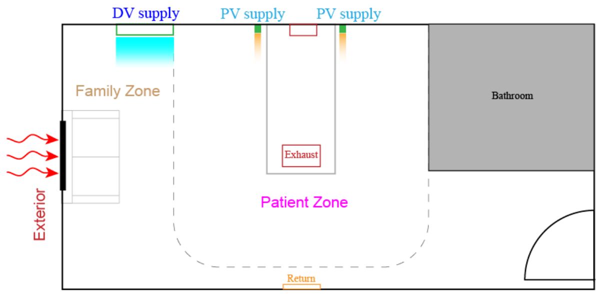

Figure 41 Private room case 1 temperature distribution

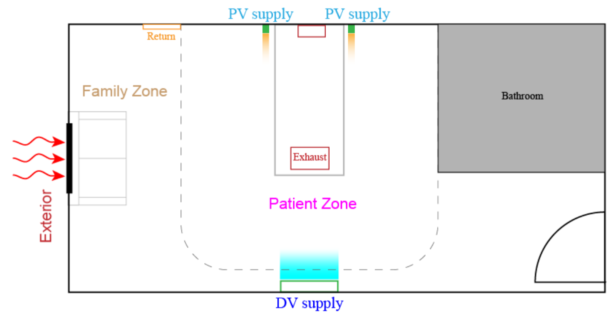

Figure 42 Private room case 2 temperature distribution

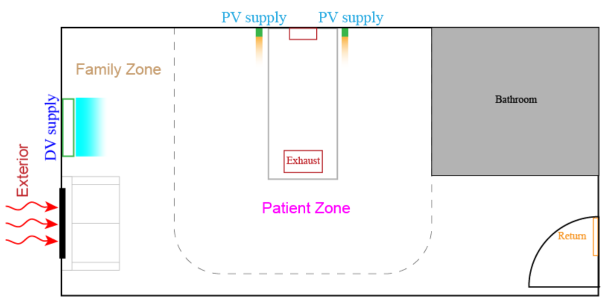

Figure 43 Private room case 3 temperature distribution

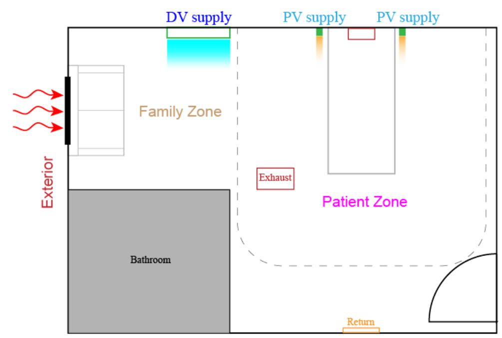

Figure 44 Private room case 4 temperature distribution

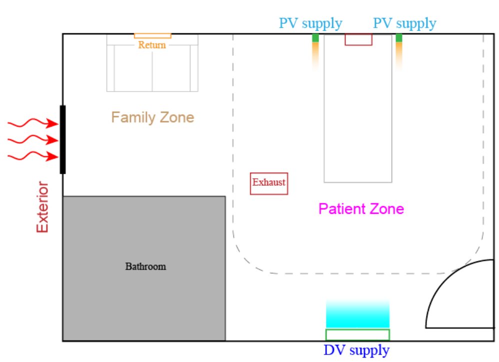

Figure 45 Private room case 5 temperature distribution

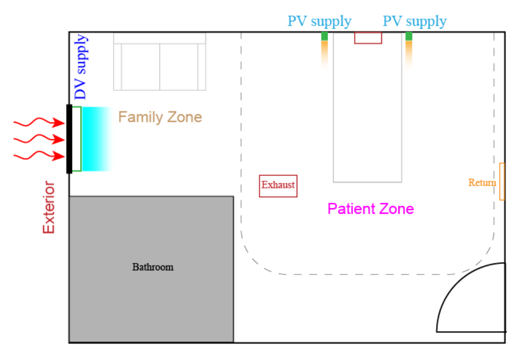

Figure 46 Private room case 6 temperature distribution

Table 4 Private patient room dual-ventilation system layouts CBA

	Layout 1 - inboard bathroom private patient room						Layout 2 - outboard bathroom private patient room					
Factors	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6	
Dual-Ventilation Airflow	DPV and PV diffusers on the same side		DPV and PV diffusers on the opposite sides		DPV and PV diffusers perpendicular to each other		DPV and PV diffusers on the same side		DPV and PV diffusers on the opposite sides		DPV and PV diffusers perpendicular to each other	
Attributes:	less air mixing	100			less air mixing	100	less air mixing	100			less air mixing	100
Temperature Distribution attributes:	on the exterior side		away from the window		on the exterior side		on the exterior side		away from the window		on the exterior side	
advantages:	closer to windows	30			closest to windows	40	closer to windows	30			closest to windows	40
Comfort Attributes:	in the family zone		outside both zones		in the family zone		in the family zone		outside both zones		in the family zone	
Advantages:	much cooler air evenly distributed in family zone	60	cooler air evenly distributed	40	much cooler air evenly distributed in family zone	60	much cooler air evenly distributed in family zone	60	cooler air evenly distributed	40	much cooler air evenly distributed in family zone	60
People Movement Attributes:	in the family zone		along the walkway		in the family zone		in the family zone, near bathroom		along the walkway		in the family zone, near bathroom	
Advantages:	least activity	20			less activity	10	less activity	10			less activity	10
Bathroom Location Attributes:	inboard bathroom						outboard bathroom					
Advantages:	less impact on air ventilation				20							
Total importance of advantages	230		60		230		200		40		210	

Step 5 Decide the advantages of each alternative:

Criteria were applied in this step. The least preferred attributes were underlined, the most important advantage for each factor was circled.

Step 6 Decide the importance of each advantage:

The researcher assigned a score to each advantage in a scale from 1 to 100. The author selected case 1 and case 3 since they have the highest total IofAs.

3.3.3 Diffuser Type

