AIRBORNE INFECTION RISKS FROM COVID-19
IN MEAT PROCESSING PLANTS
AND DIFFERENT SOLUTIONS
TO MITIGATE THE RISKS

by

Debayan Shom

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major : Architectural Engineering

Under the Supervision of Professor Josephine Lau

Lincoln, Nebraska

March, 2023

AIRBORNE INFECTION RISKS FROM COVID-19 IN MEAT PROCESSING PLANTS AND DIFFERENT SOLUTIONS TO MITIGATE THE RISKS

Debayan Shom, M.S.

University of Nebraska, 2023

Advisor: Josephine Lau

Meat processing plants are linked to the rapid spread of COVID-19 cases. A related literature review shows a lack of proper ventilation standards for the meat processing plants for workers' health and safety. Ventilation rates in these plants are considered adequate if the meat products are unadulterated. Thus, the air distribution and ventilation rate experiments were conducted in three meat processing plants. These measured ventilation rates were either compared to ASHRAE Std. 62.1 (2019) for a similar space or the design values provided by the plant's administration. The measured values were low in common spaces, such as the cafeteria and locker rooms. In addition, the total airflow rates from the diffusers also characterize the air distribution. A modified Wells-Riley model was used to calculate the COVID-19 airborne infection risk for two selected spaces to compare different engineering solutions, such as installing portable air cleaners, using ultraviolet lights in the upper room and in-duct, better filtration systems, and enhanced ventilation rates. Infection risks in a single space were used to rank these solutions. However, a worker during a whole shift moved from different spaces for

different time durations. Therefore, six case studies were simulated to compare the differences between schedules, ventilation rates, and shedder strength. In two baseline studies, based on regular shifts and existing ventilation conditions, the airborne infection risks were about 42 % and 8 % for high and low shedders, correspondingly. Study II and Study II-L comprised a hypothetical staggered schedule with the existing ventilation conditions, and the relative reductions of infection risks were 23% and 28%, respectively, when compared to the corresponding baselines. Study III and Study III-L used the staggered schedule and enhanced ventilation and found the relative reductions of infection probability were about 43% and 49% respectively. Therefore, administrations should recognize the mentioned engineering solutions and use a staggered schedule to mitigate the infection risks in the meat processing plants.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Josephine Lau for her constant guidance and support. I would also like to extend my deepest gratitude to my committee members Dr. David Yuill and Dr. Jennifer Lather.

I would also like to thank my friends and family, especially my elder brother, for constant motivation and encouragement throughout my entire master's journey and everything else I do.

Table of Contents

List of Figures

List of Tables

CHAPTER 1 INTRODUCTION

1.1 COVID-19 cases amongst meat processing plants

Coronavirus disease 2019, termed COVID-19, is a disease caused by Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2). COVID-19 was first reported in Wuhan, China back in 2019 for which it is termed COVID-19 and it is transmitted mainly through the respiratory tract [Baloch et al. (2020)]. Ever since then, COVID-19 has spread all over the world. As of 15 February 2023, the world's COVID-19 cases have crossed over 750 million people and caused over 6.8 million deaths according to the World Health Organization (WHO) [WHO COVID-19 dashboard (2023)].

Around 525,000 people are employed in the US meat processing industry [Saitone et al. (2021)]. Taylor et al. (2020) strongly suggest that meat processing plants are "transmission vectors" of COVID-19. The presence of a meat processing plant in an area is likely responsible for the spreading of the virus into the surrounding population at a rapid pace. A slaughterhouse or a meat processing plant in a county is said to be associated with an additional 4-6 COVID-19 cases for every thousand cases. A roughly estimated result suggests that 6-8% of all COVID-19 cases in the US (around July 2020) are likely related to livestock plants [Taylor et al. (2020)]. And as of October 2020, an estimation of around 334,000 COVID-19 cases can be linked to meat processing plants in the US [Saitone et al. (2021)].

On the other hand, amidst the COVID-19 pandemic, the meat processing plant employees were considered "essential critical infrastructure workers". These essential workers risked their health as well as the health of their families to provide services to the common population. Their service deserves respect and is praiseworthy, but it is also highly important that proper steps are taken to ensure the safety of these workers and prevent and control the spread of COVID-19 in their workplaces [Ramos et al. (2020)]. In order to provide worksite prevention and control, highly protective measures would be using engineering solutions (e.g., enhanced ventilation, enhanced filtration systems) and administrative controls (e.g., social distancing, screening of workers). However, the meat processing plants have often failed to completely adopt these measures in their facilities because these measures are suggestive and not yet lawfully enforceable [Dineen et al. (2022)].

Meat processing plants are linked to the rapid spread of COVID-19 cases. The susceptibility to COVID-19 for a meat processing plant worker has many responsible factors. Some of these factors are listed in Middleton et al. (2020) and discussed below. SARS-CoV-2, the virus responsible for COVID-19, thrives well in low temperatures and very low or very high relative humidity. The very high relative humidity and low temperatures are prevalent in the meat storing processes. The workers in order to be heard should be speaking very loudly to overcome the noise from the surrounding machines. This increases the probable infectious aerosols released from an infected individual. Also, it is difficult to maintain social distancing because of the overcrowded workplace. Among other factors, the workforce involved in these meat processing plants plays a significant role. The workers are not so well paid which urges them in hiding COVID-19 symptoms to avoid loss of pay. Also, the duty of workers involves standing next to each other for long durations of time. Additionally, the migrated workers are provided with housing and transportation accommodations which are often overcrowded and this in turn increases the duration of time spent in close proximities [Middleton et al. (2020)]. The transmission rate of COVID-19 for meat processing plant workers was 24 times more than that of affected people of the entire population in the US [Neisi et al. (2022)].

Enhancing ventilation is stated as one of the key measures in lessening the SARS-CoV-2 airborne transmission [Addleman et al. (2021)]. Thus, a few research studies were investigated in which the meat processing plants were studied to understand different factors prevailing in these sites which were responsible for the rapid spread of SARS-CoV-2. Finci et al. (2022) use multiple variables (e.g., sex, age, contract type, area of work, different air conditioning) to analyze the actual COVID-19 cases reported for a particular meat processing plant. However, there is no quantified amount of ventilation rate or in-situ settings of the mechanical ventilation systems provided for this study. Pokora et al. (2021) collected data from 22 different meat processing plants and poultry facilities in Germany, a reduced number of cases were reported for places that were well-ventilated and thus suggests using higher ventilation rates to mitigate the risk of infection from SARS-CoV-2. This paper also does not quantify the ventilation rate required based on the number of people or the area of the space. A meat processing plant was studied for environmental and occupational factors [Walshe et al. (2021)] and two different areas were studied for particle concentrations and carbon dioxide levels. It was observed that one space contained a high concentration of particle count with 0.4-0.5 air changes per hour and is considered poorly ventilated whereas the other area has about 8 air changes per hour and has very low carbon dioxide concentration as well as particle count. Improving the ventilation rates for meat processing plant has been mentioned in a few other studies [Günther et al. (2020); Herstein et al. (2021)] but lack quantifying the ventilation rate which could be considered sufficient ventilation. Thus, it is evident that there is a clear knowledge gap on the in-situ ventilation rates in meat processing plants and their association with COVID-19 infection risks.

Indoor air quality is highly important for everyone's health. Better indoor air quality has been stated as one of the important factors in increasing the productivity of workers [Clements-Croome and Baizhan (2000)]. Also, given all the above-mentioned factors, it was important for this research to identify the prevailing ventilation conditions and validate if proper in-situ ventilation was provided to the spaces as one of the protective measures.

There were no available documents that specifically addresses the ventilation requirements of a meat processing plant. Only a facility guideline for meat processing plants published by the USDA (United States Department of Agriculture) had a few brief points mentioned regarding ventilation [USDA (1997)]. The guidelines mentioned in this document are:

i) Ventilation design should avoid air turbulence.

ii) Ventilation system should be in accordance with the facility size.

iii) Ventilation system design should consider changes in outdoor temperature and humidity.

iv) Ventilation system should supply fresh outdoor air where natural ventilation is inadequate.

v) Ventilation system should help in preventing vapor formation.

These guidelines do not provide any conclusive evidence on the amount of ventilation required by the meat processing plants. The ventilation requirements are often defined by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) Standards. But the ventilation requirements specific to meat processing plants were not mentioned in these Standards. The research team enquired from the USDA (United States Department of Agriculture) and learned that there are no regulatory requirements set for a meat processing plant and the meat processing facilities only require to provide adequate ventilation to prevent alteration of the product. The administration of the meat processing facilities determines the amount of ventilation for the spaces inside the meat processing plant. The quality of the product is checked by USDA officials and as long as the product is unadulterated, the ventilation settings need not be changed.

This research was, thus, initially intended to study the ventilation rates and airflow of different spaces in the meat processing plants and analyze the probability of airborne infection from SARS-CoV-2. Other than proper airflow and ventilation, there are several other engineering strategies that can be considered for mitigating the spread of SARS-CoV-2. This study considers a few of these different engineering strategies (such as better filtration systems, the use of ultraviolet lights, masks, and air cleaners) and infers upon their contribution in reducing the probability of airborne infection from SARS-CoV-2.

1.2 Research Objective

From the above-listed information related to the meat processing plants during the pandemic of SARS-CoV-2, there were several factors that needed to be studied in order to understand the high spread of SARS-CoV-2 in those facilities. Thus, the research was intended to study the three selected meat processing plants and understand different engineering solutions that can be applied to their spaces and using the Wells-Riley model rank these engineering strategies. The other intent of this study was to find out the impact of a staggered schedule in order to avoid crowding in a space. Lastly, the purpose was to determine how efficient the combined effect of an engineering solution (like ventilation) with the staggered schedule would be.

Thus, to answer these questions, the objectives of this research are to :

1. measure the ventilation rates and total supply airflow rates for different spaces of the three selected meat processing plants, and then compare the ventilation rates with the available standards or design ventilation rates provided by the administration and also compare the total airflow distribution through the diffusers with the design values,
2. provide probabilities of risk from SARS-Cov-2 infection using the Wells-Riley model for two different spaces in those meat processing plants, analyze different scenarios for those two different spaces and rank the engineering strategies according to the studied scenarios,
3. create a schedule, based on the available information from the administration, that shows the distribution of the workers in different spaces, and use the above schedule for finding the probability of airborne infection risk for the selected set of workers,
4. use a relaxed or a staggered schedule to observe the change in the probability of airborne infection risks,

5. use the engineering strategy of required ventilation and staggered schedule combinedly to understand their ability in reducing the airborne infection risk probability.

1.3 Scope of Work

The study measures the ventilation rates and compares them with available standards or design conditions. This study also measures airflow from the diffusers and evaluates the total airflow supplied through the diffusers comparing it with the design values and drawing inferences about the airflow distribution as well.

This study will also assess the probability of airborne infection risks from SARS-CoV-2 for some selected spaces in the meat processing plants as well as for a particular group of workers working in those meat processing plants. The study is based on measured parameters such as ventilation rates, total airflow supply, filter ratings, airflow distribution, space dimensions, occupancy of a space, etc. The probability of airborne infection risk is calculated using the Wells-Riley model and Microsoft Excel is used to perform these calculations.

1.4 Description of Dissertation

This chapter introduced the relevant background information about the meat processing plants in the US amid the SARS-CoV-2 pandemic. It also discussed the knowledge gap in the appropriate ventilation rate for workers' safety and protection and listed the objectives aimed to achieve through this study. **Chapter 2** briefly describes the meat processing plants' infrastructure as well as states the experimental measurements, the tools for the measurements, and the procedures for the measurements. The chapter also contains the detailed results of the experiments followed by the conclusion from the experimental results. **Chapter 3** introduces the Wells-Riley model and provides a literature review on some of the previously used Wells-Riley models. This chapter further discusses the selected Wells-Riley model for the calculations and lists different scenarios for which the model is used to calculate the probabilities of airborne infection risk from SARS-CoV-2. The results of using different engineering strategies are provided so that one can rank them. Lastly, this chapter further provides the infection risk probabilities for a regular schedule, a staggered schedule, and the combination of a staggered schedule with enhanced ventilation. **Chapter 4** states a conclusion about the experimental results and the risk analysis results.

CHAPTER 2 EXPERIMENTAL STUDY

This chapter describes the overall infrastructure of meat processing plants. It also describes the experimental setups required to measure the ventilation rates and total airflow of different spaces. Lastly, this chapter discusses the results of all of the conducted experiments.

2.1 Description of the meat processing plants

Three different meat processing plants were visited for this study. These meat processing plants are referred to as Site A, Site B, and Site C due to non-disclosure agreements. Also, as per the non-disclosure agreement, there should be no reference to the layouts or any other information about the meat processing plants which could lead to identifying them. Thus, the three meat processing plants would be described briefly in terms of space divisions, room structures, total workers, HVAC (Heating, Ventilation, and Air Conditioning) units, and shift timings, for a better understanding of how these plants operate.

Out of the three meat processing plants, two of them had close to 3500 workers whereas one of them had around 1100 workers. Also, the establishment of two of these plants can be dated back more than 15 years whereas the third plant was operational for only 5 years.

For a meat processing plant, there are mainly three functional divisions of the infrastructure: kill areas, fabrication areas, and common areas. Kill areas or slaughterhouses are the spaces that are responsible for the killing of the animals, deskinning them, removing unwanted parts, washing them, etc., and sending them down the conveyor belt toward the fabrication areas. These kill areas are in general highly exhausted and mostly naturally ventilated. Fabrication areas or processing areas are the spaces that are responsible for the processing of the raw materials, cutting off different parts as per the product requirements, and packaging them. The processing and cutting off of different parts of the animals often define the infrastructural design of the conveyor belt and sometimes those areas are named as per their functions as well. For example, the processing of the tongue can be called a tongue room or tongue area, whereas the gut processing can be called a gut room. After the packaging is done, they are carried to the warehouse-like structure where it is made ready to ship. Lastly, common areas would be areas where the meat processing plant workers gather before and after their shift ends and also during breaks. These common areas would include cafeterias, locker rooms as well as different office areas for the management of the plants.

For this research, it was not possible to cover all of the above areas for the three meat processing plants that were studied and upon observing the worker's schedules, it was learned that most of the crowded areas are the common areas. Thus, common areas for all three plants were included in the experimental measurements. The kill areas were very sparsely populated with workers and had natural ventilation with high exhaust for which this research excluded the experimental measurements of the kill areas.

The common areas were easy to access and had very limited constraints for the experimental setups. The plans were communicated with the respective plants' management teams and the experiments were conducted smoothly. However, for the fabrication or processing areas, there were a lot of challenges for which only a plant's two processing areas were measured. This research didn't have the appropriate sources to run the experiments on all the plants. The challenges related to conducting experiments in the processing areas have been discussed in the experimental results section.

On average, the three studied meat processing plants had around 40 rooftop units (RTUs) for ventilation of the entire plants. As mentioned earlier, it was outside the research scope to investigate all the RTUs for their total airflow rate or ventilation rates.

The shift timings of different plants varied in terms of start times. But in general, there were two shifts – one morning shift and one afternoon shift. There were also 3 hours of shift for the cleaning team at the end of these two shifts. For example, Site A starts Shift I at 5:45 AM and the shift ends around 3:15 PM. Shift II starts at 3:30 PM and ends at 01:00 AM. The cleaning crew has their shift from 1:30 AM to 4:30 AM. The performance of the experiments and analysis depended upon these shift timings.

It was also learned from the administrative team that Site B uses staggered scheduling for its workers after the advent of SARS-CoV-2. This means that room occupancy never reaches the maximum design strength and potentially decreases the chances of crowding at peak hours. The workforce is divided in such a manner that their start times differ as well as their break times. This difference in time leads to much less crowding in common areas such as the cafeteria or locker rooms. For example, the cafeteria might be designed for 400 people but only 100 people will fill it up as per their schedules. This concept of staggered scheduling has been later applied in the chapter on risk analysis to show its effectiveness.

2.2 Experimental setup

The objective of conducting the experiments for this project was to determine the ventilation rates for different selected spaces and in some of the spaces, the total airflow was to be calculated. Ventilation rate can be defined as the rate of fresh air(external air) that flows into the building and is one of the important factors for improving indoor air quality. The ventilation rates were measured to check with the corresponding ASHRAE Std. 62.1 (2019), and the measured total airflow would be used to verify the design conditions provided by the administration. Two tests, named Test A and Test C, were conducted to evaluate the ventilation rates. Test B is named for the experimental evaluation of total airflow measurements.

In order to carry out the above tests and evaluate the HVAC systems of these sites, it was important to understand the dimension of these facilities. Either a Revit file or AutoCAD file was requested from the administration and likewise, all the dimensional measurements of the spaces concerned were calculated from the provided files. However, due to the interior complexities of the structure, some detailed dimensional measurements were required for calculating the exact ventilation rates. Internal complexities would include caged walls rather than solid walls, wall openings, and temporary structures not included in those files. These detailed dimensions were measured during the initial site visits when the spaces to be measured for were identified. These measurements were taken with the help of a laser measure named Bosch Blaze Pro and were noted down for each targeted space.

2.2.1 Equipment used

Three types of CO_2 data loggers were used. A CO_2-based fire extinguisher was used to supply CO_2 as a tracer gas. An Airflow hood was used for total airflow measurement. Their images along with their specifications are mentioned below.

Telaire 7001 CO_2 sensor with HOBO U12 data loggers

Telaire 7001 devices were programmed to read CO_2 concentrations, but it does not have the ability to record data. In order to record data, an external HOBO U12 needs to be connected to the Telaire device and programmed via Hoboware software. The Telaire devices can display each second of CO_2 concentrations, but the HOBO U12 logger can log for a minimum of one minute. The specifications of these devices are mentioned in Table 2 - 1.

