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Negative Air Pressure Isolation Room for COVID-19 Patients in the Philippines: A Simulation of the Proposed Design using SolidWorks

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***Abstract*— Since the start of the 2019 pandemic, medical staff and non-medical staff are fighting on the front line in all hospitals worldwide. However, the possibility of healthcare workers' scarcity due to the increasing medical infection rate is ignored in many recent studies. To prevent such things to happen, the installation of a negative air pressure isolation room is proposed to Norzagaray Municipal Hospital (NMH). Primary parameters such as filtration, pressure management, and dilution ventilation were investigated in SOLIDWORKS simulation software by removing one parameter per simulation. Two existing schemes were simulated, and the primary parameters present were evaluated. Three ventilation design set-ups were designed and the effects of the varying placements of the primary parameters to the airflow pattern in a negative air pressure isolation room were determined. Cost-benefit analysis (CBA) was conducted to determine if the cost of installing the negative air pressure room outweighs its benefit. The set-up where the High efficiency particulate air (HEPA) machine is inside the room is proposed to NMH as this abides by the Department of Health (DOH) memorandum and standards on Airborne Infection Isolation Rooms (AIIRs) and is the most effective of the three set-ups. Results show that filtration filters the infectious particles, pressure management manages the proper airflow direction, and dilution ventilation makes sure there are enough air changes per hour to filter a percentage of infectious particles. In the existing schemes, all the primary parameters were used to contain the infectious particles in the room, however, the effectivity of the filtration also depends on the location of the patient, supply, and exhaust. The most significant effect of the varying placements of the primary parameters can be seen in filtration as only the set-up where the HEPA machine is inside the room was able to filter 100% of the infectious particles. It is also the most profitable ventilation design set-up with a 2.08 CBA ratio and has the least payback period of 5.8 months.**

Keywords*— *Negative Air Pressure Room, COVID-19, Ventilation Design, CBA, AIIRs.

I. INTRODUCTION

The Department of Health (DOH) of the Philippines confirmed the first case of COVID-19 on January 30, 2020, who is a 38-year-old Chinese woman. Furthermore, the World Health Organization (WHO) defined the outbreak as a pandemic on March 11, 2020, and the COVID-19 risk assessment was declared as extremely high at the global level [1]. Coronavirus can be detected on different surfaces in the community and the immediate environment of patients in hospital facilities [2]. Due to catering a new strain of coronavirus illness (COVID-19) but not fully satisfying the criteria of a hospital for infectious diseases in Wuhan, China, the apparent infection rate of health care workers in a hospital is 87.9% [3]. In the Philippines, according to the Department of Health's (DOH) tally in June 2020, 15% of the coronavirus cases are health care workers. In emerging infectious diseases, health care workers are the most affected. According to the World Health Organization (WHO), 21% of the total cases in an outbreak of an infectious disease in 2005, are health care workers [4].