HVAC diffusers deliver air in rooms. They are used to change fluid velocity and air distribution. The diffuser types influence the room interior, ventilation efficiency, and patients' comfort. In this part, the author identified and made judgments based on the attributes of different diffusers.

PV diffuser

In Zheng et al.'s model, they used PV supply diffusers with adjustable blades and adjustable air volume. PV diffusers blew air toward the patient on the bed. However, since patients are normally sensitive to airflow and feel discomfort when air blows to them, it was necessary to modify Zheng et al.'s personalized ventilation system model. The author used CBA process to decide the type of PV diffuser in patient rooms.

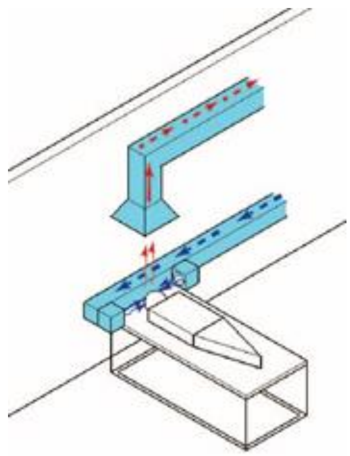

Figure 47 Zheng et al.'s PV air supply method (Zheng et al., 2011)

Step 1: Identify alternatives:

The author investigated three commonly used diffusers: linear diffuser, louvered face diffuse, and air nozzle diffuser. Linear diffusers are long and narrow diffuser with adjustment on air direction. They normally supply quiet and stable airflow. According to LTG, a company that focused on air and climate technology, linear diffusers could supply air quietly due to the design of the inner contour ("LTG Linear Diffusers," n.d.). There are various types of louvered face diffuser. Louvered diffuser can supply a large amount of air in a large room. The author selects the adjustable louvered face diffuser in this case. The air nozzle diffuser according to Price Industries, achieves a very long air projection due to its depth and geometry (Price Industries, 2011). In this case, these three types of diffusers supplied small air volume and located at the same location in the room.

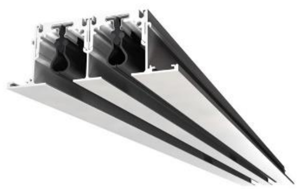

Figure 48 Linear slot diffuser (https://www.priceindustries.com/diffusers/products/sds-sdr-linear-slot)

Figure 49 Louvered face diffuser (https://www.priceindustries.com/grilles/products/hcd-drum-louver)

Figure 50 Air nozzle diffuser (https://www.priceindustries.com/grilles/products/and-air-nozzle-diffuser)

Step 2: Define factors:

In the study on locations of PV supply, the result showed that PV system supplied air on both side of the bed and align with the bed height near patients. From an architectural point of view, factors regarding patients 'comfort and PV performance were considered. Many factors about were not considered since they were either not related with this study or having similar attributes (ex., all of them have adjustable blades) or having less impact on the decision (ex., material). For example, noise was not considered since the diffusers supplied small amount of air. In this study, more factors regarding the performance of the diffusers should be studied in the future.