Table 2 - 1 : Specifications of Telaire 7001 CO_2 sensor

Measurement Range	0 to 9999 ppm
Data logging range	0 to 2500 ppm with HOBO U12
Display resolution	± 1 ppm
Repeatability	± 20 ppm
Accuracy	± 50 ppm or 5% of the reading, whichever is greater

Figure 2 - 1 : Telaire 7001 CO_2 sensor

Figure 2 - 2 : HOBO U12 data logger

Hobo MX1102A

Hobo MX1102A devices were programmed to read and log CO_2 concentrations. It also comes with the ability to use Bluetooth and allow transfer of the data to a mobile device's software Hoboconnect if within a 100-feet range. They can also be programmed using the Hoboware software and has a minimum logging time of one minute as well. The specifications of these devices are mentioned in Table 2 - 2.

Table 2 - 2 : Specifications of Hobo MX1102A CO_2 data logger

Measurement Range	0 to 5000 ppm

Display resolution	± 1 ppm
Accuracy	± 50 ppm or 5% of the reading

Figure 2 - 3 : Hobo MX1102A CO_2 data logger

Comet U3430

Comet U3430 devices were also programmed to read and log CO_2 concentrations. They can be programmed using the Comet Vision software and has a minimum logging time of one second. The specifications of these devices are mentioned in Table 2 - 3.

Table 2 - 3 : Specifications of Comet U3430 CO_2 data logger

Measurement Range	0 to 5000 ppm
Display resolution	± 1 ppm
Accuracy	± 50 ppm or 3% of the reading

Figure 2 - 4 : Hobo MX1102A CO_2 data logger

Kidde CO_2-based fire extinguisher

Kidde CO_2-based fire extinguishers were used for supplying tracer carbon dioxide as a tracer gas in a space. The fire extinguishers when sprayed elevated the carbon dioxide levels of the space and thus these fire extinguishers were found a good alternative rather than using CO_2 cylinders. A lot of precautions were taken in operating them because of their weight and high pressurized gas content. The specifications of these devices are mentioned in Table 2 - 4.

Table 2 - 4 : Specifications of Kidde fire extinguisher

Total weight	48.5 lb
CO_2 weight	20 lb

Figure 2 - 5 : Kidde fire extinguishers

Testo 420 airflow capture hood

Testo 420 airflow capture hood was used to measure the total air flowing out from the diffusers. The device had a screen display from which the readings could be obtained or using a mobile device's Testo 420 software would allow one to log in these values as well. Two different-sized rectangular hoods were used for the experiments, one was 2 feet by 2 feet and the other was 3 feet by 3 feet. The specifications of these devices are mentioned in Table 2 - 5.

Table 2 - 5 : Specifications of Testo 420 airflow capture hood

Measurement Range	25 to 2300 cfm
Display resolution	± 1 cfm
Accuracy	± 7 cfm or 3% of the reading

Figure 2 - 6 : Testo airflow capture hood of size 2 feet by 2 feet

Figure 2 - 7 : Testo airflow capture hood of size 3 feet by 3 feet

2.2.2 HVAC systems evaluating procedures –Test A, Test B, Test C

The engineering team (Dr. Lau and I) was responsible to conduct field measurements, inspections, and investigations to evaluate the performance of the ventilation systems in the facilities. The quantifying of air circulations and ventilation rates in the selected areas of different sites was carried on by the three following field tests:

1) Test A - CO_2-based tracer gas studies of airflow and ventilation rates
2) Test B – Airflow rate measurements from the diffusers
3) Test C - Measurements of carbon dioxide (CO_2) at the intake of the ventilation (roof-top) units

The below section explains how each of these tests was carried out.

Test A – CO_2-based Tracer gas method

Test A is the CO_2-based tracer gas measurement method based on (American Society for Testing and Materials) ASTM E741 (2019) and ASTM D6245 (2018) which would help in estimating the in-situ real-time ventilation rates. The ASTM D6245 (2018) helps in estimating the ventilation rates by measuring the indoor CO_2 concentrations and the ASTM E741 (2019) explains the process to determine air changes when a tracer gas is used. These methods apply to single-zone systems. So, all locations in which this test was to be conducted had to be entirely sealed up to avoid air from leaking in or leaking out. Thus, plastic sheets were used to seal all the entrance and exit points as well as any visible openings in order to isolate the selected space from surrounding spaces and make it as airtight as possible. The sites comprised several openings in those spaces and some of them were huge. Thus, several rolls of plastic were brought before each site visit and then carefully cut according to the size of the openings. For example, if a room led to a hall space with no doors and the size of the hall space was 20 feet * 12 feet, then a plastic of the dimension 21 feet * 13 feet was cut and used to cover them. Each of these cut-out plastic sheets had their dimensions marked on them and on the day of the experiments, the floor plan printout was investigated for the opening size and the corresponding plastic would be taped to the wall to cover the openings.

Hobo MX1102A, Comet U3430, and Telarie 7001 are the three types of CO_2 data loggers that were used for this test. Each of these devices was carefully calibrated before each site visit. Comet U3430 and Telaire 7001 were calibrated in the UNL's chemical laboratory using a pure nitrogen dioxide cylinder. A small calibration tool needs to be fitted in the top of these two types of devices such that all the air flowing through it would be only the nitrogen dioxide from the cylinder and thus have a zero-ppm reading. For the Hobo MX1102A, these devices need to be programmed and started using the Hoboware software and then kept outside in the open air such that it is able to calibrate themselves with the outside CO_2 concentration. This calibration method is mentioned by the manufacturer and a clean, open space was chosen every time for the calibration of these devices. Later, all three types of devices would be placed side by side and then checked if all of them had similar readings. In case a reading was more or less than 30 ppm from the other devices, then that device would be calibrated again until all of them had the approximately same reading. Telaire 7001 would also use Hoboware software to be programmed while Comet U3430 is programmed using Comet Vision software.

The general procedures for the test are mentioned in a sequential manner below:

A) Seal all the openings of the space with the plastic cuttings marked for the openings of that space. This needs to be done after emptying the space of all occupants. Only the research team operating the test was allowed to be in that space.

B) CO_2 data loggers are programmed and set to log CO_2 concentrations with a 5-minute logging interval and placed in different positions of the space such that most of the floor area of that space is covered. A data logger was also placed out in the open to get the measurement of CO_2 in outdoor air. All the devices were synchronized together to read the data at the same point of time.

C) 20 pounds CO_2-based fire extinguishers from Kidde are used to release CO_2 in all the locations. Depending upon the size of the space this experiment was conducted, more than one fire extinguisher would be necessary sometimes. Also, a fan would be used to ensure proper mixing throughout the space.

D) A Telaire 7001 model CO_2 sensor is used to monitor the real-time CO_2 concentrations in different parts of the space.

E) Different locations had different target values of CO_2 concentrations set by the research team. For some locations, it was 5000 ppm and for some locations, it was 8000 ppm. These targeted set points were decided after in-house experimental trials were conducted. A small space would reach 8000 ppm much faster but the decay back to normal would take a long time. Thus, depending on the space size, decisions were made on whether to achieve a CO_2 concentration target of 5000 ppm or 8000 ppm. Until the Telaire device read 5000 or 8000 ppm, CO_2 was sprayed continuously using the fire extinguishers. Once the CO_2 concentration reached the targeted value, the spraying of CO_2 was stopped, and the time was noted.

F) The space is emptied by the research team as well. The space is left alone at least for an hour. The Hobo MX1102A is fitted with BLE (Bluetooth Low Energy) which transmits data to mobile devices. The Hoboconnect mobile application was checked for CO_2 concentrations at regular intervals and when the space returned to the initial value of CO_2 concentration, the time was noted down again. Then the research team entered the space to take out the plastic seals and the data loggers.

G) After extracting data from the CO_2 loggers, data from the time it reached a high concentration up to the point when it decayed was taken into consideration, and then a decay curve was obtained per logger.

H) To calculate the air change per hour (ACH), the research team plotted CO_2 reading, ppm – Outdoor air CO_2, ppm and then used exponential curve fitting to find the coefficients for the exponential curve. The equations are in the form of $y = Ae^{-Bx}$. The negative sign is for the exponential decay. The value of B provides the air change per 5 minutes. So, to get ACH, B is divided by (5/60).

I) The dimensions of the space were measured, and the volume was calculated for all of the locations.

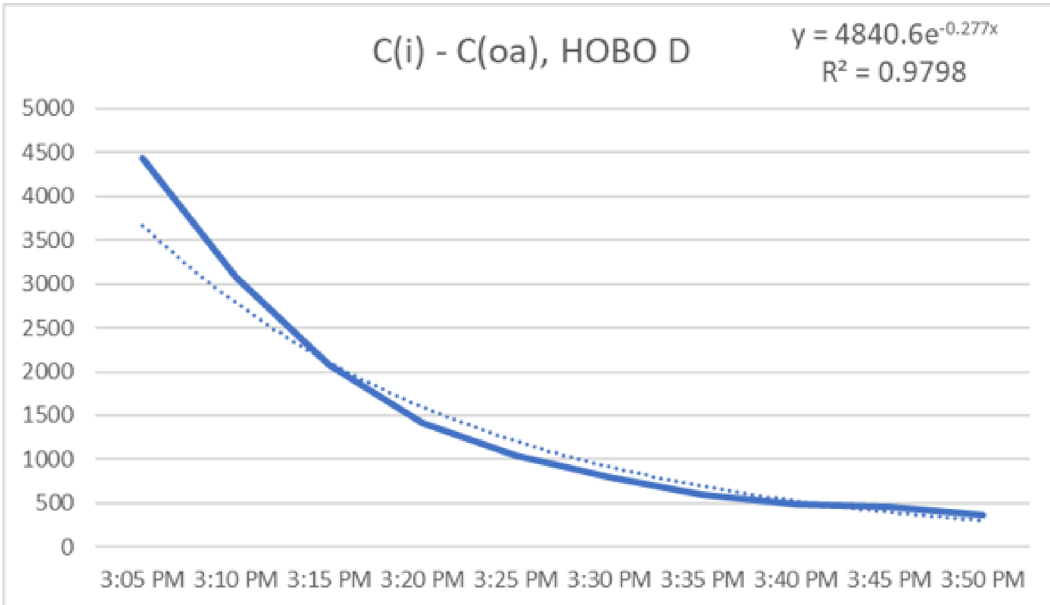
J) Q, ventilation rate in ft^3/min was calculated using the formula : $Q = \frac{ACH*V}{60}$

There are multiple data loggers involved and are placed in different positions in the space for accurate results. Then data is extracted from each data logger and the decay of CO_2 concentration is identified and used for calculations. An example of the calculations has been provided in Table 2 - 6.

Table 2 - 6 : A CO2 logger data from one of the spaces to demonstrate the decay calculation

Time	**CO2, ppm**	**C(i) - C(oa)**	**LN{C(i) -C(oa)}**	**LN(x) - LN(x+1)/(5/60)**
3:05 PM	4818	4433	8.40	
3:10 PM	3461	3076	8.03	4.39
3:15 PM	2459	2074	7.64	4.73
3:20 PM	1807	1422	7.26	4.53
3:25 PM	1433	1048	6.95	3.66
3:30 PM	1179	794	6.68	3.33
3:35 PM	984	599	6.40	3.38
3:40 PM	882	497	6.21	2.24
3:45 PM	838	453	6.12	1.11
3:50 PM	755	370	5.91	2.43
			ACH, 1/hr	**3.31**
			Volume, ft^3	24394
			Q, cfm	**1346.18**

This table denotes that the ventilation rate of that space is 1346 cfm (ft^3/min), i.e., 1346 cfm of air is brought in from outside the building into that space. Another alternate way of finding the ventilation rate would be to plot the C(i) – C(oa) against time and using Microsoft Excel functions fit an exponential curve for that decay curve and get an equation that should be in the form of $y = Ae^{-Bx}$. The B obtained is similar to the B obtained in Step H and thus the next two steps I and J need to be followed after that. It has been demonstrated in the Figure 2 - 8 provided below.



	ACH, 1/hr =	0.277/(5/60)	3.32
		Q, cfm =	1351.43
Volume, ft^3 =	24394		

Figure 2 - 8 : Alternate way of finding the cfm from CO_2 logger data

NOTE : CO_2 reading, ppm is denoted by C(i) whereas Outdoor air CO_2, ppm is denoted by C(oa)

Both these methods yield quite similar data. For the example shown, two different methods yielded 1346 cfm and 1351 cfm. For the experiments, the first method was used for calculations but all of them were verified using the alternative method.

Similarly, different CO_2 meters would provide with a similar cfm and then the average of them would be the ventilation cfm provided in that space. Then, the average calculated cfm would be divided by the occupancy and the per person cfm would be obtained. This value would be matched with ASHRAE Std. 62.1 (2019) values which have been explained later.

Test B – Airflow measurement from diffusers

Test B is the total airflow measurement method. This test was carried out using a Testo 420 – airflow capture hood. This device has a digital display attached to it which displays the amount of air flowing through the hood in ft^3/min (cfm). The device needs to have its hood opening placed against a diffuser and all the air flowing out from the diffuser would pass through the flow hood and the reading displayed on the digital display is noted. For this test, the layout of all the diffusers in a space was identified. The Testo 420 device was used to measure the airflow of each diffuser at least five times using the above-explained process. A table was created for each space to specify the total amount of airflow in that space as well as the individual average airflows of the diffusers.

Carrying out this test would help in understanding if the design supply airflow was being provided by the diffusers and also whether the airflow pattern was equally distributed. The distribution of airflow is important for indoor air quality. If a space has a non-uniform distribution of airflow, the contaminants are non-uniformly distributed as well and the poorly air-circulated areas could have high concentrations of infectious aerosols. Also, if the airflow is lesser than the design value, it would mean lesser dilution of infectious aerosols and higher chances of transmission of the virus [Khankari (2021)].

For some spaces, the total airflow of that space was not determined because some of the diffusers' positions in that space had restrictions. The restrictions would involve a very high position of the diffuser for which the engineering team was not trained enough or presence of structures right in front of the diffuser led to great difficulty in placing the capture hood against the diffuser.

Different sites had many different-sized and shaped diffusers. The most common of them were the standard 24 inches by 24 inches square diffusers. The airflow from these diffusers was measured using the Testo 420 airflow capture hood which had an opening of dimension 24 inches by 24 inches. Other diffusers smaller than the above-mentioned size were measured using this same capture hood. For diffusers greater than 24 inches by 24 inches, another capture hood was purchased of the dimensions 36 inches by 36 inches. Most of the diffusers were covered by using this greater-sized capture hood, but still, there were some circular diffusers with a diameter of 36 inches that required special adjustments. The special adjustment to the capture hood and its testing has been discussed later in this section.

Test C – CO_2 measurement in the rooftop units (RTUs)

Test C is the CO_2 measurements at the intake of the rooftop units in order to estimate the ventilation rate in a given space. This method's strategy is to learn about the occupied times in a space and then wait for the space to be vacant so that the drop in CO_2 concentration can be measured, and a ventilation rate can be estimated. Since this method is dependent on the occupancy of a space, the openings of this space are not sealed, and the ventilation rate estimated includes the infiltrations and leakages of the space as well. This method sometimes overestimates the ventilation provided by the air handling units (AHUs). Spaces were identified for which this test was to be conducted and then the related AHUs serving the space were identified as well. Similar to Test A, the three types of CO_2 data loggers that were used for this test were Hobo MX1102A, Comet U3430, and Telarie 7001. It was calibrated similarly to the process described in Test A.

Test C was adopted in replacement of Test A because Test A had a few requirements which were tough to meet. The requirements for Test A would be access to spaces during the time of no occupancy, sealing of the spaces from the surrounding areas, and lots of supplies of CO2-based fire extinguishers. Thus, Test C was used instead for some spaces for which the above requirements were not met. The Test A results are theoretically the most accurate because it involves sealing the space and thus will not overestimate the infiltrations and leakages of the space. But surprisingly, the results of Test C were pretty close to the results of Test A.

The general procedures for the test are mentioned in a sequential manner below:

A) The research team headed onto the roof to install the CO_2 data loggers inside the rooftop units. The return air parts of the rooftop units were identified, and the loggers were installed in such a way that the air drawn from the return air diffuser would be directly in line with the placed data loggers.

B) CO_2 data loggers are set to log CO_2 concentrations with a 5-minute logging interval. A data logger was also placed out in the open to get the measurement of CO_2 of outdoor air. All the devices were synchronized together to read the data at the same point of time.

C) The data loggers were uninstalled from the rooftop units after a period of five days.

D) After extracting data from the CO_2 loggers, the data was studied to identify the occupancy times of that space. The Figure 2 - 9 below displays the 5-day average CO_2 concentration recorded as an example. It is evident from the figure that the CO_2 patterns were directly related to the shift timings. There were high CO_2

readings at certain times of the day and when the shift ended the CO_2 concentrations started dropping. For example, in Figure 2 - 9, there is drop in CO_2 concentration after 12 am each day for Office Space 9 Site A as there were no people in that space at the end of the shift 2. It was verified from the site's management team if it was common to have that space occupied or unoccupied during these considered time periods. Then, the data from these time periods of no occupancy were taken into consideration and then a decay curve was obtained per logger by plotting the CO_2 readings from the time it reached a high concentration up to the point when it decayed.

E) To calculate the air change per hour (ACH), the research team plotted CO_2 reading, ppm – Outdoor air CO_2, ppm and then used exponential curve fitting to find the coefficients for the exponential curve. The equations are in the form of $y = Ae^{-Bx}$. The negative sign is for the exponential decay. The value of B provides with the air change per 5 minutes. So, in order to get ACH, B is divided by (5/60).

F) The dimensions of the space were measured, and the volume was calculated for all of the locations.

G) Q, ventilation rate in ft^3/min was calculated using the formula : $Q = \frac{ACH*V}{60}$

The decay calculation is quite similar to Test A and the last three steps involving calculations would be the same. The calculations would be similar as shown previously in Table 2 - 6.