Isolating patients in a negative pressure system provides additional protection for the healthcare workers [5] The goal of ventilation in a hospital environment is to remove hazardous and detrimental particles, heat, and infection from the building through indoor-outdoor air movement [6]. Patients who may be contaminated with any airborne and infectious illnesses are separated and treated in a negative air pressure chamber, commonly known as an Airborne Infection Isolation Room (AIIR). With the arrival of the COVID-19 pandemic, Chung Buk National University Hospital in Cheongju, South Korea, increased its AIIRs, which create negative air pressure and were previously used to treat patients with infectious illnesses. The expansion led to a comparatively low infection rate to its health care workers [7]. In the Philippines, Makati's Local Government Unit (LGU) acquired negative air pressure tents for its COVID-19 patients [8]. Air moves from high-pressure locations to low-pressure areas when there is a pressure differential between two places. Bioaerosols such as viruses, allergies, pathogens, dead or live bacteria, fungi, antigens, and others can be suspended and transported by a directional airflow pattern between a patient's room and neighboring facilities [9]. Several design parameters are required for the design process of a clean room, he listed this as Room dimension, Medical and non-medical equipment, Pressure, Air temperature, Air humidity, Air velocity, and the number of airborne particles [10]. Pressure management in a room and its surrounding vicinity is essential in implementing and maintaining negative air pressure in an isolation room. To exhibit a negative air pressure in a room, the supply flowrate must be less than 10 percent or 1.42m^3 of the exhaust flow rate of the room [11]. The air in a room or building is exchanged via dilution ventilation. The number of air changes per hour (ACH), the physical form of the area or room, and the position of the ventilation input and outlet all influence the time required to remove a percentage of airborne particles from space or the location of the ventilation supply and exhaust [12]. The process of passing polluted air through a filter is known as filtration. In hospitals, filtration needs are frequently high. It can have harmful consequences on other individuals in a medical setting and in the surrounding environment if it is not provided. Filters used in hospitals must remove at least 90% of particles with a diameter of 0.5 microns or greater [13]. The design of negative air pressure rooms must follow DOH standards for Airborne Infection Isolation Room (AIIR) from memorandum no. 2020-0062 [14].

The objective of this study is to propose ventilation design systems of a negative air pressure isolation room for Norzagaray Municipal Hospital with the consideration of the effects of varying placements of the primary parameters to the airflow pattern with the use of SOLIDWORKS simulation software. Moreover, a cost-benefit analysis was also conducted to evaluate the long-term benefit of investing in the proposed design. The proposed design could be a potential reinforcement to the healthcare system in the control of current and future airborne epidemic and pandemic

II. METHODOLOGY

A. Research Setting

The researchers picked a hospital that caters to suspected COVID-19 patients yet can still accommodate researchers; The Norzagaray Municipal Hospital (NMH). NMH, located at Poblacion Street, Norzagaray Bulacan, was established in the year 2000 and has more than a hundred staff including medical and non-medical.

B. Primary Parameters

The primary parameters include (a) pressure management, (b) dilution ventilation, and (c) filtration which will be run through SOLIDWORKS and analyzed how removing one parameter per set-up will affect the airflow pattern in two existing schemes, one is without an anteroom (Fig.1) and the other with an anteroom (Fig.2). In the first case, parameters were simulated without (c) filtration. In the second case, parameters were simulated without (a) presume management and lastly without (b) dilution ventilation.

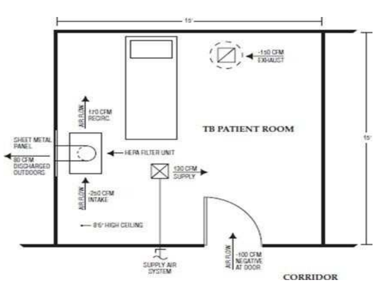

Fig.1 Existing Scheme without an Anteroom

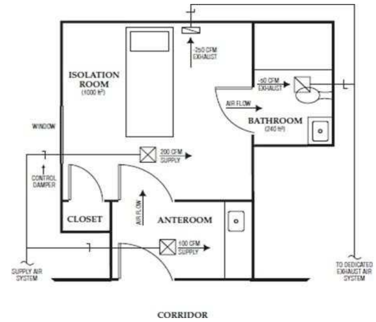

Fig. 2 Existing Scheme with an Anteroom

C. Design Process

In designing, the researchers used a comparative analysis of the effects of varying placements of the primary parameters to the airflow pattern in a negative air pressure isolation room to come up with the most appropriate design by having three (3) set-ups of High-efficiency particulate air (HEPA) filter machine [15] ;(a) inside the room (Fig.3), (b) mounted on the wall of the room (Fig.4), and (c) outside of the room (Fig.5).