Step 3: Define the must/want to have criteria for each factor:

- Factor 1 Patients' comfort: In this factor, the author considered the throw since patients would feel uncomfortable if they feel air blows to them, especially the diffusers are next to the patient. Less throw the better.

- Factor 2 Outlook: the outlooks of these diffusers are important since the author would like to minimize the existence of the PV system near patients thereby minimize the visual impact of the equipment on patients. So, the outlook is the simpler the better.
- Factor 3 Ventilation effectiveness: The dual ventilation system in this study required the cooperation of two ventilation systems. PV supplied air should not collide with the room ventilation air to avoided cross-mixing and cross-infection. According to the "Air Distribution Engineering Guide" published by Price Industries in 2011, "Spreading the air is an effective way of reducing throw to avoid air pattern collisions with boundaries or other air jets." For this factor, less air mixing is better.

Step 4: Summarize the attributes of each alternative:

The attributes of each alternative can be found in the "*Air Distribution Engineering Guide*" published by Price Industries in 2011.

Table 5 PV supply diffuser CBA

Factors	Louvre bladed diffuser		Linear slot diffuser		air nozzle diffuser	
Patients' Comfort Attributes:	Adjustable throw direction		Natural spreading with adjustable direction		long air projection	
Advantages:	more comfortable	90	most comfortable	100		
Outlook attributes:	square or rectangle, protruded from the wall		long and narrow, embeded in the wall		circular, protruded from the wall	
advantages:			simple and clean	80		
Ventilation effeciveness Attributes:	Long throw		Natural spreading		Long throw	
Advantages:			least air pattern collision	100		
Total importance of advantages	90		280		0	

Step 5 Decide the advantages of each alternative:

Criteria were applied in this step. The least preferred attributes were underlined, the most important advantage for each factor was circled.

Step 6 Decide the importance of each advantage:

The researcher assigned a score to each advantage in a scale from 1 to 100. In this case, the author decided that patients feel the most comfortable and least air pattern collisions were the paramount advantage. So, the researcher assigned 100 IofAs to these advantages. The author assigned 90 IofAs to most important advantage, which was more comfortable airflow for patients. In this case, simple and clean diffuser outlook was important advantages (80 IofAs). The total importance of advantages was calculated. The author selects the diffuser with the highest total IofAs, which was the linear slot diffuser.

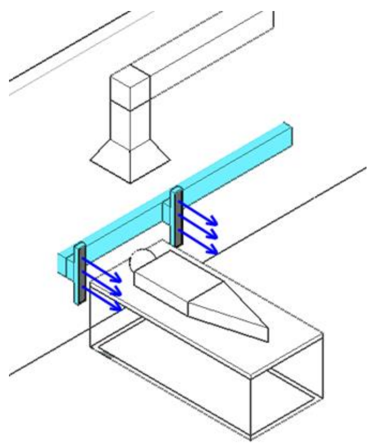

Figure 51 The air supply after the author modifies

DPV diffuser

The author used the CBA system to evaluate each type of DPV diffuser.

Step 1: Identify alternatives:

There are many types of displacement diffusers on the market. The author selected four commonly used diffuser types: wall-mounted diffusers, floor-mounted diffusers, freestanding diffusers, and ceiling-mounted diffusers.

Figure 52 Wall-mounted diffuser (https://www.priceindustries.com/displacement/products/df1-rectangular-1way-displacement-diffuser)

Figure 53 Floor-mounted diffuser (https://www.priceindustries.com/underfloor/products/dfgl-linear-displacement-floor-grille)

Figure 54 Freestanding diffuser (https://www.priceindustries.com/displacement/products/full-round-360-displacement-diffuser)

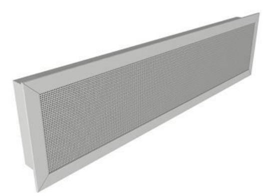

Figure 55 Ceiling-mounted diffuser (https://www.priceindustries.com/displacement/products/dfc-displacement-flow-ceiling-diffuser)

Step 2: Define factors:

In this study, the DPV served the cooling and heating of the room. The author considered the factors based on architectural knowledge and assumed all the DPV alternatives had the same performance. Therefore, factors regarding the diffuser performance were not discussed in this study (ex., noise, air velocity…).