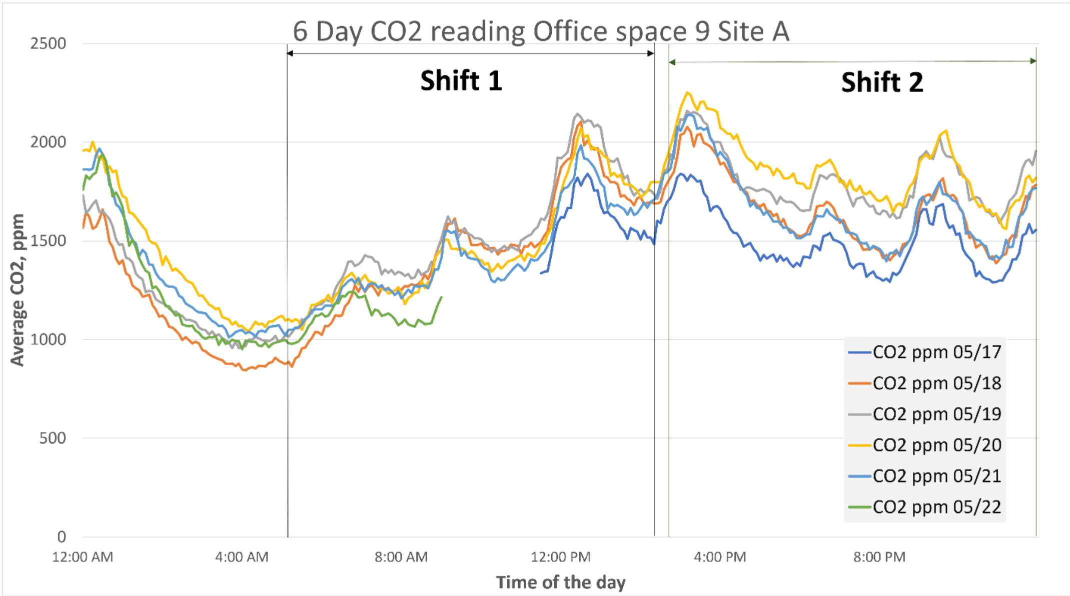


Figure 2 - 9 : The 5-day CO_2 reading of Office Space 9 Site A

2.2.3 In-house testing

It was decided that Test A should be carried out in a known environment so that the research team can perform Test A in the sites accurately. Thus, a classroom in University of Nebraska-Lincoln was chosen to be the trial room. The room had a door, so no plastic seal was required. A fire extinguisher was sprayed over the room until the CO_2 concentration reached 8000 ppm. Different types of loggers were placed covering all parts of the room after calibrating each of those loggers. And once the data from the logger was downloaded and calculations were done, the ventilation rate was found to be 576 cfm. This was checked with the HVAC team, and they said the HVAC was in economizer mode. The research team was informed the ventilation of that room to be set at about 400 cfm in general and during the time of economizer mode, the ventilation rate goes much higher.

Thus, another test was planned. The research team confirmed with the administration team that the economizer mode was not running and then started the experiment. The same process was repeated as above and after downloading and calculating the data, the ventilation rate of the room was found to be 402 cfm, which is highly accurate to the number provided to the research team by the administration team. Thus, it was learned that whenever the measurement for ventilation rate was to be done, it must be cross-checked with the HVAC team to turn off the economizer mode.

Next, the research team had the opportunity to test out the instruments in a local church. It was Easter Sunday and there were prayer services scheduled with an approximate occupancy of 250 people to be present. Before the prayer services started, the hall space was fitted with the calibrated CO_2 loggers in different places. Slowly people started showing up for the prayer services and the CO_2 level started rising. After the event was over, everyone left the hall, and the time was noted. The data from the loggers provided the decay calculations and a ventilation rate of 1880 cfm was obtained. It was noted that one of the loggers fitted in the hall entrance showed very absurd readings compared to others, and it was realized that it was placed in front of one of the doorways of the hall. It is suspected that with the random opening of the door, the data suggested CO_2 levels rising and decreasing abruptly. These tests gave the research team confidence and knowledge on the use of CO_2 loggers and where they needed to be placed to get accurate results.

The last in-house test carried out was for the airflow hood measurement. During the initial site visits, it was learned that one of the sites has circular diffusers of diameter 36 inches. These diffusers would be bigger than the dimensions of the square-shaped airflow capture hood which were 24 inches by 24 inches or 36 inches by 36 inches. Thus, a makeshift plastic was cut out and pasted on the rim of the 36 inches by 36 inches capture hood. The plastic cut-off was big enough to cover the whole of the circular diffusers and direct all the air into the capture hood. This was tested over a 24-inches diameter circular diffuser in the university and the result was extremely accurate to the result obtained with the original 36 inches by 36 inches square capture hood.

2.3 Experimental results

In order to estimate the outdoor air ventilation Test A and Test C were conducted in the three sites. However, owing to the complexity of the processes involved and evacuating all the occupants of the space, Test A was conducted in only six spaces. The initial reason for using Test A as a method of ventilation rate measurement was because of the use of dry ice in the processing areas. The meat processing plants use dry ice in some of the processing spaces to keep the meat fresh. The dry ice liberates carbon dioxide and thus it would be not possible to have a proper estimation of the ventilation rate using Test C which considers the natural decay of carbon dioxide concentrations. Thus, Test A which involves an injection of tracer gas and no occupancy during the test procedures was thought as an alternative to estimate the ventilation rates. For most of the spaces, Test C was used to determine the ventilation rates. The total airflow was also evaluated using Test B for all possible spaces which allowed the test to be conducted. The result and calculations for these spaces are discussed below.

The challenges related to conducting experimental measurements for the processing areas were:

1) The volumes of these fabrication areas were around 200,000 cubic ft. It would have been extremely difficult to estimate the ventilation rates of all of the spaces because conducting Test A would have required a lot of CO_2-based fire extinguishers.
2) There were lots of spaces that were difficult to seal off with plastic because of the conveyor belts running through other rooms and thus would be difficult to estimate the ventilation rate correctly using Test A.
3) The design conditions of the fabrication areas required the room temperature to be around 37 F to 40 F for most of the plants which required a lot of cold air to be supplied from the HVACs to maintain the set temperature. This meant that the volumetric airflow rate from the diffusers would be extremely high and when the HVACs were turned on, the place was tough to be kept sealed off with plastic for air tightness due to the high air pressure. This air leaking for Test A could have led to an overestimation of the ventilation rate.
4) Test B was also difficult to conduct because of the huge number of diffusers and also many of the diffusers were placed in very high locations.
5) In order to prevent adulteration of the meat in the fabrication areas, the storage of the processed meat required a lot of dry ice and dry ice generates CO_2. Thus, using Test C to estimate ventilation would be difficult as the CO_2 decay curve would be heavily influenced by the CO_2 generated from dry ice.
6) The shift timings for the fabrication areas had two shifts of 9 hours each and 3 hours of cleaning in between. Thus, conducting any tests within these shift

timings could cause production loss as per the management team and no experiments were conducted for the same.

Thus, Test A was only conducted for two of the processing area locations and probably the ventilation rates were overestimated for the above-mentioned reasons.

For Test A and C, the results are compared to the ASHRAE Std. 62.1 (2019). It was found out that ASHRAE Std. 62.1 (2019) does not have any defined spaces related to the meat processing plants. The gut room, offal room, intestine room, and many other such rooms are all part of the meat processing unit, and these rooms have no defined ventilation rates defined by the ASHRAE standards. In an email conversation with the chairperson of ASHRAE's Technical Committee 9.2 Industrial Air Conditioning and Ventilation, the representative mentioned several sites that advise the meat processing plants to provide sufficient ventilation such that there is no accumulation of dust, smoke, steam, or condensation and is enough to remove contaminated air. It also advises using adequate filters and timely replacement. Lastly, it states to have positive air pressure maintained so that the direction of airflow is from clean to less clean spaces. However, there is no indication of the minimum ventilation that is set as a standard. Spaces such as hallways, classrooms, office rooms, cafeteria, etc. have designated minimum ventilation requirement set by the ASHRAE which depends upon the area of a similar space and the number of occupants in it. With this piece of information missing from the ASHRAE standards, it was very difficult to judge if a space is adequately ventilated or not.

In another email conversation with a representative of the USDA (United States Department of Agriculture), it was learned that as per the Code of Federal Regulations Title 9, 416.2(d) [Code of Federal Regulations (1999)] ventilation should be adequate to prevent alteration of the product as well as prevent the creation of insanitary conditions. Each meat processing establishment being different, there are no regulatory requirements set based on quantifying the ventilation rate. The establishment should provide proper ventilation to prevent condensation which causes product adulteration. If an establishment cannot demonstrate that they are controlling condensation to the extent necessary to prevent adulteration of products through proper ventilation, they would not have adequate ventilation and would not be meeting the regulatory requirement for ventilation. The representative further clarified that it would be up to the establishment to determine the ventilation rates they would need to meet the above regulatory requirements.

2.3.1 Test A results

After the Test A experimental procedures were over, data from each of the data loggers were extracted. Each data logger placed in different areas of the space had different readings and different times of CO_2 concentration decay. Each logger led to a ventilation rate whose calculations have been explained previously. The average of all of the loggers in a space was taken as the estimated ventilation rate for that space. Then it was compared to the available ASHRAE Std. 62.1 (2019).

Locker 1 Site A :

The volume of Locker 1 from Site A was 59306 ft^3 and the floor area was 3210 ft^2. Five ventilation rates were obtained from different data loggers used in the experiment. Out of these ventilation rates obtained, the maximum ventilation rate was 414 ft^3/min, the minimum ventilation rate was 315 ft^3/min, the average ventilation rate was 376 ft^3/min, and the standard deviation of the ventilation rates was 38 ft^3/min.

Thus, the average value of the ventilation rate is found to be 376 cfm for Locker 1 Site A. And the room is designed to host 617 people as provided in the occupancy document. Thus, at maximum occupant capacity, the cfm/person would be 0.61 cfm/person.

All these room dimensions and ventilation rate details for Test A are repetitive for the other spaces and will be presented in only a table format for the remaining spaces. For Locker 1 Site A, the dimension details and ventilation rates are presented in Table 2 - 7.

Table 2 - 7 : Locker 1 Site A's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
59306	3210	617	414	315	376	38	0.61

When Test A was carried out for this space, it was noticed that the damper for outdoor air was closed in the rooftop unit, and it is anticipated that the outdoor air that reached the room is in the form of infiltration and duct leakages.

The ASHRAE Std. 62.1 (2019) Table 6-1 contains different spaces and building types. Each of these spaces has its defined requirements for outdoor air rates for people (R_p) as well as the space area (R_a) and their values are provided in that Table 6-1 of ASHRAE Std. 62.1 (2019). The breathing zone outdoor airflow of a space (V_{bz}) is the ventilation rate that should be supplied to the space and is calculated in cubic feet per minute (cfm) using the equation (2 - 1).

$$V_{bz} = \left(R_p * P_Z\right) + \left(R_a * A_Z\right) \qquad (2 - 1)$$

where,

V_{bz} is the required breathing zone ventilation airflow,

R_p is the outdoor airflow rate required per person,

P_z is the number of people in the space,

R_a is the outdoor airflow rate required per unit area,

A_z is the area of the space.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 8.

Table 2 - 8 : Calculations to determine Zone outdoor airflow required per person for Locker 1 Site A.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	617
A_z, ft^2	3210
V_{bz}, cfm	3277.6
V_{bz}, cfm/person	5.312156

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires general break rooms to supply at least 5.31 cfm/person. It is to be noted that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Processing area 1 Site A :

For Processing area 1 Site A, the dimension details and ventilation rates are presented in Table 2 - 9.

Table 2 - 9 : Processing area 1 Site A's dimensions and measured ventilation rates

Volume (ft^3)	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
		Maximum	**Minimum**	**Average**	**Standard Deviation**	
38402	30	4109	2642	3679	631	122.63

Thus, at maximum capacity, the cfm/person would be 122.63 cfm/person. This is considered to be a very high per-person ventilation rate but not having any reference in the ASHRAE Std. 62.1 (2019) did not lead to conclude anything about the ventilation rate. The readings, however, also indicated that the well-mixed condition maybe not achieved during this tracer gas measurement. This is because of the complex structures of the processing areas having numerous conveyer belts running through other rooms which caused difficulty in estimating the ventilation rate correctly and the ventilation rates varied in different areas of the room. Also, the HVAC being on, the space was tough to seal with plastic for air tightness.

Processing area 2 Site A :

For Processing area 2 Site A, the dimension details and ventilation rates are presented in Table 2 - 10.

Table 2 - 10 : Processing area 2 Site A's dimensions and measured ventilation rates

Volume (ft^3)	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
		Maximum	**Minimum**	**Average**	**Standard Deviation**	
189196	170	27888	12790	19465	5880	114.5

Thus, at maximum capacity, the cfm/person would be 114.5 cfm/person. This is considered to be a very high per-person ventilation rate but not having any reference in the ASHRAE Std. 62.1 (2019) did not lead to conclude anything about the ventilation rate. The readings, however, also indicated that the well-mixed condition maybe not achieved during this tracer gas measurement. This is because of the complex structures of the processing areas having numerous conveyer belts running through other rooms which caused difficulty in estimating the ventilation rate correctly and the ventilation rates varied in different areas of the room. Also, the HVAC being on, the space was tough to seal with plastic for air tightness.

Cafeteria 1 Site A:

For Cafeteria 1 Site A, the dimension details and ventilation rates are presented in Table 2 - 11.

Table 2 - 11 : Cafeteria 1 Site A's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
49413	3801	280	860	751	785	45	2.8

Thus, at maximum occupant capacity, the cfm/person would be 2.8 cfm/person. It was also noticed during the time of the experiment that the damper for outdoor air was closed in the rooftop unit for this space, and it is anticipated that the outdoor air that reached the room is in the form of infiltration and duct leakages.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for cafeteria (under food and beverage services), the ventilation rate is calculated as shown in Table 2 - 12.

Table 2 - 12 : Calculations to determine Zone outdoor airflow required per person for Cafeteria 1 Site A.

R_p, cfm/person	7.55
R_a, cfm/ft^2	0.18
P_z	280
A_z, ft^2	3801
V_{bz}, cfm	2784
V_{bz}, cfm/person	9.94

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires cafeteria (under food and beverage services) to supply at least 9.94 cfm/person.

Training room 1 Site B:

For Training room 1 Site B, the dimension details and ventilation rates are presented in Table 2 - 13.

Table 2 - 13 : Training room 1 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
24394	1963	66	1351	1015	1212	128	18.36

Thus, at maximum occupant capacity, the cfm/person would be 18.36 cfm/person.

The ventilation rate obtained is overestimated as per the research team's understanding. This ventilation rate does not match the ventilation rate that was determined from the rooftop unit calculations. There could be several possible reasons for the difference in readings:

- The washrooms in this space had exhaust fans and might have considerably reduced the levels of carbon dioxide from the surrounding spaces.

- The time at which the experiment was conducted had a very pleasant outdoor temperature which might have triggered the use of economizer mode and thus more outdoor air was supplied.
- The space might be highly pressurized in comparison to the adjacent spaces. Thus, even after sealing the space, the space became positively pressurized and forced the air to leak through the smallest of gaps and cracks to adjacent spaces.

Any or all of the above could be the reason for the rapid decay of carbon dioxide levels than expected. But considering these assumptions void, the research team went ahead and compared the obtained values of ventilation with the required ASHRAE Std. 62.1 (2019) ventilation rate.

The training classrooms are designed more in the form of conference rooms or office spaces rather than conventional classrooms. Thus, the standard used for the classroom is the standard for the conference room. Also, the presence of a corridor and washroom in the calculated space would require different ventilation rates. There are no ventilation requirements for the washroom set by ASHRAE, but for the rest of the spaces, the standards from ASHRAE are obtained. As per ASHRAE Std. 62.1 (2019) Table 6-1, for conference rooms and corridor (under General), the ventilation rate is calculated as shown in Table 2 - 14.

Table 2 - 14 : Calculations to determine Zone outdoor airflow required per person for training room.

Training Room		**Corridor**	
Area, ft^2	1408	Area, ft^2	555
R_p, cfm/person	5	R_p, cfm/person	0

R_a, cfm/ft^2	0.06	R_a, cfm/ft^2	0.06
P_z	66	P_z	0
A_z, ft^2	1408	A_z, ft^2	555
V_{bz}, cfm	414.48	V_{bz}, cfm	33.3
V_{bz}, cfm/person	**6.79**		

Thus, the space can be stated as highly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires general conference rooms and similar corridor space to supply at least 6.79 cfm/person.

Cafeteria 2 Site B:

Cafeteria 2 from Site B was a bit different from the other spaces listed above. The rooftop unit responsible for this space also supplied air to an adjacent room and accessing the room during the time of the experiment was not possible. Similar to the above spaces, a total of five ventilation rates were obtained from different data loggers. For Cafeteria 2 Site B, the dimension details and ventilation rates are presented in Table 2 - 15.

Table 2 - 15 : Cafeteria 2 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
87087	4466	290	1550	1480	1508	29	5.2

Thus, at maximum capacity, the cfm/person would be 5.2 cfm/person.

Again, the ventilation rate obtained is overestimated as per the research team's understanding. This ventilation rate does not match the ventilation rate that was determined from the rooftop unit calculations. There could be several possible reasons for obtaining an over-estimated result in this decay test:

- The method of measurement used is ASTM D6245 (2018) with a decay method that works only for single zones. The single zone for this space should also have included the adjacent room, but the adjacent room was separate, and having equally mixed CO_2 concentrations in these two rooms would have been difficult. Thus, the adjacent room was ignored, and it is suspected the recirculated air from cafeteria 2 to the adjacent room helped in reducing the CO_2 concentration during the decay test.
- All spaces adjacent to Cafeteria 2 had their rooftop units (RTUs) shut down during the performance of the test. Plastic sheets were used to separate different zones and the plastic sheets were impossible to be attached to the openings with the huge rush of air being supplied from the RTU to these adjacent spaces. Thus, the RTU had to be shut down. Unfortunately, Cafeteria 2 might have become a highly positively pressurized room and air might have leaked into these rooms as well as the corridor spaces.
- The time at which the experiment was conducted had a very pleasant outdoor temperature which might have triggered the use of economizer mode and thus more outdoor air was supplied.