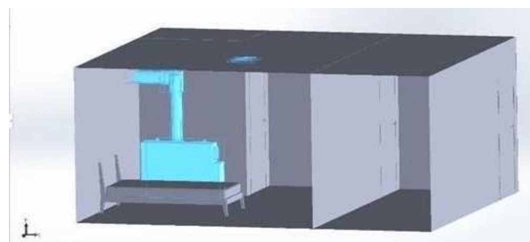

Fig.3 HEPA Machine inside the Room

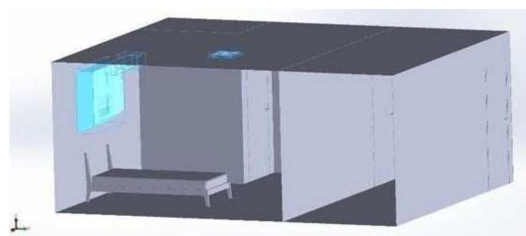

Fig.4 HEPA Machine Mounted on the Wall

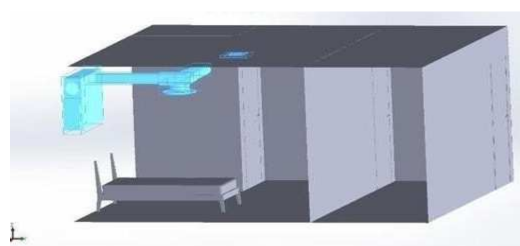

Fig. 5 HEPA Machine Outside of the Room

D. Cost-Benefit Analysis

To determine if the installation of a negative air pressure isolation room to Norzagaray Municipal Hospital is justifiable and feasible, the researchers did a cost-benefit analysis. Currently, the Norzagaray Municipal Hospital is using a temporary triage tent and manual disinfection to their isolation room. In computing for the payback period and the CBA ratio, (1) and (2) were used:

$$\text{CBA Ratio} = \frac{Total\ Benefit}{Total\ Cost} \quad (1)$$

$$\text{Payback Period}=\frac{Total\ Costs}{Total\ Benefits} \quad (2)$$

III. RESULTS AND DISCUSSION

A. Importance of Filtration, Pressure Management, and Dilution Ventilation in a Negative Air Pressure Isolation Room's Ventilation System

a) Filtration is Removed in the System

The (light blue lines) air that traveled through the door had a velocity of 12.69 to 25.37 feet per second, whereas the (dark blue lines) air that was distributed around the room had a velocity of 0 to 6.34 feet per second, according to the legend on the left side of Fig. 6. Due to the absence of filtration in the room, 55% of the infectious particles in the (red lines) contaminated air was scattered and absorbed in the room, 5% stayed on the air, and the remaining 40% went to the corridor. 55% of the infectious particles were absorbed in the room due to the location of the patient and the supply. This ventilation system without filtration does not abide by the DOH memorandum and standards on AIIRs.

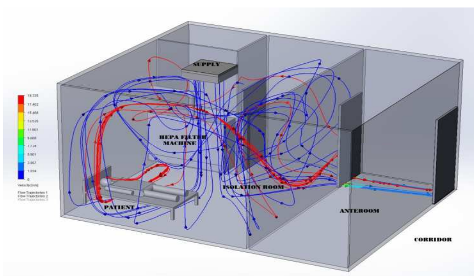

Fig. 6 Air Flow Pattern inside the Isolation Room when Filtration is Removed in the System

The air pressures within the (red area) isolation room vary from 101,484.00 to 101,501.67 Pa, inside the (green area) anteroom range from 101,395.67 to 101,413.34 Pa, and in the corridor are exactly 101,325.00 Pa, according to the legend on the left side of Fig. 7. As a result, air flows towards the corridor since air flows from high to low-pressure zones.