Step 3: Define the must/want to have criteria for each factor:

- Hygiene: In healthcare facilities, hygiene is the most important factor in keeping people healthy. In the patient rooms, it is problematic for the ventilation system to spread contaminants. Criteria: it is better if the diffuser is less able to spread contaminants.
- Maintenance: This factor accounts for the accessibility of the devices. Criteria: the closer the equipment is to the ground, the better.
- Impact on room layout: for this factor, the author considers the impact of each type of diffuser on the patient room design. Criteria: Less impact is better.

Step 4: Summarize the attributes of each alternative:

The attributes of diffusers were based on the common knowledge and the "*Displacement Ventilation Engineering Guide.*"

Table 6 DPV supply diffuser CBA

Factors	Wall-mounted diffuser		Floor-mounted diffuser		Freestanding diffuser		Ceiling-mounted diffuser	
Hygiene Attributes:	great		awful		good		poor	
Advantages:	Fewer pollutants spread in the room	100			Fewer pollutants spread in the room	100	slightly fewer pollutants spread in the room	20
Maintenance Attributes:	in the wall		in the floor		on the ground		in the ceiling	
Advantages:	easier to access the equipment	10	easiest to access	20	easier to access the equipment	10		
Impact on room layout Attributes:	influence		influence		great influence		small	
Advantages:	less impact on the layout	40	less impact on the layout	40			least impact on the layout	60
Total importance of advantages		150		60		110		80

Step 5 Decide the advantages of each alternative:

Criteria were applied in this step. The least preferred attributes were underlined, the most important advantage for each factor was circled.

Step 6 Decide the importance of each advantage:

The researcher assigned a score to each advantage in a scale from 1 to 100. In this case, fewer pollutants spread in the room was the paramount advantage (100 IofAs). least impact on the layout was an important advantage (60 IofAs). After the author assigned importance points to the advantages, she calculated the total importance of advantages. The author selects the DPV diffuser with the highest total IofAs, which was the wall mounted diffuser.

4. Chapter 4 Discussion

Due to the emergence of the airborne disease COVID-19, the author focused on the infection control in healthcare facilities. In the preliminary research, the author found out a new personalized ventilation system that can effectively remove the contaminated air from the source that can be applied in offices, hospital consultation rooms, and patient rooms. After the literature review, the author assumed the displacement ventilation system is the most ideal system to cooperate with the personalized ventilation system for airborne infection control. Based on an understanding of both ventilation systems, the author integrated this dual-ventilation system in the private and semi-private patient room designs. By considering comfort, safety, the interplay of PV and DPV, and the impact of room layout on the efficiency of the dual-ventilation system, the author proposed optimized designs of the private and semi-private patient rooms that prevent cross-infection under the application of the dual-ventilation system.

4.1 Results and findings

- PV should use linear diffusers. The top of the linear diffuser should align with the patient bed.

- The minimum height of the PV exhaust is 7 ft. The PV system should have small-scale PV exhaust so that it does not drag the surrounding air to pollute the microenvironment around each patient, and it does not disturb the outside air movement in the room.
- PV systems are small scale assistant ventilation systems. So, the DPV should meet the minimum air change rate in the patient rooms.
- Patients' comfort is important when applying the PV system since this system supplies air close to patients.
- DPV system is the preferred ventilation system to pair with the PV system.
- Patient rooms should use wall mounted displacement diffusers. The DPV diffuser should not be on the opposite side of the PV supply because it will cause air turbulence and interrupt the air flow of the PV system.
- For ventilation efficiency, the DPV diffuser should locate on the exterior side so that it can cool the warm air quickly and allow for even air distribution.
- Room exhaust should locate in the center of the ceiling to get an even air distribution in the room.
- The room exhaust and return should be located away from the PV system so that the negative pressure around the air inlets does not affect the PV air circulation.
- Hydronic heating system is better than the other heating strategies when using dual ventilation system in patient rooms.
- Room layout, supply and return locations, and types of diffusers impact the ventilation efficiency. Types of ventilation system selected impact the room layout.