Any or all of the above could be the reason for the rapid decay of carbon dioxide levels than expected. But considering these assumptions void, the research team went ahead and compared the obtained values of ventilation with the required ASHRAE standard ventilation rate.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for Cafeteria (under Food and Beverage Service), the ventilation rate is calculated as shown in Table 2 - 16.

Table 2 - 16 : Calculations to determine Zone outdoor airflow required per person for cafeteria 2.

R_p, cfm/person	7.5
R_a, cfm/ft^2	0.18
P_z	290
A_z, ft^2	4466
V_{bz}, cfm	2978.88
V_{bz}, cfm/person	10.27

Thus, the space can be stated as under-ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires cafeteria to supply at least 10.27 cfm/person.

The ventilation rates obtained for Site B seem overestimated. The HVAC design for the plant is in such a manner that it would be very hard to isolate each zone separately and perform the decay test. Also, there is a good chance of the use of an economizer with the weather being pleasant outside. Even though the damper position was checked before the start of the test, the damper position might have changed during the course of the experiment which might have induced more outside air and thus, a faster decay.

The occupancy of cafeteria 2 is considered to be 290 but the administration had mentioned that the shift for this plant is quite flexible, and all the workers never arrive at the same time for their shift. This also suggests that different workers choose different break times and thus the maximum occupancy of 290 should never be achieved. Upon calculation, it is found out that if a maximum of 100 people is seated in this cafeteria 2, then the ventilation rate obtained from this decay test is good as per ASHRAE Std. 62.1 (2019).

2.3.2 Test B results

For Test B, a space was selected for inspection and all the diffusers in that space were measured for their airflow moving through the diffusers. The total airflow was calculated by adding up the airflow from all the diffusers and then it was compared to the design airflow condition provided in the documents from the administration team. The results from this test have been described below.

Cafeteria 1 Site A:

Cafeteria 1 from Site A had 10 supply air diffusers. To determine the Cafeteria 1 total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 2540 cfm.

As per the ventilation system design conditions provided by the maintenance team, Cafeteria 1 has a 20-ton HVAC unit and should have a supply of 7982 cfm. Given that the cafeteria volume is 50,413 cubic feet, the measured air exchange rate for this space is 3.02 hr^{-1}. Comparing the design airflow to the measured airflow, the total measured flow is about 32% of the design condition.

In addition, the research team identified that the diffusers closer to the supply fan deliver higher flow rates while the farther ones deliver less air. This suggests that the system needs to be recommissioned and the air distribution system needs rebalancing.

The airflow rates are not uniformly distributed across Cafeteria 1 and that could compromise human comfort and increase the infection risk in the region with the lower flow rate.

Cafeteria 3 Site A:

Cafeteria 3 from Site A had 28 supply air diffusers. To determine the Cafeteria 3 total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 7576 cfm.

As per the ventilation system design conditions provided by the maintenance team, Cafeteria 3 has a 25-ton HVAC unit and should have a supply of 10028 cfm. Therefore, the total measured flow is about 75.5% of the design condition and the actual air changes per hour of recirculated air is 12.7 hr^{-1}.

The overall air distribution for the west cafeteria is satisfactory. The airflow is equally distributed and reaches all parts of the room.

Locker 2 Site A:

The Locker 2 from Site A had 32 supply air diffusers. It was not feasible to insert the airflow hood covering the diffuser and measure the airflow since there was a structural barrier in front of the diffusers. Owing to the complex nature of the structures it was not possible to get any readings. However, it was noted that the dampers were closed for most of these diffusers which led to no air movement in these diffusers. The maintenance team was notified about it, and they learned that the dampers were manually closed probably by the workers using the locker rooms. The maintenance team informed that 24 out of 32 diffusers were closed which prevented airflow from the diffusers. These dampers were later reverted to their open positions.

Locker 1 Site A:

Locker 1 from Site A had 22 supply air diffusers. To determine the Locker 1 total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 5940 cfm.

As per the design conditions provided by the maintenance team, the Locker 1 should have a supply of 9983 cfm provided by a 25-ton HVAC unit. The total measured flow is about 60% of the design condition. The measured air exchange rate is 6.01 air changes per hour.

Locker 1 has an irregular air distribution pattern. Some of the diffusers are supplying very low values of air which can cause improper mixing within the room. The tall lockers and big furniture in the locker rooms also hinder air mixing.

Office space 1 Site B:

Office space 1 from Site B had 5 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 1665 cfm.

As per the design conditions provided by the administration team, Office space 1 should have a supply of 1575 cfm. This site B had also performed commissioning previously and the total airflow mentioned in it was 1629 cfm. The space also had a perfect air distribution pattern as per the design document.

Office space 2 Site B:

Office space 2 from Site B had 11 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 4416 cfm.

As per the design conditions provided by the administration team, Office space 2 should have a supply of 4000 cfm. This site B had also performed commissioning previously and the total airflow mentioned in it was 4068 cfm. The space also had a perfect air distribution pattern as per the design document.

Office space 3 Site B:

Office space 3 from Site B had 4 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 2302 cfm.

As per the design conditions provided by the administration team, Office space 3 should have a supply of 1600 cfm. This site B had also performed commissioning previously and the total airflow mentioned in it was 1686 cfm. The space also had a perfect air distribution pattern as per the design document. However, very higher airflow than required may result in the use of more power consumption and consequently fewer energy savings.

Office space 4 Site B:

Office space 4 from Site B had 15 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 4018 cfm.

It is to be noted that for 2 of the diffusers, the airflow rates were not measurable because of the presence of a structural barrier in front of them. For the other 2 diffusers, the airflow rates were not measured because the rooms were locked. But still, it is observed that the team's measured airflow rate is very close to the airflow rate of 4425 cfm provided in the commissioning report. Also, the total airflow rate (neglecting 4 of the diffusers) is just below the design airflow rate of 4150 cfm which shows that Office space 4's RTU is running perfectly as required. If those 4 diffusers were measured for their airflow rates, it is most likely the total airflow rate would be higher than the design airflow rate.

Training room 1 Site B:

Training room 1 from Site B had 11 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 3813 cfm.

It is to be noted that for one of the diffusers, the airflow rates were not measurable because of the presence of a structural barrier in front of them. For another one of the diffusers, the airflow rates were not measured because the diffuser was very highly placed. But still, it is observed that the team's measured airflow rate is a bit low to the airflow rate of 4802 cfm provided in the commissioning report. Also, the total airflow rate (neglecting 2 of the diffusers) is much below the design airflow rate of 5000 cfm. Ignoring those 2 diffusers, it is found that the total measured airflow rate is 85% of the design airflow rate.

Locker 3 Site C:

The Locker 3 from Site C had 3 supply air diffusers. The total airflow rate measured was 398 cfm. It was noted that out of the three diffusers, two of the diffusers had zero airflow from them.

Based on the design conditions provided by the maintenance team, the Locker 3 should have a supply flow rate of 3479 cfm because the design air exchange rate for this space is 5.8 hr^{-1} and the room volume is 35,990 cubic feet. Comparing the design airflow to the measured airflow, the total measured flow is only 12% of the design condition.

Nevertheless, there was no airflow from two of the diffusers. The only working diffuser has a value of only 12% of the design conditions. Ideally, for proper air distribution in the room, each diffuser should have approximately 33% of the total design conditions. This suggests that the system needs to be recommissioned and the air distribution system needs rebalancing.

The airflow rates are not sufficient and neither uniformly distributed across the Locker 3 and that could compromise human comfort and increase the infection risk in the region with the lower flow rate.

Locker 4 Site C:

The Locker 4 from Site C had 5 supply air diffusers. There was no reading from any of the supply air diffusers. This means that the HVAC system was not running for this room. Based on the CO_2 continuous monitoring, the research team observed that the HVAC system does not run before 8:30 AM (even though the first shift starts around 6 am). The diffuser readings were taken at around 7:30 AM which justifies the reason for having no readings.

Based on the design conditions provided by the maintenance team, the Locker 4 should have a supply of 4,524 cfm because the design air exchange rate for this space is 5.8 hr^{-1} and the room volume is 46,800 cubic feet. This observation calls for immediate attention. The HVAC system should be turned on during the entire occupancy times (such as before the shift starts or during breaks) as the chances of infection and human discomfort are increased due to insufficient airflow rate.

Locker 5 Site C:

The Locker 5 from Site C had 6 supply air diffusers. To determine the Locker 5 total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 1315 cfm.

As per the design conditions provided by the maintenance team, the Locker 5 should have a supply of 2009 cfm because the design air exchange rate for this space is 7.4 hr^{-1} and the room volume is 16,293 cubic feet. The total measured flow is about 66% of the design condition. In addition, Locker room 5 has an irregular air distribution pattern. Comparing two of the diffuser readings, one diffuser had four times the airflow rate than the other diffuser. Thus, there is a high chance of improper mixing, and the system should be re-commissioned, and the air distribution system needs re-balancing. Also, the lower supply of air than design conditions could compromise human comfort and increase the infection risk in the region with the lower flow rate.

Locker 6 Site C:

Locker 6 from Site C had 11 supply air diffusers. To determine the Locker 6 total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 2389 cfm.

As per the design conditions provided by the maintenance team, the Locker 6 should have a supply of 3172 cfm because the design air exchange rate for this space is 6 hr^{-1} and the room volume is 31,721 cubic feet. The total measured flow is about 76% of the design condition. The Locker room 6 has satisfactory levels of air distribution pattern although the total airflow rate is a bit lower than the design airflow rate.

Office space 5 Site C:

Office space 5 from Site C had 8 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 1157 cfm.

As per the design conditions provided by the maintenance team, Office space 5 should have a supply of 1260 cfm because the design air exchange rate for this space is 8 hr^{-1} and the room volume is 9,448 cubic feet. The total measured flow is about 92% of the design condition. Office space 5 has one of the diffusers with no airflow and should be checked for the absence of airflow. Overall, the airflow rate and air distribution pattern are excellent.

Office space 6 Site C:

Office space 6 from Site C had 4 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 737 cfm.

As per the design conditions provided by the maintenance team, Office space 6 should have a supply of 570 cfm because the design air exchange rate for this space is 7 hr^{-1} and the room volume is 4,882 cubic feet. The total measured flow is about 130% of the design condition. Office space 6 has an excellent overall airflow rate and a balanced air distribution pattern.

Training room 2 Site C:

Training room 2 from Site C had 4 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 1239 cfm.

As per the design conditions provided by the maintenance team, Training room 2 should have a supply of 2000 cfm because the design air exchange rate for this space is 34.6 hr^{-1} and the room volume is 3,468 cubic feet. The total measured flow is about 62% of the design condition. However, having a design air exchange rate of 34.6 hr^{-1} is not logical as the space is similar to other conference/office rooms. If this is considered an office space to have an air exchange rate of 7 hr^{-1}, then the space should have a supply of 405 cfm, and the measured airflow rate would then be excellent. The air distribution of the space is very good.

Office space 7 Site C:

Office space 7 from Site C had 6 supply air diffusers. There was no air flowing from any of the diffusers and which meant that the HVAC was not running for this space.

Based on the design conditions provided by the maintenance team, Office space 7 should have a supply of 979 cfm because the design air exchange rate for this space is 7 hr^{-1} and the room volume is 8,395 cubic feet. Comparing the design airflow to the measured airflow (i.e., no flow), the total measured flow is about 0% of the design condition.

The observation calls for immediate attention. The HVAC system that serves Office space 7 should be inspected and re-commissioned as the chances of infection and human discomfort are high for this space because of no airflow.

Office space 8 Site C:

Office space 8 from Site C had 7 supply air diffusers. To determine the total airflow rate, the average of each diffuser's airflow rate is summed to estimate the total airflow and is found to be 1587 cfm.

It is to be noted that for 2 of the diffusers, there was no airflow recorded for them. No design conditions were identified for this region in the documents provided by the maintenance team. But since it was an office space, similar to all other surrounding office spaces, the research team used the average air exchange rate of 7 hr^{-1}. Thus, Office space 8 should have a supply of 1882 cfm, as the space volume is 16,128 cubic feet. Comparing the design airflow to the measured airflow, the total measured flow is about 85% of the design condition. Two of the diffusers did not have any air flowing through them. Follow-up actions are suggested to check the reason for the absence of airflow through them. The overall airflow rate is good as per guessed design conditions for Office space 8.

2.3.3 Test C results

After the Test C experimental procedures were over, data from each of the data loggers were extracted. For most of the spaces mentioned below, one or more data loggers were installed in the rooftop unit (RTU) for a period of five days. When the CO2 concentrations were plotted against time, a pattern was observed. Most of the peaks in concentrations were during the start of the shift and the drops at the end of the shifts. Decay curves were identified from these plots and following the previously explained Test C procedures, five ventilation rates were obtained for each different day. Then it was compared to the available ASHRAE Std. 62.1 (2019).

Cafeteria 1 Site A :

The details of the results are presented in the same table format as that of Test A which contains the analysis of the measured five ventilation rates for five different days and the dimensions of the space.

For Cafeteria 1 Site A, the dimension details and ventilation rates are presented in Table 2 - 17.

Table 2 - 17 : Cafeteria 1 Site A's dimensions and measured ventilation rates

Volume (ft^3)	Area (ft^2)	Occupancy	Ventilation rates (ft^3/min or cfm)				Average Ventilation rate (cfm/person)
			Maximum	Minimum	Average	Standard Deviation	

58464	4176	280	783	635	679	54	2.49

Thus, at maximum occupant capacity, the cfm/person would be 2.49 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for cafeteria (under food and beverage service), the ventilation rate is calculated using equation (2 - 1) as shown in Table 2 - 18.

Table 2 - 18 : Calculations to determine Zone outdoor airflow required per person for Cafeteria 1 Site A.

R_p, cfm/person	7.5
R_a, cfm/ft^2	0.18
P_z	280
A_z, ft^2	4176
V_{bz}, cfm	2852
V_{bz}, cfm/person	13.58

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires cafeteria (under food and beverage service) to supply at least 13.58 cfm/person.

Locker 2 Site A :

For Locker 2 Site A, the dimension details and ventilation rates are presented in Table 2 - 19.

Table 2 - 19 : Locker 2 Site A's dimensions and measured ventilation rates

		Occupancy	**Ventilation rates (ft^3/min or cfm)**	

Volume (ft^3)	Area (ft^2)		Maximum	Minimum	Average	Standard Deviation	Average Ventilation rate (cfm/person)
92430	7110	888	433	333	377	41	0.43

Thus, at maximum occupant capacity, the cfm/person would be 0.43 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 20.

Table 2 - 20 : Calculations to determine Zone outdoor airflow required per person for Locker 2 Site A.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	888
A_z, ft^2	7110
V_{bz}, cfm	4867
V_{bz}, cfm/person	5.48

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires general break rooms (under General) to supply at least 5.48 cfm/person. It is to be noted that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Office space 9 Site A :

For Office space 9 Site A, the dimension details and ventilation rates are presented in Table 2 - 21.

Table 2 - 21 : Office space 9 Site A's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
30600	3060	15	248	142	203	44	13.67

Thus, at maximum occupant capacity, the cfm/person would be 13.67 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for office space (under Office Buildings), the ventilation rate is calculated as shown in Table 2 - 22.

Table 2 - 22 : Calculations to determine Zone outdoor airflow required per person for Office space 9 Site A.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	15
A_z, ft^2	3060
V_{bz}, cfm	259
V_{bz}, cfm/person	17.24

Thus, the space can be stated as under-ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires office spaces (under Office Buildings) to supply at least 17.24 cfm/person.

Office space 1 Site B :

For Office space 1 Site B, the dimension details and ventilation rates are presented in Table 2 - 23.

Table 2 - 23 : Office space 1 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
5508	612	21	251	150	192	53	9.15

Thus, at maximum occupant capacity, the cfm/person would be 9.15 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for office space (under Office Buildings), the ventilation rate is calculated as shown in Table 2 - 24.

Table 2 - 24 : Calculations to determine Zone outdoor airflow required per person for Office Space 1 Site B.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	21
A_z, ft^2	612
V_{bz}, cfm	141.72

V_{bz}, cfm/person	6.75

Thus, the space can be stated as highly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires office spaces (under Office Buildings) to supply at least 6.75 cfm/person. Site B also had a recent commissioning done for their site and in that commissioning report, it was stated that Office space 1 was designed for a supply of 200 cfm and their measured value was 210 cfm. This was in alignment with the measured value of 192 cfm.

Office space 3 Site B :

For Office space 3 Site B, the dimension details and ventilation rates are presented Table 2 - 25.

Table 2 - 25 : Office space 3 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
16380	1092	12	469	437	453	15	37.77

Thus, at maximum occupant capacity, the cfm/person would be 37.77 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for office space (under Office Buildings), the ventilation rate is calculated as shown in Table 2 - 26.

Table 2 - 26 : Calculations to determine Zone outdoor airflow required per person for Office space 3 Site A.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	12
A_z, ft^2	1092
V_{bz}, cfm	125.52
V_{bz}, cfm/person	10.46

Thus, the space can be stated as highly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires office spaces (under Office Buildings) to supply at least 10.46 cfm/person. Site B's commissioning report stated that Office space 3 was designed for a supply of 200 cfm and their measured value was 215 cfm while the measured value of outdoor airflow was 453 cfm.

Office space 10 Site B :

For Office space 10 Site B, the dimension details and ventilation rates are presented in Table 2 - 27.

Table 2 - 27 : Office space 10 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
86598	5586	44	1291	1058	1208	103	27.46

Thus, at maximum occupant capacity, the cfm/person would be 27.46 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for office space (under Office Buildings), the ventilation rate is calculated as shown in Table 2 - 28.

Table 2 - 28 : Calculations for Zone outdoor airflow required per person for Office space 10 Site A.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	44
A_z, ft^2	5586
V_{bz}, cfm	555.16
V_{bz}, cfm/person	12.62

Thus, the space can be stated as highly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires office spaces (under Office Buildings) to supply at least 12.62 cfm/person. Site B's commissioning report stated that Office space 3 was designed for a supply of 800 cfm and their measured value was 775 cfm while the measured value of outdoor airflow was 1208 cfm.