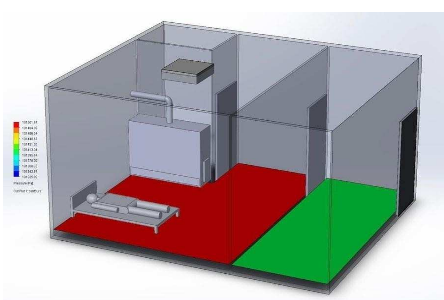

Fig.7 Pressure inside the Isolation Room when Filtration is Removed in the System

b) Pressure Management is Removed in the System

Due to the minimum differential pressure between the isolation chamber and the anteroom, the air velocity within the room and the anteroom is uniform, ranging from 0 to 6.34 feet per second, as presented in the description in Fig. 8. This room has 14 air changes per hour, which is higher than the 12 which is allowed by the DOH memorandum and AIIR guidelines. This ventilation system does not comply with the DOH memorandum and AIIR requirements because it lacks pressure control.

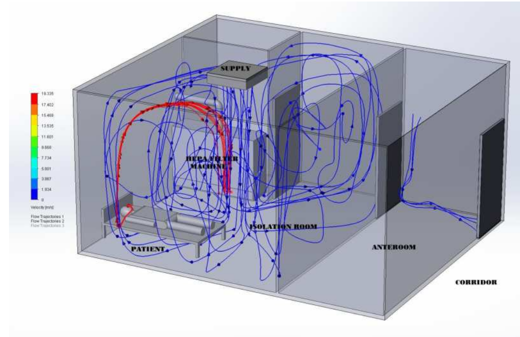

Fig. 8 Air Flow Pattern inside the Isolation Room when Pressure Management is Removed in the System

The air pressures in the isolation room (yellow-green area) and anteroom (yellow-green area) in Fig. 9 vary from 101,324.88 to 101,325.19 Pa. Because the recommended differential pressure from higher pressure areas to lower pressure areas must be more than 2.5 Pa to be considered negative, the 0.12 to 0.19 Pa difference in pressure in the corridor does not qualify it as a negative air pressure isolation room, according to the Korea Centers for Disease Control and Prevention.

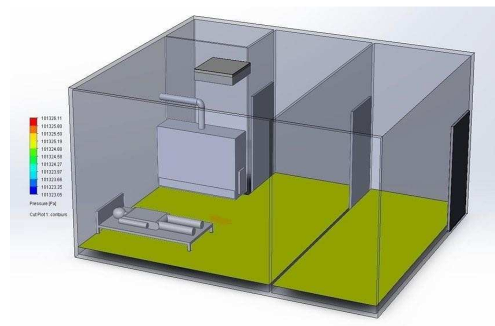

Fig. 9 Pressure inside the Isolation Room when Pressure Management is Removed in the System

c) Dilution Ventilation is Removed in the System

The air velocity (dark blue lines) is uniform, ranging from 0 to 6.34 feet per second, according to the caption on Fig. 10. With less ACH, 45 percent of the infectious particles in the contaminated air (red lines) were absorbed in the isolation room, 10% remained on the air, and 45 percent were filtered in the HEPA machine. This ventilation system does not comply with the DOH memorandum and AIIR requirements because it lacks the necessary ACH.

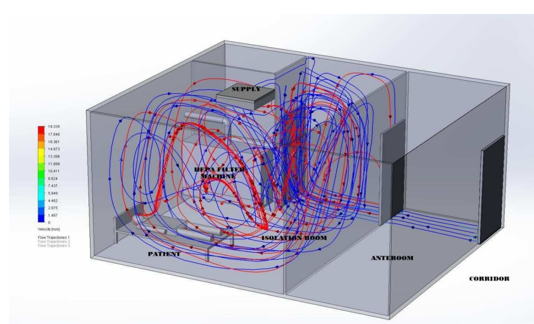

Fig.10 Air Flow Pattern inside the Isolation Room when Dilution Ventilation is Removed in the System

The pressure within the (green area) isolation room, inside the (red area) anteroom, and in the hallway varies from 101,291.19 to 101,295.08 Pa, 101,310.63 to 101,314.51 Pa, and 101,325 Pa, respectively, as shown in the description of Fig. 11. Because air goes from high-pressure regions to low-pressure places, air will flow from the hallway to the anteroom and then to the isolation room.