• Semi-private patient room Case 3

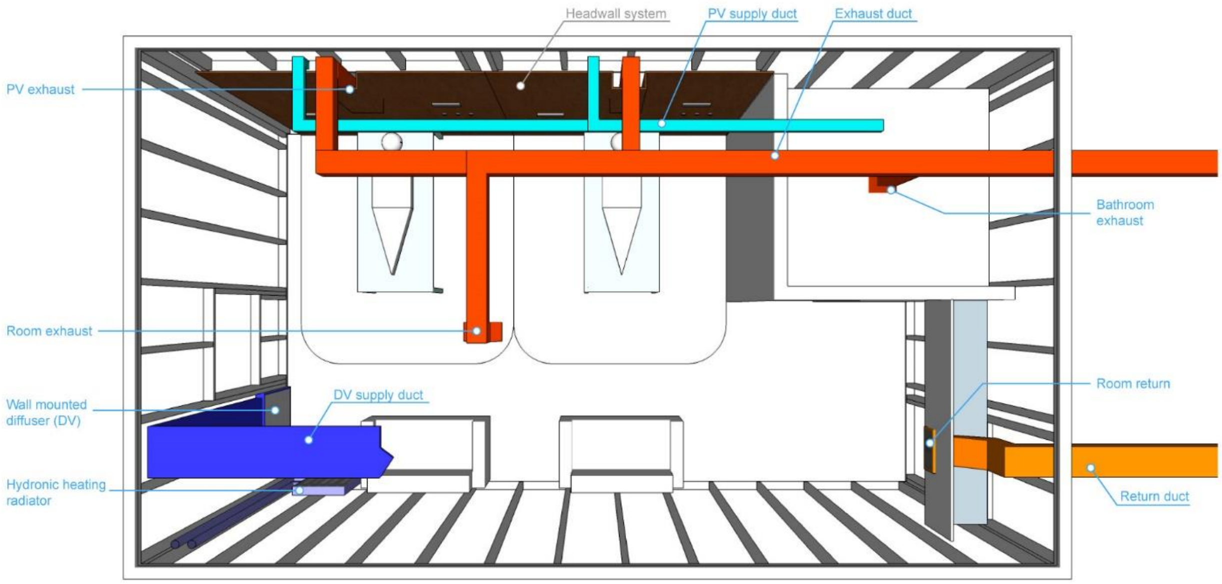

Figure 56 Semi-private patient room Case 3 top view

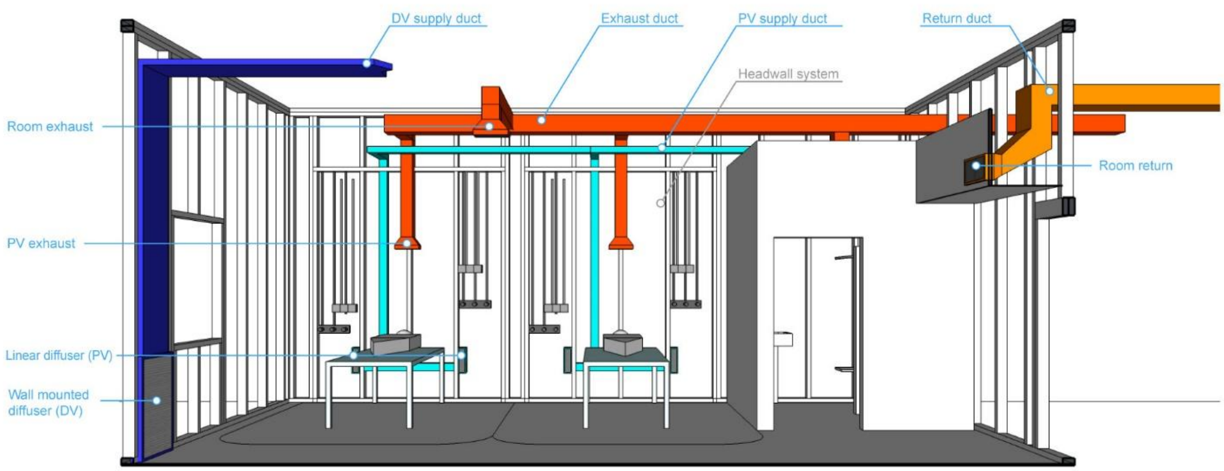

Figure 57 Semi-private patient room Case 3 section view

- Private patient room Case 1

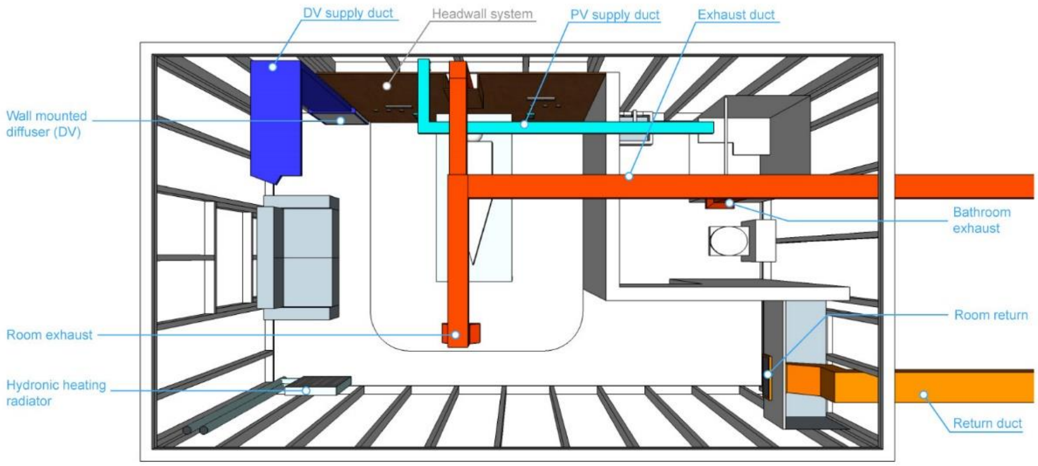

Figure 58 Private patient room Case 1 top view

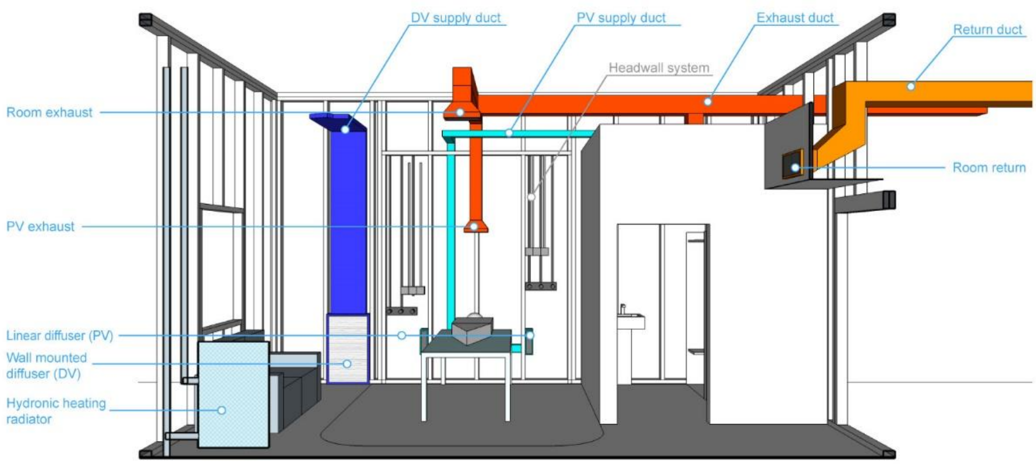

Figure 59 Private patient room Case 1 section view

• Private patient room Case 3

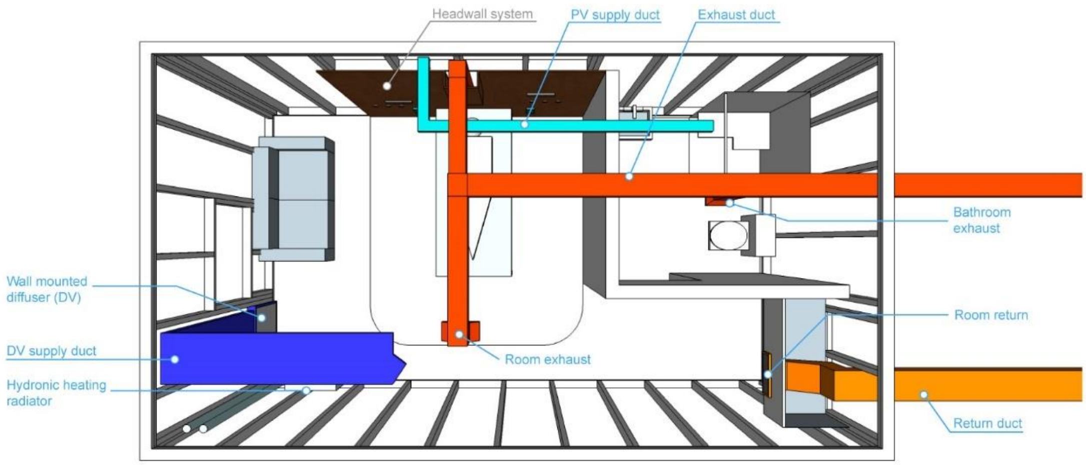

Figure 60 Private patient room Case 3 top view

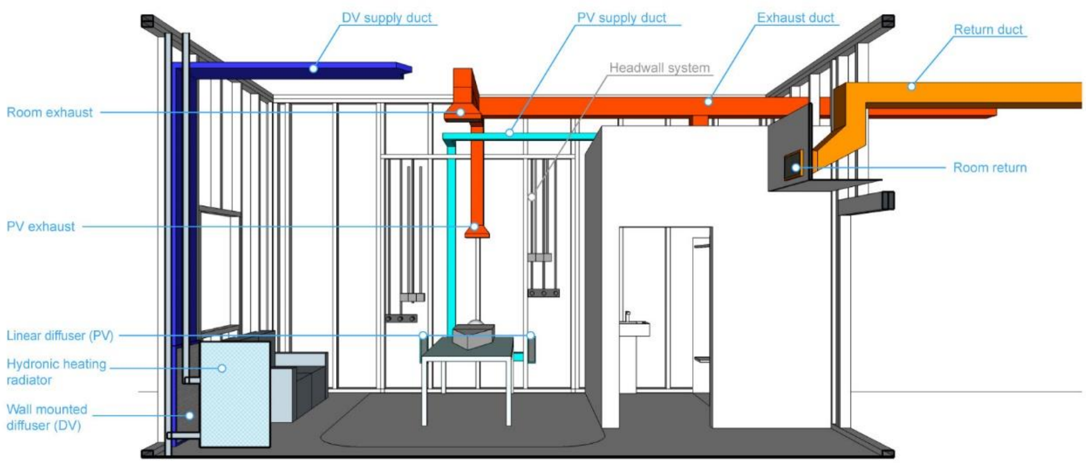

Figure 61 Private patient room Case 3 section view

4.2 Conclusion

This study offers a solution to improve ventilation in patient rooms. From an architectural point of view, this study gives instructions on where to apply dual ventilation systems in the patient rooms, and how to apply personalized ventilation systems