Cafeteria 4 Site B :

For Cafeteria 4 Site B, the dimension details and ventilation rates are presented in Table 2 - 29.

Table 2 - 29 : Cafeteria 4 Site B's dimensions and measured ventilation rates

		Occupancy	**Ventilation rates (ft^3/min or cfm)**	

Volume (ft^3)	Area (ft^2)		Maximum	Minimum	Average	Standard Deviation	Average Ventilation rate (cfm/person)
165800	7865	510	1974	1576	1694	188	3.32

Thus, at maximum occupant capacity, the cfm/person would be 3.32 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for cafeteria (under food and beverage service), the ventilation rate is calculated as shown in Table 2 - 30.

Table 2 - 30 : Calculations to determine Zone outdoor airflow required per person for Cafeteria 4 Site B.

R_p, cfm/person	7.5
R_a, cfm/ft^2	0.18
P_z	510
A_z, ft^2	7865
V_{bz}, cfm	5240.7
V_{bz}, cfm/person	10.28

Thus, the space can be stated as under-ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires cafeteria (under food and beverage service) to supply at least 10.28 cfm/person. Site B's commissioning report stated that Cafeteria 4 was designed for a supply of 1200 cfm and their measured value was 1225 cfm while the measured value of outdoor airflow was 1694 cfm. However, it was mentioned by the administration that in order to avoid crowding, the workers are allowed flexible shifts and thus the maximum occupancy of 510 people is never achieved.

Cafeteria 2 Site B :

For Cafeteria 2 Site B, the dimension details and ventilation rates are presented in Table 2 - 31.

Table 2 - 31 : Cafeteria 2 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
95180	4458	290	802	634	701	89	2.42

Thus, at maximum occupant capacity, the cfm/person would be <u>2.42 cfm/person</u>.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for cafeteria (under food and beverage service), the ventilation rate is calculated as shown in Table 2 - 32.

Table 2 - 32 : Calculations to determine Zone outdoor airflow required per person for Cafeteria 2 Site B.

R_p, cfm/person	7.5
R_a, cfm/ft^2	0.18
P_z	290
A_z, ft^2	4458
V_{bz}, cfm	2977.44
V_{bz}, cfm/person	10.27

Thus, the space can be stated as under-ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires cafeteria (under food and beverage service) to supply at least 10.27 cfm/person. Site B's commissioning report stated that Cafeteria 2 was designed for a supply of 600 cfm and their measured value was 587 cfm while the measured value of outdoor airflow was 701 cfm. However, it was mentioned by the administration that in order to avoid crowding, the workers are allowed flexible shifts and thus the maximum occupancy of 290 people is never achieved.

Training room 1 Site B :

For Training room 1 Site B, the dimension details and ventilation rates are presented in Table 2 - 33.

Table 2 - 33 : Training room 1 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
24394	1963	66	612	458	507	71	7.68

Thus, at maximum occupant capacity, the cfm/person would be 7.68 cfm/person.

The Training classroom space is similar to an office space or meeting space. As per ASHRAE Std. 62.1 (2019) Table 6-1, for meeting space and corridor (under General), the ventilation rate is calculated as shown in Table 2 - 34.

Table 2 - 34 : Calculations for Zone outdoor airflow required per person for Training room 1 Site B.

Training Room		**Corridor**	
Area, ft^2	1408	Area, ft^2	555
R_p, cfm/person	5	R_p, cfm/person	0
R_a, cfm/ft^2	0.06	R_a, cfm/ft^2	0.06
P_z	66	P_z	0
A_z, ft^2	1408	A_z, ft^2	555
V_{bz}, cfm	414.48	V_{bz}, cfm	33.3
V_{bz}, cfm/person	**6.79**		

Thus, the space can be stated as highly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires meeting space and corridor (under General) to supply at least 6.79 cfm/person. Site B's commissioning report stated that Training room 1 was designed for a supply of 500 cfm and their measured value was 476 cfm while the measured value of outdoor airflow was 507 cfm.

Locker 7 Site B :

For Locker 7 Site B, the dimension details and ventilation rates are presented in Table 2 - 35.

Table 2 - 35 : Locker 7 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	

72204	4380	66	1194	1078	1111	56	16.83

Thus, at maximum occupant capacity, the cfm/person would be 16.83 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 36.

Table 2 - 36 : Calculations to determine Zone outdoor airflow required per person for Locker 7 Site B.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	66
A_z, ft^2	4380
V_{bz}, cfm	592.8
V_{bz}, cfm/person	8.98

Thus, the space can be stated as highly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires break rooms (under General) to supply at least 8.98 cfm/person. Site B's commissioning report stated that Locker 7 was designed for a supply of 600 cfm and their measured value was 591 cfm while the measured value of outdoor airflow was 1111 cfm. Please note that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Locker 8 Site B :

For Locker 8 Site B, the dimension details and ventilation rates are presented in Table 2 - 37.

Table 2 - 37 : Locker 8 Site B's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
41098	1642	22	376	309	347	30	15.76

Thus, at maximum occupant capacity, the cfm/person would be 15.76 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 38.

Table 2 - 38 : Calculations to determine Zone outdoor airflow required per person for Locker 8 Site B.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	22
A_z, ft^2	1642
V_{bz}, cfm	208.52
V_{bz}, cfm/person	9.48

Thus, the space can be stated as highly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires break rooms (under General) to supply at least 9.48 cfm/person. Site

B's commissioning report stated that Locker 8 was designed for a supply of 400 cfm and their measured value was 434 cfm while the measured value of outdoor airflow was 347 cfm. Please note that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Cafeteria 5 Site C :

For Cafeteria 5 Site C, the dimension details and ventilation rates are presented in Table 2 - 39.

Table 2 - 39 : Cafeteria 5 Site C's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
141680	8855	420	1005	619	743	177	1.77

Thus, at maximum occupant capacity, the cfm/person would be 1.77 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for cafeteria (under food and beverage service), the ventilation rate is calculated as shown in Table 2 - 40.

Table 2 - 40 : Calculations to determine Zone outdoor airflow required per person for Cafeteria 5 Site C.

R_p, cfm/person	7.5
R_a, cfm/ft^2	0.18
P_z	420
A_z, ft^2	8855

V_{bz}, cfm	4743.9
V_{bz}, cfm/person	11.3

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires cafeteria (under food and beverage service) to supply at least 11.3 cfm/person.

Cafeteria 6 Site C :

For Cafeteria 6 Site C, the dimension details and ventilation rates are presented in Table 2 - 41.

Table 2 - 41 : Cafeteria 6 Site C's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
74800	4675	212	955	573	720	175	3.4

Thus, at maximum occupant capacity, the cfm/person would be 3.4 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for cafeteria (under food and beverage service), the ventilation rate is calculated as shown in Table 2 - 42.

Table 2 - 42 : Calculations to determine Zone outdoor airflow required per person for Cafeteria 6 Site C.

R_p, cfm/person	7.5

R_a, cfm/ft^2	0.18
P_z	212
A_z, ft^2	4675
V_{bz}, cfm	2431.5
V_{bz}, cfm/person	11.47

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires cafeteria (under food and beverage service) to supply at least 11.47 cfm/person.

Locker 3 Site C :

For Locker 3 Site C, the dimension details and ventilation rates are presented in Table 2 - 43.

Table 2 - 43 : Locker 3 Site C's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
26350	2635	417	482	256	390	119	0.93

Thus, at maximum occupant capacity, the cfm/person would be 0.93 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 44.

Table 2 - 44 : Calculations to determine Zone outdoor airflow required per person for Locker 3 Site C.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	417
A_z, ft^2	2635
V_{bz}, cfm	2243.1
V_{bz}, cfm/person	5.38

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires break rooms (under General) to supply at least 5.38 cfm/person. Please note that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Locker 4 Site C :

For Locker 4 Site C, the dimension details and ventilation rates are presented in Table 2 - 45.

Table 2 - 45 : Locker 4 Site C's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
52490	5249	823	1067	681	819	172	0.99

Thus, at maximum occupant capacity, the cfm/person would be <u>0.99 cfm/person</u>.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 46.

Table 2 - 46 : Calculations to determine Zone outdoor airflow required per person for Locker 4 Site C.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	823
A_z, ft^2	5249
V_{bz}, cfm	4429.94
V_{bz}, cfm/person	5.38

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires break rooms (under General) to supply at least <u>5.38 cfm/person</u>. Please note that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Locker 5 Site C :

For Locker 5 Site C, the dimension details and ventilation rates are presented in Table 2 - 47.

Table 2 - 47 : Locker 5 Site C's dimensions and measured ventilation rates

		Occupancy	**Ventilation rates (ft^3/min or cfm)**	

Volume (ft^3)	Area (ft^2)		Maximum	Minimum	Average	Standard Deviation	Average Ventilation rate (cfm/person)
12220	1222	149	442	326	442	49	2.51

Thus, at maximum occupant capacity, the cfm/person would be 2.51 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 48.

Table 2 - 48 : Calculations to determine Zone outdoor airflow required per person for Locker 5 Site C.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	149
A_z, ft^2	1222
V_{bz}, cfm	818.32
V_{bz}, cfm/person	5.49

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires break rooms (under General) to supply at least 5.49 cfm/person. Please note that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Locker 6 Site C :

For Locker 6 Site C, the dimension details and ventilation rates are presented in Table 2 - 49.

Table 2 - 49 : Locker 6 Site C's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
24440	2444	366	896	490	688	145	2.04

Thus, at maximum occupant capacity, the cfm/person would be 2.04 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for break rooms (under General), the ventilation rate is calculated as shown in Table 2 - 50.

Table 2 - 50 : Calculations to determine Zone outdoor airflow required per person for Locker 6 Site C.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	366
A_z, ft^2	2444
V_{bz}, cfm	1976.64
V_{bz}, cfm/person	5.4

Thus, the space can be stated as poorly ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires break rooms (under General) to supply at least 5.4 cfm/person. Please note that there is no specific classification for locker rooms in ASHRAE Std. 62.1 (2019).

Office space 5 Site C :

For Office space 5 Site C, the dimension details and ventilation rates are presented in Table 2 - 51.

Table 2 - 51 : Office space 5 Site C's dimensions and measured ventilation rates

Volume (ft^3)	Area (ft^2)	Occupancy	Ventilation rates (ft^3/min or cfm)				Average Ventilation rate (cfm/person)
			Maximum	Minimum	Average	Standard Deviation	
11520	1440	12	155	125	140	15	11.66

Thus, at maximum occupant capacity, the cfm/person would be 11.66 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for office space (under Office Buildings), the ventilation rate is calculated as shown in Table 2 - 52.

Table 2 - 52 : Calculations for Zone outdoor airflow required per person for Office space 5 Site C.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06
P_z	12
A_z, ft^2	1440
V_{bz}, cfm	146.4

V_{bz}, cfm/person	12.2

Thus, the space can be stated as well-ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires office spaces (under Office Buildings) to supply at least 12.2 cfm/person.

Office space 6 Site C :

For Office space 6 Site C, the dimension details and ventilation rates are presented in Table 2 - 53.

Table 2 - 53 : Office space 6 Site C's dimensions and measured ventilation rates

Volume (ft^3)	**Area (ft^2)**	**Occupancy**	**Ventilation rates (ft^3/min or cfm)**				**Average Ventilation rate (cfm/person)**
			Maximum	**Minimum**	**Average**	**Standard Deviation**	
26082	2898	20	229	112	155	64	7.76

Thus, at maximum occupant capacity, the cfm/person would be 7.76 cfm/person.

As per ASHRAE Std. 62.1 (2019) Table 6-1, for office space (under Office Buildings), the ventilation rate is calculated as shown in Table 2 - 54.

Table 2 - 54 : Calculations for Zone outdoor airflow required per person for Office space 6 Site C.

R_p, cfm/person	5
R_a, cfm/ft^2	0.06

P_z	20
A_z, ft^2	2898
V_{bz}, cfm	273.88
V_{bz}, cfm/person	13.69

Thus, the space can be stated as under-ventilated as per ASHRAE Std. 62.1 (2019) Table 6-1, which requires office spaces (under Office Buildings) to supply at least 13.69 cfm/person.

2.4 Conclusions

This chapter initially explains the general infrastructure of the meat processing plants. The three major functional divisions of spaces (i.e., kill areas, fabrication areas, common areas) is prevalent in most of the meat processing plants and it was learned due to the workers' schedules, the common areas are often the most crowded especially during the breaks or shift changes.

The next step was to determine the ventilation rates as well as the total airflow rates for some of the selected spaces. The experimental setups along with the required equipment have been described to measure these ventilation rates and total airflow rates. Lastly, the experiment results section discusses the measured results in detail.

The overall Test A results are shown in Table 2 - 55. The table contains the locations and sites of the experiments along with the measured ventilation rates. The required ventilation rates for those spaces as per the ASHRAE Std. 62.1 (2019) and the ratio of the measured value to ASHRAE Std. 62.1 (2019) values are also mentioned in this table.

Table 2 - 55 : Test A results of ventilation rates

Location	**Site**	**Occupancy**	**Measured ventilation rate (ft^3/min or cfm)**	**ASHRAE Std. 62.1 (2019) ventilation rate (ft^3/min or cfm)**	**Ratio of measured value to ASHRAE value**
Locker 1	A	617	376	3278	0.1147
Processing Area 1	A	30	3679	-	-
Processing Area 2	A	170	19465	-	-
Cafeteria 1	A	280	785	2784	0.2820
Training room 1	B	66	1212	448	2.7054
Cafeteria 2	B	290	1508	2979	0.5062

As evident from the ratios in Table 2 - 55, the Site A areas had very low ventilation rates compared to Site B. Site C was not measured with Test A due to lack of resources and schedule conflicts with the administration.

The overall Test B results are shown in Table 2 - 56. The table contains the experimental locations and sites along with the design occupancy of those spaces. The measured total airflow through all the diffusers of the spaces as well as the design total airflow rates of these spaces are provided as well. The last column provides the ratio of the measured total airflow rates to the design total airflow rates.

Table 2 - 56 : Test B results of total airflow rates

Location	**Site**	**Occupancy**	**Measured total airflow (ft^3/min or cfm)**	**Design total airflow (ft^3/min or cfm)**	**Ratio of measured value to design value**
Cafeteria 1	A	280	2540	7982	0.3182
Cafeteria 3	A	272	7576	10028	0.7555
Locker 1	A	617	5940	9983	0.5950
Office space 1	B	21	1665	1575	1.0572
Office space 2	B	22	4416	4000	1.1040
Office space 3	B	12	2302	1600	1.4388
Office space 4	B	22	4018*	4425	0.9080
Training room 1	B	66	3813*	4802	0.7940
Locker 3	C	417	398	3479	0.1144
Locker 5	C	149	1315	2009	0.6546

Locker 6	C	366	2389	3172	0.7532
Office space 5	C	12	1157	1260	0.9183
Office space 6	C	10	737	570	1.2930
Training room 2	C	4	1239	2000	0.6195
Office space 8	C	20	1587	1882	0.8433

*Structural barrier restricted all diffusers' airflow measurements in the space

The ratio of measured total airflow to the design total airflow rates shown in Table 2 - 56 indicates that Site B mostly had the required total airflow rates as per the design conditions. For Site A and Site C, some of their cafeterias and locker rooms had very poor total supply airflow. The office areas have a decent total airflow supply.

The overall Test C results are shown in Table 2 - 57. Similar to Test A results, this table also contains the locations and sites of the experiments along with the measured ventilation rates. It also provides the required ventilation rates for those spaces as per the ASHRAE Std. 62.1 (2019) and the ratio of the measured value to ASHRAE Std. 62.1 (2019) value.

Table 2 - 57 : Test C results of ventilation rates

Location	**Site**	**Occupancy**	**Measured ventilation rate (ft^3/min or cfm)**	**ASHRAE Std. 62.1 (2019) ventilation rate (ft^3/min or cfm)**	**Ratio of measured value to ASHRAE value**
Cafeteria 1	A	280	679	2852	0.2381
Locker 2	A	888	377	4867	0.0775
Office Space 9	A	15	203	259	0.7838
Office Space 1	B	21	192	142	1.3521
Office Space 3	B	12	453	126	3.5952
Office space 10	B	44	1208	555	2.1766
Cafeteria 4	B	510	1694	5241	0.3232
Cafeteria 2	B	290	701	2977	0.2355
Training room 1	B	66	507	448	1.1317
Locker 7	B	66	1111	593	1.8735
Locker 8	B	22	347	209	1.6603
Cafeteria 5	C	420	743	4744	0.1566
Cafeteria 6	C	212	720	2432	0.2961

Locker 3	C	417	390	2243	0.1739
Locker 4	C	823	819	4430	0.1849
Locker 5	C	149	442	818	0.5403
Locker 6	C	366	688	1977	0.3480
Office Space 5	C	12	125	146	0.8562
Office Space 6	C	20	155	274	0.5657

As evident from the ratios in Table 2 - 57, the Site A and Site C areas had very low ventilation rates. Site B had the best ventilation rates as the ratios of measured ventilation rates to required ASHRAE Std. 62.1 (2019) values were greater than 1 for all the spaces except for the cafeteria. Even for the cafeterias of Site B, the administration mentioned that the schedule is made in such a way that not more than 100 people would be in the cafeteria at a single point in time. For all the sites, the office areas out of all the spaces seem to have better ventilation than the rest of the common areas. The locker rooms and cafeterias of Site A and Site C had very poor ventilation and the administration teams were notified to provide immediate attention in order to get the ventilation rates higher to the required ventilation.

The research team shared the measured data with the administration teams and notified them about those spaces which had very less total airflow rates or ventilation rates. The areas which had ratios close to 0 in any of the three tables demanded immediate attention and needed to have their HVAC system checked to bring in more filtered outdoor air or increase their supply of total airflow.