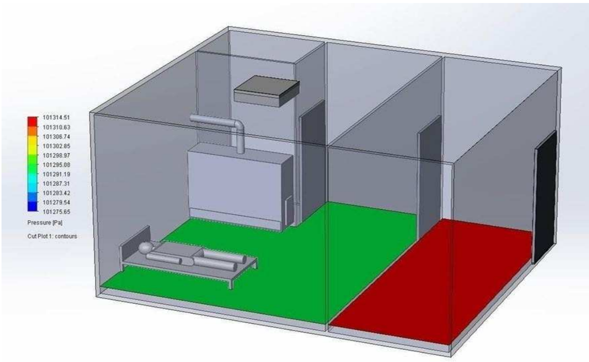

Fig.11 Pressure inside the Isolation Room when Dilution Ventilation is Removed in the System

B. *Primary Parameters used in the Existing Schemes*

a) Existing Scheme with an Anteroom

The air velocity (dark blue lines) is consistent, ranging from 0 to 6.34 feet per second, as described in Fig. 12. In the filtering process, 85 percent of the infectious particles in the polluted air red lines were absorbed in the room, while only 15% were filtrated in the exhaust. This scheme's air changes per hour are 18, which is more than the DOH guidelines and regulations on AIIRs' minimum necessary ACH. As a result, this current method relied on pressure control, diluted ventilation, and a faulty filtering system.

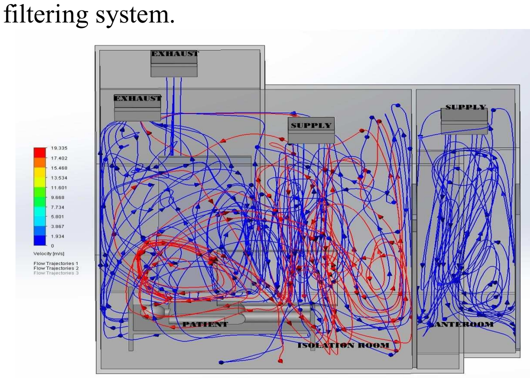

Fig.12 Air Flow Pattern inside the Existing Scheme with an Anteroom

The legend on the left side of Fig.13 shows the air pressure inside the (yellow-orange areas) anteroom and the isolation room, and the (red area) comfort room ranges from 101328.73 to 101329.27 Pa and 101329.80 to 101330.34, respectively. This shows that the anteroom, isolation room, and comfort room are positively pressurized to the corridor because the air pressure in the following areas is higher than the pressure in the corridor which is 101325.00 Pa.

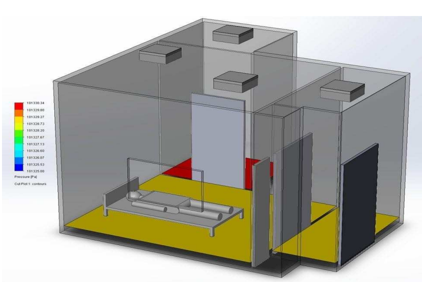

Fig.13 Pressure inside the Existing Scheme with an Anteroom

b) Existing Scheme without an Anteroom

The (light blue lines) air near the gap on the door has a velocity of 9.8 to 13.09 feet per second, which is greater than the (dark blue lines) air within the room, which has a velocity of 0 to 3.27 feet per second, as shown in Fig. 14. The HEPA machine filtered 100 percent of the pathogenic particles in the (red lines) polluted air during filtering. This room has a ventilation rate of 12.4 air changes per hour, which is higher than the DOH memorandum and AIIR minimum standard requirement of 12. As a result, this current design, which lacked an anteroom, efficiently used pressure control, dilution ventilation, and filtration.