with a displacement ventilation system. When applying dual ventilation systems in the inpatient facilities, it is necessary to involve both architects and engineers at the early stage of design since this system has impacts on the layout of patient rooms and may have impacts on the room layouts in buildings. This research provides primary models for the subsequent application of PV systems in inpatient facilities or other healthcare facilities.

4.3 Limitations and further research

Even though the personalized ventilation system has many advantages in infection control, it still has limitations.

- Unlike room ventilation systems (mixing and displacement ventilation systems), the PV system is inflexible: one device can only serve one bed. If inpatient facilities need to enlarge their capacities, PV systems, as local ventilation systems, are restricted to their locations and cannot be applied to all the patients.
- The author focused on the application of the PV system in patient rooms. Therefore, the impact of PV systems on buildings is unknown.
- This research was based on a series of assumptions. Author’s assumptions require further research and test.

- Even though there was literature proved that DPV was the ideal ventilation system to be cooperated with PV, CFD models are necessary to test the airflow pattern of private and semi-private patient rooms with PV and DPV systems.
- This study requires stakeholder's involvement to refine the choosing by advantages system.
- Practical models /simulation rooms are required to test the impact of PV systems on patients' and nurses' daily activities.
- The author assumed that PV supply and exhaust generate low noise and small air stream so that patients will not feel uncomfortable. However, this required further study on diffusers.

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