These experimental measurements have been further used in analyzing the probability of airborne infection from SARS-CoV-2 using a modified Wells-Riley model. To show the importance of ventilation and high total airflow rates, the experimental measurements as well as the standard or design requirements are also used in the risk assessments. The risk assessments are discussed in the upcoming sections.

CHAPTER 3 RISK ANALYSIS

The three meat processing plants were measured for their in-situ ventilation rates and total supply airflow, and it was clear from some studied spaces that the ventilation rates were not adequate compared to the available ASHRAE standards or the design conditions. The inadequate ventilation rates would also mean that there would be an increased infection risk for the occupants from COVID-19. This led way to find the risk of infection associated with the studied spaces and further suggest ways to reduce those risks. For this, it was decided to use the Wells-Riley model to assess the probability of infection for selected spaces.

The assessment of infection risks is very important as it would help in understanding the dynamics involved in the transmission of infectious diseases. The assessment would also be very helpful in predicting the infection risk associated with a space used by the public. The quantification of the risk assessment further helps in providing quantitative numbers to the risk analysis and would also be very useful in comparing different infection control strategies. The frequently used risk analysis model for quantitative risk analysis is the Wells-Riley Model [Sze-To and Chao (2010)].

3.1 Wells-Riley Models

Riley et al. (1978) mentions about the airborne transmission of measles in the suburban elementary school that saw the first use of the Wells-Riley equation which used the concept of quantum of infection which was previously defined by Wells (1955). Since the equation used in Riley et al. (1978) is based on the use of ‘quantum of infection’ that was developed by Wells, the equation is termed as the Wells-Riley model. Many models from this equation have been used widely used to analyze the effectiveness of ventilation in the airborne transmission of infectious diseases. The equation considers the space to be well-mixed with the ventilation being the solely responsible reason for the decay of the infectious particle concentration [Sze-To and Chao (2010)].

The general form of the equation [Riley et al. (1978)] is :

$$P_I = \frac{C}{S} = 1 - \exp\left(-\frac{Iqpt}{Q}\right) \qquad (3 - 1)$$

where :

P_I is the probability of infection,

C is the number of new infection cases,

S is the number of susceptible individuals exposed,

I is the number of infectors,

p is the pulmonary ventilation rate of susceptible individuals,

q is the quanta production rate by the infectors,

t is the exposure time interval, and

Q is the room ventilation rate with clean air.

This equation (3 - 1) is the basic form of the equation and has been used in several studies to learn about the infection probability in a space. In this equation, the only factor that is considered to influence the probability of infection is the ventilation rate. This equation (3 - 1) takes into account some major assumptions [Dai and Zhao (2020)] and they are listed below:

i. The considered space is well-mixed.

ii. Even distribution of droplet nuclei which infers that the probability of infection depicted by this model would be uniformly distributed within the space.

iii. An individual is considered to be infected if his/her pathogen intake is greater than one and that all inhaled particles would successfully deposit the infectious particles on the targeted individual [Sze-To and Chao (2010)].

But over time and further research, researchers have incorporated several other influencing factors as well as control measures in the equation. To use the Wells-Riley model in the analysis for the meat processing plants, the research team had to figure out the Wells-Riley model that would consider the influential factors that were measured in the experiments or the control measure settings that were installed in those meat processing plants. Thus, a literature review was conducted for the use of different forms of the Wells-Riley model in different scenarios.

Basic Wells-Riley model

The Wells-Riley model in its original form, equation (3 - 1), was used in Escombe et al. (2007), Nardell et al. (1991), Buonanno et al. (2020), Sha et al. (2021), Xu et al. (2022). Escombe et al. (2007) established natural ventilation in the form of opening windows and doors reduces the risk of airborne disease transmissions. Xu et al. (2022) uses three different forms of ventilation namely mixed ventilation, personalized ventilation, and displacement ventilation for analyzing the most effective ventilation for infection transmission control and also states the need for novel ventilation strategies in order to interrupt airborne infection transmission from the infection source to the susceptible receptor. Nardell et al. (1991) conducted an office simulation which results in fewer tuberculosis cases if the ventilation is increased, however, if the quanta emission rate i.e., the infectiousness is high, the ventilation would likely be offering less protection. Different quanta emission rates for SARS-CoV-2 for different respiratory activities as well as activity levels are suggested in Buonanno et al. (2020) and using these defined quanta emission rates, airborne infection risks were simulated via the Wells-Riley method for Italian indoor microenvironments. The ventilation rates required for a high-rise building in order to reduce the airborne infection risk of SARS-CoV-2 to a minimum were modeled in Sha et al. (2021). Sha et al. (2021) also presented a wide range of ventilation rates as per the protective measures taken to mitigate the infection risks and also showcased that if the occupants were to follow the protective measures properly, the corresponding mechanical ventilation system requirement can be reduced significantly leading to huge energy savings.

Additional variables included in basic Wells-Riley model

Fennelly and Edward (1998), Shao and Li (2020), Park et al. (2021), Nazaroff et al. (1998), Fisk et al. (2004), Noakes and Sleigh (2008), Stephens (2013), Sun and Zhai (2020), Aganovic et al. (2021), and Harmon and Lau (2021) accommodated additional variables in the Wells-Riley model to account for factors that help in reducing the airborne transmission risks of infections. Fennelly and Edward (1998) and Shao and Li (2020) used an additional variable to factor for the relative effectiveness of personal respiratory protection (masks) and both the test results showed that the infection risk decreases exponentially with increased personal respiratory protection and increasing the supply of fresh outdoor air. Similar to Escombe et al. (2007), Park et al. (2021) inferred natural ventilation to significantly reduce the risk of airborne infection transmission. However, for spaces where proving a high ventilation rate would be difficult, wearing masks could significantly reduce the risk of airborne infection transmission as well. Nazaroff et al. (1998) calculated the probability of infection for occupants of a zone when the infector is present in another zone where the infection spread from one zone to another zone takes place from the probable leakages. Control measures such as masks, higher ventilation, filtration, and ultraviolet germicidal irradiation are also modeled into the model used in Nazaroff et al. (1998) to explore these variables. Fisk et al. (2004) in its modified Wells-Riley model included the effect of recirculation flow rate, the efficiency of filtration as well as deposition rate for infectious particles. The effects of multi-zone ventilation and the proximity to an infectious source were studied in Noakes and Sleigh (2008) and the study demonstrates that risk assessments made with the assumption of complete mixing may vary significantly from the real risk possessed to someone who is significantly close to the infective person. Stephens (2013) performed risk assessments of four different infectious aerosols using the Wells-Riley method and the report stresses on the use of various filtration systems and the airborne risks associated with them. Sun and Zhai (2020) introduced a modified Wells-Riley model to include the effects of social distancing and air distribution effectiveness to predict the risks of airborne infection from SARS-CoV-2. Sun and Zhai (2020) also studies different cases with the suggested Well-Riley model which suggested reasonable accuracy of prediction. Aganovic et al. (2021) used a modified Wells-Riley model to predict the impact of relative humidity for removing the SARS-CoV-2 aerosols by inactivating them in their biological decay process or their depositing through gravitational settling. Although Aganovic et al. (2021)

does not focus on the susceptibility of acquiring SARS-CoV-2 in a particular relative humidity environment, the study results concluded that the change of indoor relative humidity is not much effective in reducing the airborne infection risk compared to the significant risk reduction in increasing ventilation. Harmon and Lau (2021) expanded the Wells-Riley model to include several engineering strategies such as the use of upper air ultraviolet germicidal irradiation, the use of different air cleaners, and vaccination efficiencies of different available vaccines. Harmon and Lau (2021) also provided validation of the model using two documented spreading events.

Accommodating a space's carbon dioxide concentrations in the Wells-Riley model

Rudnick and Milton (2003), Liao et al. (2005), Burridge et al. (2021), and Peng and Jimenez (2021) incorporated the concept of using carbon dioxide concentration in a space. Since rates of outdoor air supply is often difficult to measure or determine, Rudnick and Milton (2003) modified the Wells-Riley equation to consider the air fractions of carbon dioxide inside the space as well as in the outdoor air and thus help in determining the risk associated with relative carbon dioxide concentration levels. The measured carbon dioxide of different regions in a space has been used in Burridge et al. (2021) and Peng and Jimenez (2021) to evaluate the airborne infection risk by using the concepts of the modified Wells-Riley model proposed by Rudnick and Milton (2003) and this method of assessing risk is found to be very useful and cost-effective if the occupancy of a space is available and multiple carbon dioxide monitors are fitted in the room to evaluate the spatial risk. The model used by Rudnick and Milton (2003) was further modified to substitute the outdoor air supply rate as a function of indoor air fraction resembling the exhaled breath [Liao et al. (2005)]. Liao et al. (2005) used a range of reproductive numbers to establish that with an increase in the outdoor air supply rates, there is a decrease in the indoor carbon dioxide concentration level, as well as a decrease in the contact rate, which would be effective in reducing the spread of airborne infection.

Integrating computational fluid dynamics with the Wells-Riley model

The original Wells-Riley model assumes uniform spatially distributed infected cases for a given space. This assumption is not accurate for most cases. Qian et al. (2009), Zhu et al. (2012), Liu et al. (2021), Foster and Kinzel (2021), Li and Tang (2021), Wang et al. (2022), and Li et al. (2022) have used the integration of Wells-Riley model along with computational fluid dynamics (CFD) to predict the spatial distribution of the airborne transmission's infection risks. Zhu et al. (2012) took into consideration different ventilation methods that are used in a bus along with different air recirculation values and different filtration efficiencies for the risk assessments. Zhu et al. (2012) suggested that CFD when combined with the Wells-Riley model could be used as a powerful tool in establishing risks for a given space. Liu et al. (2021) analyzed different operation scenarios for a laboratory setting and concluded that the infection risks varied hugely among different regions inside the space. Foster and Kinzel (2021) performed risk assessments of airborne infectious diseases using both the Wells-Riley model as well as the computational fluid dynamics models with different ventilation inputs and concluded that the Wells-Riley model is a strong tool in order to assess risks. Foster and Kinzel (2021) also ranks different mitigation methods to reduce the associated transmission risks. Li and Tang (2021) established the requirement of higher ventilation rates for lesser infection risks whereas Li et al. (2022) suggests a mixture of personal protective equipment (PPE), and optimum ventilation when considering factors such as occupant location, vaccination details of occupants, occupant activity. Wang et al. (2022) predicted the airborne infection risks associated with SARS-CoV-2 in long-distance trains and the predictions were matched with the actual available infection data for validation. Wang et al. (2022) also discussed the infection mitigation techniques and ranked them in relation to associated infection risks.

Different unique models incorporated in original Wells-Riley model

The Wells-Riley equation incorporated into SEIR epidemic model to understand the transmission dynamics of aerosol infectious particles in ventilated rooms [Noakes et al. (2006)]. SEIR stands for Susceptible, Exposed, Infected or Removed. Noakes et al. (2006) model makes use of parameters to examine the effect of environmental factors such as room occupancy, ventilation rates and assesses the impacts of infection control measures.

A new approach of assessing airborne infection risks is proposed in Guo et al. (2021) which uses the integration of the Wells-Riley model with the spatial flow impact factor (SFIF). This method is based on the calculated flow field from computational fluid dynamics but is somewhat different from the other computational fluid dynamics integrated Wells-Riley method.

Yan et al. (2017) of infection risks for airborne diseases in airline cabin environment was conducted using the integrated form of the Lagrangian-based Wells-Riley model. One of the advantages of using the Lagrangian-based approach is being more robust since both the time for particle residence and concentrations of particles in the breathing zones of every occupant can be determined by this method.

The risk assessment of airborne infection in Zhang and Lin (2021) is evaluated using an expanded Wells-Riley model along with the concept of dilution. This method of assessing risks can evaluate both the spatial and temporal airborne infection risks. The study also uses experiments in a mock hospital to showcase the effectiveness of the proposed integrated method of evaluating airborne infection risks.

3.2 Equation used

The literature review on the use of the Wells-Riley methods gave a lot of options for this research. The closest resemblance found for studying the probabilities of airborne infection risks from SARS-CoV-2 was found in Harmon and Lau (2021). The author of this paper has provided a Wells-Riley model with long detailed explanations related to the mechanisms involved in inactivating infections. It also discusses in detail the model inputs, the assumptions considered as well as the limitations of the model.

The Wells-Riley model provided in Harmon and Lau (2021) looks almost similar to the equation used for this research. The equation is provided below :

$$P = \left[1 - \exp\left(\frac{-(q*I*p*s*t)}{V*(\lambda_{ventilation}+k_{filtration}+k_{RH}+k_{UVduct}+k_{UVGI}+\lambda_{aircleaner}+k_{mask})}\right)\right] * v_{adjusted} \quad (3 - 2)$$

where :

P is the probability of airborne infection from SARS-CoV-2,

q is the quanta generation rate,

I is the number of infective individuals, p is the pulmonary ventilation rate,

s is the modified p scaling factor for masks,

t is the exposure time,

V is the volume of the space,

$\lambda_{ventilation}$ is the ventilation removal factor,

$k_{filtration}$ is the building system filtration removal factor,

k_{RH} is the relative humidity inactivation removal factor,

k_{UVduct} is the in-duct UV inactivation removal factor,

k_{UVGI} is the upper room UVGI inactivation removal factor,

$\lambda_{aircleaner}$ is the portable air cleaner removal factor,

k_{mask} is the mask removal factor,

$v_{adjusted}$ is the adjusted vaccination factor.

The equation (3 - 3) above has two changes from the Wells-Riley model provided in Harmon and Lau (2021). Firstly, the term $k_{settling}$, has been removed from that paper's equation because it had a negligible impact on the overall probability. This has been demonstrated in a later section which explains the use of variables. Also, a new term k_{UVduct}, has been introduced to account for the impact of the ultraviolet lights used in the return air ducts in the rooftop units. The use of this variable has also been explained later.

The assumptions of using this Wells-Riley model are the same as that of the equation (3 - 1) which have been stated in the literature review section of the Wells-Riley model. Assumptions related to input variables will be stated in the variable descriptions section later.

The meat processing plants were measured for their ventilation rates and the total airflow through the diffusers for a given space. The overall occupancy schedules were provided by the administration and observed by the research team. Upon inspection of the sites, it was found that two of the three sites used ultraviolet lights in the return air duct of the rooftop units. Some of the office spaces also had portable air cleaners for better indoor air quality. It was mandatory for everyone to wear a mask inside the plant.

All of the above-mentioned factors led to the use of Harmon and Lau (2021) paper's Wells-Riley model by slightly modifying it as this model best fits the research's purpose. Although using computational fluid dynamics would have been better to analyze the spatial probability of infection, the research team didn't have enough required sources or data to implement the use of computational fluid dynamics. Unlike computational fluid dynamics, the equation (3 - 3) provides the overall probability of infection from SARS-CoV-2 throughout the space, but the model's use has been validated by Harmon and Lau (2021) using two real documented events.

The research's use of the equation (3 - 3) intends to provide the probability of infection from SARS-CoV-2 and uses different infection control techniques to compare the reduction in infection probabilities.

3.3 Variable Descriptions

The equation (3 - 3) has a lot of input variables that help in determining the probability of airborne infection from SARS-CoV-2. This section will discuss each variable in detail. While most of the variable values are chosen from literature, some of them are experimentally observed values and a few values are hypothetically chosen with reasonable justifications.

Quanta generation rate - q

The quanta generation rate is the ‘hypothetical infectious dose unit’ whose value is determined using back calculations from the epidemiological studies observed before. The single dose unit corresponds to the number of generated particles and the corresponding infectivity of those particles. This number is also indicative of an individual’s susceptibility to getting infected and considers the different effects of these particles’ sizes. This quanta generation rate is different for different pathogens [Azimi and Stephens (2013)]. The unit for quanta generation rate is 1/ hour.

The quanta value is highly dependent upon an individual’s activity type and the amount of the individual’s virus shedding. The activity type influences the breathing rates and directly impacts the quanta of the virus generated. The type of shedding can be linked to the phase of infection for the infected individual. The shedding is said to peak before the onset of symptoms [He et al. (2020)].

For this study based on SARS-CoV-2, the quanta generation numbers are referenced from Table 1 of Harmon and Lau (2021). For this research, only two activity levels are considered: moderate activity level and heavy activity level. The spaces studied for infection risk in this research are processing areas, cafeterias, and locker rooms. In processing areas, the working individuals work very hard and thus their activity levels are considered heavy whereas in the other areas, the workers are relaxed, and their activity level can be considered moderate. The shedding type of infective individuals is identified as high shedders because the shedding peaks before the onset of symptoms for symptomatic infective individuals and if symptoms are evident, a worker might not be allowed inside the plant [He et al. (2020)]. The use of a high value for quanta generation rate helps in estimating the highest possible airborne infection probabilities and can be thought of as the "worst-case" scenario risk analysis.

Thus, two quanta values of SARS-CoV-2 are considered from Table 1 of [Harmon and Lau (2021)] :

1. High shedder moderate activity – 1190 quanta/hour
2. High shedder heavy activity – 2856 quanta/hour

However, in section 3.4.3, low shedder quanta values were adopted in a sensitivity analysis to evaluate the "best-case" risk analysis as well.

Number of infective individuals - I

The number of infective individuals could be any number starting from 0 to all the people in the space. For a room with 0 infective individuals, the probability of infection becomes 0 and the probability increases with an increase in the number of infective individuals. Considering a hypothetical situation, the number of infective individuals for this research is chosen as 10% of the total occupancy for all of the studied spaces. For example, if at any point a space has 400 people in it, the number of infective persons in the space is considered 10% of 400, i.e., 40 infective persons.

Pulmonary ventilation rate - p

The inhaling of the virus can be directly related to the breathing rate of an individual. And as mentioned before, the activity type influences the breathing rate. The inhalation rates are obtained from Table 6-31 of the EPA's Exposure Factors Handbook [Environmental Protection Agency (2011)]. These inhalation rates need to be divided by 24 hours in order to obtain the pulmonary ventilation rate. The unit of the pulmonary ventilation rate is cubic meter per hour.