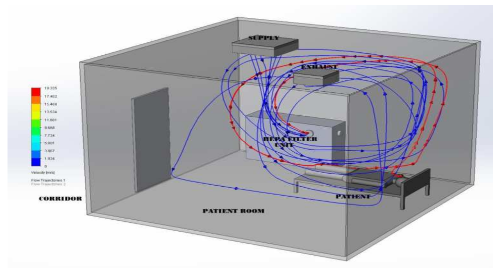

Fig.14 Air Flow Pattern inside the Existing Scheme without an Anteroom

The air pressure inside the current scheme (yellow region) ranges from 101,291.13 to 101,308.61 Pa, which is lower than the corridor pressure of 101,325.00 Pa (see Fig. 15). As a result, air will flow from the hallway into the room since air flows from high to low-pressure zones.

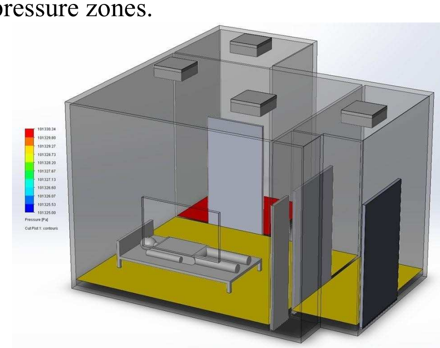

Fig.15 Pressure inside the Existing Scheme without an Anteroom

C. *Design of a Ventilation System which Maximized the Function of the Primary Parameters such as Filtration, Pressure Management, and Dilution Ventilation*

The researchers recommended three possible room configurations: a HEPA machine within the room (Fig. 16), a HEPA machine installed on the wall (Fig. 17), and a HEPA machine outside the room (Fig. 18). The impacts of different placements of main factors such as filtration, pressure management, and dilution ventilation in a ventilation system of a negative air pressure isolation chamber were simulated in SOLIDWORKS.

The three set-ups differ a little when it comes to the differential pressure between the corridor and the anteroom, however, all of them are more than 2.5 Pa, the required differential pressure. When it comes to dilution ventilation, the air changes per hour of the three set-ups are the same since the volume of the room and the outflow rate in the exhaust is constant.

In the set-up where the HEPA machine is inside the room, 100% of the infectious particles in the (red lines) contaminated air were filtered in the HEPA machine. In the set- up where the HEPA machine is mounted on the wall, only 10% of the infectious particles in the (red lines) contaminated air was filtered in the HEPA machine and the remaining 90% were absorbed in the room. And in the set-up where the HEPA machine is outside of the room, only 45% of the infectious particles in the contaminated (red) air were filtered in the HEPA machine, 10% stayed on the air, and the remaining 45% were absorbed in the room.

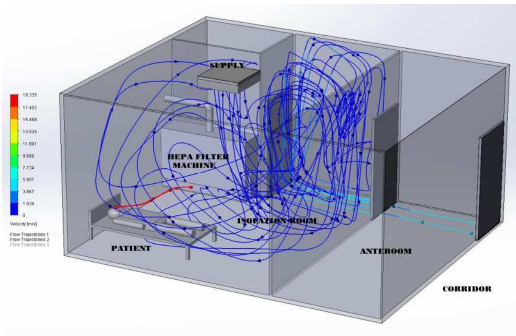

Fig.16 Air Flow Pattern when the HEPA Machine is inside the Room

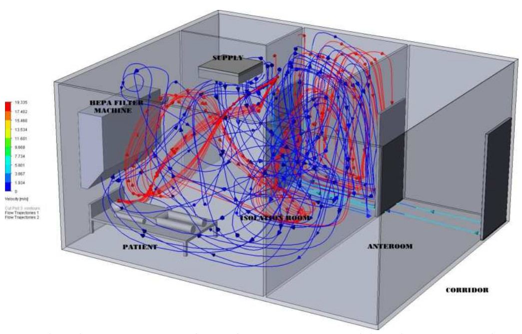

Fig.17 Air Flow Pattern when the HEPA Machine is Mounted on the Wall

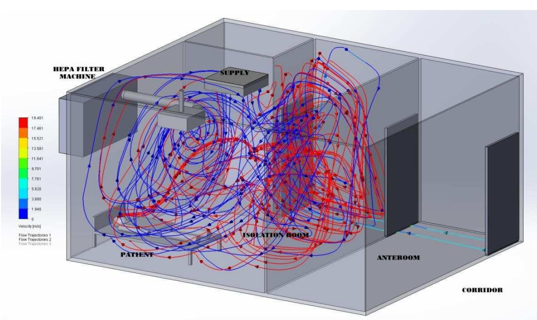

Fig.18 Air Flow Pattern when the HEPA Machine is outside the Room

D. Cost-Benefit Analysis

Based on the quoted prices in 2021, the researchers compared the annual cost of three set-ups of negative air pressure rooms such as when the HEPA machine is inside the room, when the HEPA machine is mounted on the wall, and when the HEPA machine is outside of the room. Table 1 shows that the HEPA machine inside the room which filters 100% of the infectious particles has a total annual cost of ₱149,553.08. This annual cost will be used in determining the cost-benefit.

Table 1. Annual Cost of Installation of the HEPA Machine inside the Room

SET-UP 1: HEPA machine inside the room (annually)			
Item	***Unit Price***	***Life-Span***	***Annual Cost***
HEPA Machine	₱96.950.26	10 Years	₱9,695.03
Duct	₱1,280.00	10 Years	₱128.00
Filter	₱6,150.00	6 Months	₱12,300.00
Electricity	₱291.37	Daily	₱106,350.05
Maintenance	₱1,000.00	6 Months	₱2,000.00
Installation Cost	₱12,000.00	10 Years	₱1,200.00
Room Disinfection	₱745.00	15 Days	₱17,880.00
Total:			₱149,553.08

Table 2 shows that the HEPA machine mounted on the wall which filters 10% of the infectious particles has a total annual cost of ₱403,598.08. This annual cost will be used indetermining the cost-benefit.

Table 2. Annual Cost of Installation of the HEPA Machine is mounted on the Wall

SET-UP 1: HEPA machine mounted (annually)			
Item	***Unit Price***	***Lifespan***	***Annual Cost***
HEPA Machine	₱96.950.26	10 Years	₱9,695.03
Duct	₱1,280.00	10 Years	₱128.00
Filter	₱6,150.00	6 Months	₱12,300.00
Electricity	₱291.37	Daily	₱106,350.05
Maintenance	₱1,000.00	6 Months	₱2,000.00
Installation Cost	₱12,000.00	10 Years	₱1,200.00
Room Disinfection	₱745.00	Daily	₱271,925.00
Total:			₱403,598.08

Table 3 shows that the HEPA machine outside the room which filters 45% of the infectious particles has a total annual cost of ₱167,433.08. This annual cost will be used indetermining the cost-benefit.

Table 3. Annual Cost of Installation of the HEPA Machine is outside of the Room

SET-UP 1: HEPA machine outside (annually)			
Item	***Unit Price***	***Lifespan***	***Annual Cost***
HEPA Machine	₱96.950.26	10 Years	₱9,695.03
Duct	₱1,280.00	10 Years	₱128.00
Filter	₱6,150.00	6 Months	₱12,300.00
Electricity	₱291.37	Daily	₱106,350.05
Maintenance	₱1,000.00	6 Months	₱2,000.00
Installation Cost	₱12,000.00	10 Years	₱1,200.00
Room Disinfection	₱745.00	7 Days	₱35,760.00
Total:			₱167,433.08

To compute for the benefit, the researchers used the manual disinfection cost for one-year against the annual cost of the three negative air pressure room set-ups. In manual disinfection, the labor cost, PPE, insurance, and disinfectant solution have a daily cost as shown in table 4.