The values of the pulmonary ventilation rates were chosen depending on the space studied. For common spaces, the adult average was considered, whereas for locker rooms either adult men or women were considered. Similarly, the processing areas had activity level as heavy whereas the other areas had moderate activity level. The required table format of the pulmonary ventilation rate values is provided in Table 3 - 1.

Table 3 - 1 : Pulmonary ventilation rates

	Pulmonary Ventilation Rate (m^3/hr)	
Subject	**Moderate**	**Heavy**
Adult Male	0.147083	0.04375
Adult Female	0.094167	0.026667
Adult Average	0.120625	0.035208

Modified p scaling factor for masks - s

The modified p-scaling factor, s, takes into consideration the efficiency of masks being worn by individuals in preventing the spread of the virus. The formula to calculate ‘s’ is given by :

$$modified\ p\ scaling\ factor, s = 1 - (mask\ efficiency * \%non - infected\ wearing\ mask) \qquad (3 - 3)$$

The percentage of non-infected wearing a mask was 100% since everyone needed to wear a mask. Also, for simplicity, it was assumed that everyone was wearing the same type of mask which is a 2-layer woven nylon mask with ear loops along with an aluminum nose bridge. This type of mask has an efficiency of 56.3% [Clapp et al. (2021)]. Thus, the equation (3 - 4) when evaluated results as 0.437 and is unit less. The value of the modified p scaling factor is considered as 0.437 in most of the spaces except for cafeterias where workers would eat taking off their masks.

Time of exposure - t

The time of exposure is the amount of time an individual is spending their time in that space. The meat processing plants mostly have fixed schedules for which it was easy to determine how long individuals can spend their time in a particular space. The unit of time considered is hours.

Volume of the space - V

The floor plans of all the meat processing plants were provided by the respective administration teams. The volumes of the concerned spaces, which were selected for risk analysis, were calculated in cubic meter.

Ventilation removal factor - $\lambda_{ventilation}$

The supply of filtered outdoor air into the space is referred to as ventilation. Outdoor air is assumed to be free of any contaminants and is held responsible for diluting the contaminants when supplied inside the space. The research used Test A and Test C to obtain the ventilation rates of required spaces. The results obtained from these tests are actual or measured ventilation rates. These spaces either had minimum ventilation rate requirements set by ASHRAE Std. 62.1 (2019) or administration decided design ventilation rates. The measured ventilation rates obtained from Test A or Test C were obtained in units of cubic feet per minute (cfm) and were converted to air changes per hour (ACH) which has a unit of 1/hour. The equation (3 - 5) can be used for this conversion.

$$ACH = \frac{cfm * 60}{Volume\ of\ space\ in\ cubic\ feet\ (V)} \qquad (3 - 4)$$

The measured and design ventilation rates were both used in this research to find their corresponding influence on the probability of infection.

Building system filtration removal factor - $k_{filtration}$

Filtration systems are used to keep the air clean from various contaminants. The filters used in the building systems are identified with a rating system. This rating system is termed as minimum efficiency reporting value (MERV) and is rated from 1 to 16. The rating system is indicative of the efficiency with which the filter is able to work and is considered effective if the clean air delivery rate is high. Both, the efficiency of the filter (η_{filter}) and the recirculation rate of air ($\lambda_{recirculation}$) determines the clean air delivery and is calculated by the equation (3 - 6).

$$k_{filtration} = \lambda_{recirculation} * \eta_{filter} \qquad (3 - 5)$$

The $\lambda_{recirculation}$ is to be determined from equation (3 - 7) and its value is in air changes per hour (ACH) which has a unit of 1/hr.

$$\lambda_{recirculation} = Total\ air\ changes\ per\ hour - \lambda_{ventilation} \qquad (3 - 6)$$

The total air changes per hour is obtained from Test B results or administration-provided design values.

For the η_{filter} values, Table 4 of Stephens (2013) is referred to. Stephens (2013) assumes that the filter efficiencies are determined with the concept that 15% of the particles are of size 0.3-1 μm, 25% of the particles are of size 1-3 μm, and the remaining 60% of the particles are of size 3-10 μm.

The meat processing plants had MERV 7 filters installed in the rooftop units and it was only after the COVID-19 pandemic, the administration started to use MERV 13 filters. The filter removal efficiencies for these two filters based on the droplet nuclei weighted average [Stephens (2013)] are provided below :

a. MERV 7 → 0.44
b. MERV 13 → 0.87

MERV 16 would have an efficiency of 0.95 [Stephens (2013)], but the risk analysis performed in this research will only aim on using MERV 7 and 13 filters to show the effect on the probability of infection.

Also, the overall unit for $k_{filtration}$ is 1/hr.

Relative humidity inactivation removal factor - k_{RH}

Virus inactivation is the process of making a virus non-infectious. Membrane-bound viruses such as SARS-CoV-2 have higher or favorable conditions for surviving when the relative humidity is higher than 70% or below 40% [Harmon and Lau (2021)]. The Department of Homeland Security provided a calculator to account for the survival of airborne viruses under the effect of ambient relative humidity [Department of Homeland Security (2021)]. The inactivation rate for SARS-CoV-2 due to relative humidity has been established in the Harmon and Lau (2021) paper and can be calculated using the equation (3 - 8):

$$k_{RH} = (0.0135 * Relative\ humidity) - 0.0028 \qquad (3 - 7)$$

This equation (3 - 8) has been obtained from the available calculator provided by the Department of Homeland Security (2021). This equation assumes that the indoor temperature is consistent throughout the room at 72 F and since it is indoors, the UV index is 0.

The meat processing plants were not measured for their relative humidity by the research team and upon seeking information from the administration team, it was learned that most of the spaces are designed to have a relative humidity of 30% and the processing areas to have a relative humidity of 50%. Also, the processing areas of the plants are designed to be maintained at a much cooler indoor temperature (temperatures not measured in this research) than 72 F.

It is not practically possible for all the spaces to have a fixed relative humidity and the same temperature throughout a space. For simplicity and unavailability of data, the research team assumed all spaces to have an indoor temperature of 72 F and a relative humidity of 50% for processing areas and 30% for the rest of the spaces in order to use equation (3 - 8).

Also, the overall unit for k_{RH} is 1/hr.

In-duct ultraviolet inactivation removal factor - k_{UVduct}

The term k_{UVduct} is a term to describe the inactivation of the SARS-CoV-2 by using ultraviolet (UV) light in the ducts or in the rooftop units. Enough UV radiation is provided to "inactivate the SARS-CoV-2 viruses by photochemical disruption of viral RNA upon absorbing UV photons" [Harmon and Lau (2021)].

The UV lamps are generally placed in the duct where the recirculated air from the space mixes with the outdoor air inside the rooftop unit. Thus, the air flowing over the UV lamps is equivalent to the total airflow (outdoor air plus recirculated air) from the diffusers. However, the outdoor air is assumed to be free from contaminants (in this case SARS-CoV-2), and to account for the inactivation rate due to in-duct UV, only the recirculated air fraction is considered. The inactivation rate for SARS-CoV-2 due to in-duct UV can be calculated using equation (3 - 9) and involves two factors: the efficiency of the in-duct UV (η_{UVduct}) and the recirculation rate of air ($\lambda_{recirculation}$).

$$k_{UVduct} = \lambda_{recirculation} * \eta_{UVduct} \qquad (3 - 8)$$

This equation (3 - 9) is similar to equation (3 - 6) as the concept of inactivation is similar to both and involves inactivating SARS-CoV-2 from the air recirculated from the space.

The $\lambda_{recirculation}$ is to be determined from equation (3 - 7) and its value is in air changes per hour (ACH) which has a unit of 1/hr. The η_{UVduct} needs to be calculated as well for which equation (3 - 10) [Lau et al. (2009)] is used.

$$\eta_{UVduct} = 1 - S = 1 - e^{-kIt} \qquad (3 - 9)$$

where,

S is the survival fraction of the microbial population that was exposed to UV light,

k is the inactivation rate constant for SARS-CoV-2 (in $cm^2/\mu J$),

I is the irradiance from the UV lamp (in $\mu W/cm^2$),

t is the exposure time of air (in seconds).

In the meat processing plants, the UV lights used are lamp products from certain manufacturers who mention the irradiance of the lamp in the product specifications. The irradiance provided in the lamp specification is 180 $\mu W/cm^2$ and 4 of the lamps were installed per rooftop unit. Thus, a total irradiance of 720 $\mu W/cm^2$ should be produced from these lamps. However, as per the ASHRAE Handbook-HVAC Applications (2019), the irradiance or the overall performance of these UV lamps can be affected because of the placement of the UV fixtures, air velocity, or lamp/ballast characteristics such as the wind chill effect. Lau et al. (2012) established that a UV lamp when operated in crossflow movement of air with an air velocity of 4.92 ft/s and air temperature of 73.4 F, output generated around 80% of the peak output. For this research, it was assumed that the lamps performed at 80% of their output as well and thus the total irradiance generated from 4 of the UV lamps was (80% of 720 $\mu W/cm^2$) 576 $\mu W/cm^2$. This assumption was a rough estimate to account for the impact of wind chill [Lau et al. (2012)] and no necessary calculations or measurements were made to support this assumption.

The susceptibility parameter or the inactivation rate constant, k, is chosen as 0.002074 $cm^2/\mu J$ [Harmon and Lau (2021)].

The calculation of exposure time, t, requires three other parameters as shown in equation (3 - 11).

$$t = \frac{\text{"Effective" distance in feet}}{\text{Airspeed in fpm}} * 60 = \frac{\text{"Effective" distance in feet} * \text{Duct Area}}{\text{Total airflow in cfm}} * 60 \qquad (3 - 10)$$

The “effective” distance in feet is the irradiance zone of the UV lamps along the duct length. This “effective” distance was assumed to be 1 foot in either direction of the UV lamps because as per common practices, the placement of the UV fixtures should be in such a way that it can achieve at least 2 feet of irradiation zone [Martin et al. (2008)]. The duct area was measured in square feet during the site visits and the total airflow in cubic feet per minute (cfm) is available from Test B. It is to be noted that the total airflow was selected for calculating the exposure time since the total air is flowing across the surfaces of the UV lamps [VanOsdell and Foarde (2002)] even though the recirculating air (as explained previously) is considered for inactivation rate.

An example of the calculation of k_{UVduct} is provided in Table 3 - 2.

Table 3 - 2 : Example of calculating k_{UVduct}

Variables	**Values**	**Units**
Irradiance, I	576	$\mu W/cm^2$
‘k' for Sars-Cov-2	0.002074	$cm^2/\mu J$
Duct area	9	ft^2
Airflow	2540	cfm
“Effective” distance	2	feet
Exposure time, t	0.42519	secs
η_{UVduct}	0.39819	

$\lambda_{recirculation}$	1.89142	1/hr
$\boldsymbol{k_{UVduct}}$	0.753161	1/hr

Upper room UVGI inactivation removal factor - $\boldsymbol{k_{UVGI}}$

UVGI stands for Ultraviolet germicidal irradiation. The upper room UVGI is another use of ultraviolet light in the form of lamp fixtures either installed on walls or hung from ceilings. The upper portion of the room is irradiated while the occupied zone is shielded from UV radiations [Martin et al. (2008)].

The meat processing plants did not have any installed upper room UVGI. However, the use of upper room UVGI has been proven very effective in inactivating different pathogens [Harmon and Lau (2021)] and was included in the Wells-Riley equation to show its effect on reducing the probability of airborne infection. The effectiveness of these systems varies with different configurations such as air mixing, UVGI irradiance, airflow movement, relative humidity, and temperature [CDC (2009)]. The most influential factor among the above may be the airflow movement for the speed at which the pathogens are carried to the upper room irradiation region as well as the exposure time of these pathogens in the irradiated zone [Harmon and Lau (2021)]. However, this research model is based on the assumption that the room is in well-mixed conditions.

The upper zone irradiance recommended in NIOSH guidelines [National Institute for Occupational Safety and Health (NIOSH) 2009] should be within the range of 30 to 50 μW/cm^2 to inactivate pathogens. The modeled values of irradiance often fall short of this mentioned range because irradiance value depends upon the room parameters, the layout of fixtures, the total number of lamps used, and lamp wattages [Miller et al. (2002); Mphaphlele et al. (2015)]. And in order to account for these factors, the average effective irradiance for the whole room can be evaluated by simply multiplying the average irradiance of the upper zone by the ratio of upper room volume to total room volume [Harmon and Lau (2021)].

The k_{UVGI} can be calculated by simply multiplying the average irradiance produced by the upper room UVGI system (E) with the ratio of upper room volume to total room volume and SARS-CoV-2's susceptibility parameter (Z) [Harmon and Lau (2021)]. Equation (3 - 12) helps in calculating the inactivation rate for the upper air UVGI system, k_{UVGI} and its unit is 1/hr.

$$k_{UVGI} = E * Z * \frac{Upper\ room\ volume}{Total\ room\ volume} = E * Z * \frac{Room\ height - Height\ of\ UVGI\ mounting}{Room\ height} \quad (3 - 11)$$

The susceptibility parameter or the inactivation rate constant for SARS-CoV-2, Z, is selected as 0.002074 $cm^2/\mu J$ [Harmon and Lau (2021)]. The average upper zone irradiance (E) was chosen from Table 7 of Miller et al. (2002) which listed the average irradiance measured in the upper zone of a space. The space was assumed to have a total of 4 lamps operating in 4 corners while the center had 2 lamp fixtures operating and all these lamps had a power rating of 108 W. Thus, for proceeding with calculations of k_{UVGI}, the average upper zone irradiance (E) was chosen as 20 $\mu W/cm^2$ as per the above configuration from Table 7 [Miller et al. (2002)].

An example of the calculation of k_{UVGI} is provided in Table 3 - 3.

Table 3 - 3 : Example of calculating k_{UVGI}

Variables	**Values**	**Units**
Upper zone average Irradiance, E	20	μW/cm^2
‘Z' for Sars-Cov-2	0.002074	cm^2/μJ
Room height	14	ft
UVGI mounting height	12	ft
$\boldsymbol{k_{UVGI}}$	21.32743	1/hr

Portable air cleaner removal factor - $\boldsymbol{\lambda_{aircleaner}}$

Portable air cleaners are used to provide an additional layer of filtration and ventilation as it cleans the ambient air to deliver better indoor air quality. Each of the portable air cleaners has manufacturer-specified clean air delivery rate (CADR) values along with the respective room sizes it should operate in. The unit of CADR is generally provided in cubic feet per minute (cfm) [Kirkman et al. (2020)]. The three CADR values that are specified by each of the manufacturers are smoke, dust, and pollen. Since the size of SARS-CoV-2 droplets or aerosols is more similar to the sizes of smoke and dust, the $\lambda_{aircleaner}$ calculations would consider the average CADR values of smoke and dust [Harmon and Lau (2021)].

The portable air cleaner removal rate, $\lambda_{aircleaner}$ can be calculated using equation (3 - 13) and its unit is 1/hr.

$$\lambda_{aircleaner} = \frac{No.of\ cleaners * CADR\ (in\ cfm) * 60}{Volume\ in\ cubic\ feet} \qquad (3 - 12)$$

For the meat processing plants, no information was available on the specifications of the air cleaners used. But in order to show its effectiveness in reducing the probability of infection, Table 1 of Kirkman et al. (2020) is referred and a random portable air cleaner model is selected. The chosen portable air cleaner model is ‘Oransi EJ120’ which uses activated carbon and HEPA (High-Efficiency Particle Arresting) filter, and the recommended room size is 500 square feet of area. The number of air cleaners would depend upon the area of the room to be served and can be obtained by dividing the total room area by the recommended room area. As shown in Table 3 - 4, the recommended area is 500 square feet and since the room area is 4236 square feet, the number of air cleaners required would be approximately 8. The smoke CADR is 323 and Dust CADR is 332. Thus, the corresponding CADR value for SARS-CoV-2 should be the average of 323 and 332 i.e., 327.5.

An example of the calculation of $\lambda_{aircleaner}$ is provided in Table 3 - 4.

Table 3 - 4 : Example of calculating $\lambda_{aircleaner}$

Variables	**Values**	**Units**
SARS-CoV-2 CADR	327.5	cfm
Room area	4236	ft^2
Room height	14	ft
Recommended room area for ‘Oransi EJ120’	500	ft^2
No. of portable air cleaners required	8	
Room volume	59306	ft^3

$\lambda_{aircleaner}$	2.650659	1/hr

Mask removal factor - k_{mask}

Masks have been widely used in the SARS-CoV-2 pandemic. Masks have the capability to prevent big droplets as well as restrict a fraction of airborne infectious aerosols from entering into an individual when the individual is wearing a mask during the process of inhalation. Different masks are designed differently and the masks can be made of different materials as well as the masks would vary in tightness around the edges and can have leakages. These factors lead differently manufactured masks to have different efficiency of filtering out particles [Harmon and Lau (2021)]. The mask efficiency could act differently for two different scenarios, one for the infected person and the other for the non-infected person.

Mask removal factor for non-infected individuals

The mask removal factor for non-infected is calculated using the equation (3 - 14). The mask removal factor for non-infected has a unit of 1/hr.

$$Non-infected\ mask\ removal\ factor\ = \left(\frac{1.2\ cfm*\%non-infected\ wearing\ mask*no.of\ non-infected*\frac{60\ min}{hr}}{Volume\ in\ cubic\ feet}\right) * mask\ efficiency$$

(3 - 13)

The equation (3 - 14) takes into account the percentage of non-infected individuals wearing masks, the mask efficiency as well as the number of non-infected individuals present in the space. It also considers an estimated breathing-generated air change rate of 1.2 cubic feet per minute (cfm) across the individual's mask and this rate is representative of the respiration of the individual at rest [Harmon and Lau (2021)]. The research assumed the respiration rate of 1.2 cfm for all individuals as a conservative measure.