Table 4. Manual Disinfection Cost

Manual Disinfection (Annual)				
Item	***Price***	***Qty***	***No. of Days***	***Annual Cost***
Labor	₱400.00	1	365	₱146,000.00
PPE	₱650.00	1	365	₱237,250.00
Disinfection Kit	₱1,600.00	1	1 Year	₱1,600.00
Insurance	₱50.00	1	365	₱18,250.00
Disinfection Solution	₱158.00	1	365	₱57,670.00
TOTAL:				₱460,770.00

To compute the total benefit, the researchers compared the annual cost incurred in manual disinfection against the annual cost of three set-ups of negative air pressure rooms as shown in table 5.

Table 5. Benefit

Benefits			
	Set-Up 1	***Set-Up 2***	***Set-Up 3***
Negative Air Pressure Room	₱149,553.08	₱403,598.08	₱167,433.08
Manual Disinfection	₱460,770.00	₱460,770.00	₱460,770.00
Total Benefit	₱311,216.92	₱57,171.92	₱293,336.92

The researchers used the cost-benefit ratio as shown in table 6 to obtain and select the most profitable set-up to Norzagaray Municipal Hospital. Therefore, the most profitable based on the CBA ratio is set-up 1 where the HEPA machine is inside the room because according to Adam Hayes if the cost-benefit ratio is greater than 1.0, the investment is profitable.

Table 6. Cost-Benefit Ratio

Cost-Benefit Ratio			
	Set-Up 1	***Set-Up 2***	***Set-Up 3***
Total Cost	₱149,553.08	₱403,598.08	₱167,433.08
Total Benefit	₱311,216.92	₱57,171.92	₱293,336.92
Cost-Benefit Ratio	2.08	0.14	1.75

Table 7 shows the number of months to recover the cost of investment. To compute thereturn of investment, the payback period is multiplied by 12 months (Annual). Set-up 1 where the HEPA machine is inside the room is the best proposal for Norzagaray Municipal Hospital because they can recover the investment in 5.8 months. The hospital can recover the investment in shorter months compared to the other set-ups.

Table 7. Payback Period

Payback Period			
	Set-Up 1	***Set-Up 2***	***Set-Up 3***
Total Cost	₱149.553.08	₱403,598.08	₱167,433.08
Total Benefit	₱311,216.92	₱57,171.92	₱293,336.92
Payback Period	0.48	7.06	0.57
Return Of Investment (Months)	5.8 MONTHS	84.7 MONTHS	6.8 MONTHS

IV. CONCLUSIONS AND RECOMMENDATIONS

The researchers proposed the installation of a negative air pressure isolation room to Norzagaray Municipal Hospital where the HEPA machine is inside the room beside the patient. This ventilation design abides by the DOH memorandum and standards on AIIRs and is the most effective among the three set-ups as it can filter 100% of the infectious particles. The presence of the primary parameters such as pressure management, dilution ventilation, and filtration in the existing schemes contained the infectious particles in the room. However, having filtration does not mean all the infectious particles in the room will be filtered. The most significant effect of the varying placement of the primary parameters can be seen in filtration. Among the three ventilation design set-ups, only the set-up where the HEPA machine is inside the room was able to filter 100% of the infectious particles. For the cost-benefit analysis, the set-up where the HEPA machine is inside the room is the most profitable among the three set-ups with a 2.08 CBA ratio and the set-up with the least payback period within 5.8 months. Other aspects that may impact the effectiveness of the major parameters in a ventilation system of a negative air pressure isolation chamber, such as thermal comfort, the rapid opening of the doors, and other equipment in the room, can also be investigated. Future research could look at what happens to the airflow pattern within a room with a HEPA machine when the outflow rate in the exhaust of the HEPA machine is set to the minimum necessary to meet the DOH memorandum and requirements on the minimum required ACH by the AIIR.

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