Mask removal factor for infected individuals

The mask removal factor for infected individuals is calculated using the equation (3 - 15). If an infected individual is wearing a mask, it means that the source of generating infectious aerosols is reduced and thus mask removal factor for infected individuals is stated as source reduction [Harmon and Lau (2021)].

$$Source\ reduction = \%\ Infected\ wearing\ mask * mask\ efficieny \qquad (3 - 14)$$

The equation (3 - 15) takes into account the percentage of infected individuals wearing masks and the mask efficiency. This term, $Source\ reduction$, is normalized in the sense that it is not time-dependent and would have the same value for a second or for an hour. The unit used here is 1/hr.

Ultimately, the mask removal factor, k_{mask} can be obtained by adding the source reduction and non-infected mask removal factor as shown in equation (3 - 16).

$$k_{mask} = Non - infected\ mask\ removal\ factor + Source\ reduction \qquad (3 - 15)$$

For the meat processing plant, it is assumed that everyone is wearing a mask and it is the same type of mask for everyone, i.e., a 2-layer woven nylon mask with ear loops along with an aluminum nose bridge. As an example, to demonstrate the calculation for k_{mask}, a room having 300 occupants is considered. 10% of them are infected, i.e., 30 individuals. The number of non-infected individuals is 270. The room volume is 58464 ft^3. The calculation of k_{mask} with the above parameters is provided in Table 3 - 5.

Table 3 - 5 : Example of calculating k_{mask}

Variables	**Values**	**Units**
Total occupants	280	
Infective occupants	28	
Non-infected occupants	252	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	58464	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.174724	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.737724	1/hr

Adjusted vaccination factor - $v_{adjusted}$

SARS-CoV-2 virus caused the spread of Covid-19 (coronavirus disease 2019) worldwide in a rapid pace and there are no known cures for the virus and only vaccines can stop the spread of the virus [Cai et al. (2021)].

There is still a lot of ongoing research regarding the efficacy of the vaccines and including the various available vaccine efficiencies would have been difficult in this research's model. Also, there was no available information on the workers of the meat processing plants if they were vaccinated with a single dose, double dose, or booster dose. Thus, a simple hypothetical situation is imagined where everyone is vaccinated, and the vaccine efficiency is the average of the highest vaccination efficiency and the lowest vaccine efficiency. As per Cai et al. (2021), the lowest vaccine efficiency is 70% whereas the highest vaccine efficiency is 94.29%. Thus, the average value of 82.145% is considered as the vaccine efficiency.

The adjusted vaccination factor, $v_{adjusted}$ can be calculated using equation (3 - 17).

$$v_{adjusted} = 1 - (\%\ of\ vaccinated\ individuals * vaccine\ efficieny) \quad (3 - 16)$$

3.3.1 Example to calculate the probability of airborne infection from SARS-CoV-2

Different scenarios are imagined (discussed in the next section) which use different parameters, and their respective probabilities of infections are compared. But for now, a space, Cafeteria 1 Site A, from the three meat processing plants is randomly selected to demonstrate the method of calculating all the above variables. The calculations shown here demonstrate the probability of infection for an ideal situation in which all the factors are involved including vaccination. The parameters used here represent the ideal settings of Cafeteria 1 Site A in which this space should be operating to minimize the probability of airborne infection from SARS-CoV-2. Table 3 - 6 shows the values of the variables with their assumptions.

Table 3 - 6 : Example of calculating probability of airborne infection using Wells-Riley method.

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)

p	0.120625	m^3/hr	Adult average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	2.926929	1/hr	ASHRAE Std. 62.1 (2019) ventilation rate
$k_{filtration}$	4.580357	1/hr	Design recirculation value of 5.264778 ACH and MERV 13
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0.785598	1/hr	Design recirculation value of 5.264778 ACH and η_{UVduct} calculated in Table 3 - 7
k_{UVGI}	21.32743	1/hr	Calculations shown in Table 3 - 3
$\lambda_{aircleaner}$	2.688834	1/hr	Calculations shown in Table 3 - 8
k_{mask}	0.737724	1/hr	Calculations shown in Table 3 - 5
$v_{adjusted}$	0.17855	-	All occupants vaccinated and average vaccination efficiency is 82.145%
Probability of infection, *P*	**0.002842**		Solved using equation (3 - 3)

Table 3 - 7 : Calculating η_{UVduct} for Cafeteria 1 Site A example.

Variables	Values	Units

Irradiance, I	576	μW/cm^2
‘k' for Sars-Cov-2	0.002074	cm^2/μJ
Duct area	9	ft^2
Airflow	7982	cfm
“Effective” distance	2	feet
Exposure time, t	0.135304	secs
$\boldsymbol{\eta_{UVduct}}$	0.149218	

Table 3 - 8 : Calculating $\lambda_{aircleaner}$ for Cafeteria 1 Site A example.

Variables	**Values**	**Units**
SARS-CoV-2 CADR	327.5	cfm
Room area	4176	ft^2
Room height	14	ft
Recommended room area for ‘Oransi EJ120’	500	ft^2
No. of portable air cleaners required	8	
Room volume	58464	ft^3
$\lambda_{aircleaner}$	2.68883	1/hr

As previously mentioned in the equation used section, the term $k_{settling}$ has been ignored for all spaces when calculating the probability of infection. Firstly, the term $k_{settling}$ has been defined below and the process of calculating it has been explained. Then, a few variations are shown as well as why it was ignored.

Settling removal factor- $k_{settling}$

The rate of the viral aerosols settling due to gravity is considered the settling removal factor. Small droplets/aerosols float by the ambient flow of air. However, the large droplets/aerosols are highly influenced by the relative humidity. Low relative humidity would make droplets evaporate faster which would thereby keep the aerosols suspended in the air for longer times. Also, higher temperatures would slow down the settling velocity as it increases the dynamic viscosity of air. The dynamic viscosity of air is considered for a pressure setting of 1 atmosphere and temperature of 72.5 F. This consideration is done because the dynamic viscosity of air does not significantly differ for the operational temperature ranges used in a space, i.e., 68 F to 76 F [Harmon and Lau (2021)].

In order to calculate $k_{settling}$, settling velocity needs to be determined as well using equation (3 - 18) [Chakraborti and Kaur (2014)].

$$Settling\ velocity = \frac{g*\rho*{D_{eq}}^2}{18*\mu} \qquad (3 - 17)$$

where,

g = acceleration due to gravity, 9.8 m/s^2,

ρ = particle density (in kg/m^3),

D_{eq} = equilibrium particle diameter (in µm),

μ = dynamic viscosity of air (in kg/m.s)

The initial particle diameter is selected from Table 3 of Harmon and Lau (2021) and for the cases of a meat processing plant, it is expected that the closest representation of an expiratory event by a worker would be that of breathing. Thus, the breathing average is considered, and the value of the initial particle diameter is selected as 1.4 µm. The ratios of equilibrium particle diameter to initial particle diameter at different relative humidity levels are provided in Table 4 of Harmon and Lau (2021) from which Table 3 - 9 is created as per the range of relative humidity the meat processing plant may have.

Table 3 - 9 : Average D_{eq}/D_i ratios at respective relative humidity levels

Relative humidity %	**Average D_{eq}/D_i ratios**
30%	0.409
40%	0.413
50%	0.424
60%	0.432

So, for example, if the relative humidity of 30% is considered, then the D_{eq}/D_i the ratio is 0.409 and D_{eq} is obtained by multiplying 0.409 to 1.4 µm.

Dynamic viscosity of air at 72.5 F and 1 atmospheric pressure equals 0.00001837 kg/(m.s). The particle density of SARS-CoV-2 is considered as 1350 kg/m^3 [Wang et al. (2020)]. The $k_{settling}$ is to be calculated using the equation (3 - 19).

$$k_{settling} = \frac{Settling\ velocity}{Height\ of\ room} \qquad (3 - 18)$$

Four different values for relative humidity were considered and the $k_{settling}$ values were calculated as shown in Table 3 - 10, Table 3 - 11, Table 3 - 12, and Table 3 - 13.

Table 3 - 10 : $k_{settling}$ value when RH is 30%

Variables	**Values**	**Units**
Dynamic viscosity of air, μ	0.000018325	kg/m.s
Initial Particle Diameter, D_i	1.4	µm
D_{eq}	0.5726	µm
g	9.8	m/s^2
ρ	1350	kg/m^3
Settling velocity	1.31506E-05	m/s
Height of room	4.27	m
$\boldsymbol{k_{settling}}$	0.011087169	1/hr

Table 3 - 11 : $k_{settling}$ value when RH is 40%

Variables	**Values**	**Units**
Dynamic viscosity of air, μ	0.000018325	kg/m.s
Initial Particle Diameter, D_i	1.4	µm
D_{eq}	0.5782	µm
g	9.8	m/s^2
ρ	1350	kg/m^3
Settling velocity	1.34091E-05	m/s
Height of room	4.27	m
$\boldsymbol{k_{settling}}$	0.011305093	1/hr

Table 3 - 12 : $k_{settling}$ value when RH is 50%

Variables	**Values**	**Units**
Dynamic viscosity of air, μ	0.000018325	kg/m.s
Initial Particle Diameter, D_i	1.4	µm
D_{eq}	0.5936	µm
g	9.8	m/s^2
ρ	1350	kg/m^3
Settling velocity	1.41329E-05	m/s
Height of room	4.27	m
$\boldsymbol{k_{settling}}$	0.011915322	1/hr

Table 3 - 13 : $k_{settling}$ value when RH is 60%

Variables	**Values**	**Units**
Dynamic viscosity of air, μ	0.000018325	kg/m.s
Initial Particle Diameter, D_i	1.4	µm
D_{eq}	0.6048	µm
g	9.8	m/s^2
ρ	1350	kg/m^3
Settling velocity	1.46712E-05	m/s
Height of room	4.27	m
$\boldsymbol{k_{settling}}$	0.012369198	1/hr

Thus, for breathing respiratory event, $k_{settling}$ values range from 0.011087169 1/hr to 0.012369198 1/hr for a relative humidity range of 30% to 60%.

The $k_{settling}$ variable depends upon temperature, relative humidity, respiratory event, and particle density of SARS-CoV-2. There is not enough evidence of particle densities of SARS-CoV-2 with temperature and relative humidity. The respiratory event of breathing influences the initial particle diameter which in turn changes the equilibrium diameter as well and it is not expected for a worker to only breathe all the time in a space as the worker might speak loudly, cough, or sneeze as well. The different respiratory events will change the calculations for $k_{settling}$. It is also not expected of the worker to speak, sneeze, or cough for the entire duration of their stay. Moreover, the values of $k_{settling}$ are quite low compared to the other removal factors calculated in Table 3 - 6 and thus, $k_{settling}$ was neglected. Arguably, k_{RH} has a lower value than $k_{settling}$, but the assumptions and calculations for k_{RH} are not that complex.

3.3.2 Limitations of the Wells-Riley model used

There are a few limitations of the Wells-Riley model used as there are assumptions made while forming this model. These limitations are specific to the use of the model in this research and the model might be modified to account for some of the limitations.

The biggest limitation would be that it only considers the airborne infection risk alone and ignores any other contact route. Also, since one of the assumptions of the model is that the room is well-mixed, this infers that the viral aerosols are evenly distributed in the space and the probability of infection calculated reflects the space's average value [Harmon and Lau (2021)]. However, the literature review on the Wells-Riley model suggests that the spatial distribution for the probability of infection can vary significantly. The other assumption, stating that an individual is considered infected if the person's pathogen intake is one or more than one; and that all the inhaled viral particles are deposited successfully, might not be accurate as well.

The model does not accommodate variations of pulmonary ventilation or activity levels for more than one infected individual. For example, if out of three infected individuals, two of them have heavy activity levels and one has a light activity level, the model cannot accommodate the different activity levels. The model will probably select activity level for the higher percentage of individuals. The other limitation would be assuming the temperature to be within the interior temperature range of 68 F to 76 F. If a space is operated at higher or lower temperatures, model accuracy can be affected.

Also, only one mask type has been considered for everyone which may not be true in a real scenario. The vaccination efficiency is just used to demonstrate how the vaccine would help in reducing the probability of infection and needs future work to accommodate for an accurate efficiency number.

3.4 Results of risk analysis

3.4.1 Analysis of probability of airborne infection based on individual spaces

The Wells-Riley model will be used to analyze the associated probability of airborne infection from SARS-CoV-2 for two different spaces under different scenarios. Cafeteria 1 and Locker 1 from Site A are randomly selected to demonstrate these probabilities of infections. Both these rooms had similar structures except for the number of occupants in them and the fact that Locker 1 consisted of all women because it was a women's locker room. The occupancy was almost double for Locker 1. All of the variables listed in equation (3 - 3) have been used for calculating the probabilities of infections.

The World Health Organization (WHO) declared COVID-19 as a global pandemic on March 11, 2020 [CDC (2021)]. The tests conducted or the experimental measurements were done in the time period from April to September 2021. Most of the meat processing plants had already implemented mask mandates and various engineering strategies by the time the tests were conducted for measurements. For this research, the risk analysis would also be performed for the scenario before the onset of the pandemic as well as the risk analysis for the scenario when the experiments were conducted (described here as the 'actual' scenario). The scenarios that have been studied refer to Site A and are explained below :

i) Pre-Covid

This scenario refers to the settings prevailing inside Site A before the pandemic. It was learned from the administration team that Site A did not have any ultraviolet installations in their rooftop unit's duct nor any upper air ultraviolet light installations. There was no use of air cleaners. None of the workers wore a mask or were vaccinated. Thus, these variables k_{UVduct}, k_{UVGI}, $\lambda_{aircleaner}$, k_{mask} had a value of 0 and $v_{adjusted}$ had a value of 1. For the scenario 'Pre-Covid', the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 14 for Cafeteria 1 Site A and Table 3 - 15 for Locker 1 Site A.

Table 3 - 14 : Airborne infection probability for 'Pre-Covid' scenario for Cafeteria 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)
p	0.120625	m^3/hr	Adult average, moderate activity
s	1	-	No occupant wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	0.715312	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	0.8322248	1/hr	Measured recirculation value of 1.89142 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0	1/hr	No use of UV in ducts
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0	1/hr	No occupant wearing mask
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.54321**		Solved using equation (3 - 3)

Table 3 - 15 : Airborne infection probability for 'Pre-Covid' scenario for Locker 1 Site A

Variable	**Value**	**Unit**	**Assumption**

q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	1	-	No occupant wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	0.380399	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.476808	1/hr	Measured recirculation value of 5.62911 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0	1/hr	No use of UV in ducts
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0	1/hr	No occupant wearing mask
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.50364**		Solved using equation (3 - 3)

For the scenario, ‘Pre-Covid’, Site A’s Cafeteria 1 has an airborne infection probability of 54.32% while Site A’s Locker 1 has an airborne infection probability of 50.36%.

ii) Actual

This scenario refers to the actual settings prevailing inside Site A when the Tests were conducted. It was learned from the administration team that Site A installed ultraviolet light in their rooftop unit's duct. There was still no use of air cleaners. All the workers wore a mask but were considered unvaccinated due to lack of data. Thus, for this scenario k_{UVGI}, and $\lambda_{aircleaner}$ had a value of 0 and $v_{adjusted}$ had a value of 1. For the scenario, 'Actual', the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 16 for Cafeteria 1 Site A and Table 3 - 17 for Locker 1 Site A.

Table 3 - 16 : Airborne infection probability for 'Actual' scenario for Cafeteria 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)
p	0.120625	m^3/hr	Adult average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	0.715312	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	0.832225	1/hr	Measured recirculation value of 1.89142 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%

k_{UVduct}	0.753161	1/hr	Measured recirculation value of 1.89142 ACH and η_{UVduct} calculated in Table 3 - 2
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.737724	1/hr	Calculations shown in Table 3 - 5
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.16009**		Solved using equation (3 - 3)

Table 3 - 17 : Airborne infection probability for 'Actual' scenario for Locker 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	0.380399	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.476808	1/hr	Measured recirculation value of 5.629110 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%

k_{UVduct}	1.098759	1/hr	Measured recirculation value of 5.629110 ACH and η_{UVduct} calculated in Table 3 - 18
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.932093	1/hr	Calculations shown in Table 3 - 19
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.16386**		Solved using equation (3 - 3)

Table 3 - 18 : ‘Actual’ scenario’s Locker 1 Site A calculations for η_{UVduct}

Variables	**Values**	**Units**
Irradiance, I	576	$\mu W/cm^2$
‘k' for Sars-Cov-2	0.002074	$cm^2/\mu J$
Duct area	9	ft^2
Airflow	5940	cfm
“Effective” distance	2	feet
Exposure time, t	0.18182	secs
$\boldsymbol{\eta_{UVduct}}$	**0.19519**	

Table 3 - 19 : ‘Actual’ scenario’s Locker 1 Site A calculations for k_{mask}

Variables	**Values**	**Units**

Total occupants	600	
Infective occupants	60	
Non-infected occupants	540	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	59306	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.369093	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.932093	1/hr

For the scenario, 'Actual', Site A's Cafeteria 1 has an airborne infection probability of 16.01% while Site A's Locker 1 has an airborne infection probability of 16.39%.

iii) Filtration enhancement

This scene is a modified version of the 'Actual' scenario, with just the filters being upgraded from MERV 7 to MERV 13. MERV 7 has an efficiency of 44% and MERV 13 has an efficiency of 87%. This scenario will provide the change in airborne infection probability only by enhancing the filters used. For the scenario 'Filtration enhancement', the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 20 for Cafeteria 1 Site A and Table 3 - 21 for Locker 1 Site A.

Table 3 - 20 : Airborne infection probability for ‘Filtration enhancement’ scenario for Cafeteria 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)
p	0.120625	m^3/hr	Adult average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	0.715312	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	1.645535	1/hr	Measured recirculation value of 1.89142 ACH and MERV 13
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0.753161	1/hr	Measured recirculation value of 1.89142 ACH and η_{UVduct} calculated in Table 3 - 2
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.737724	1/hr	Calculations shown in Table 3 - 5
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.12859**		Solved using equation (3 - 3)

Table 3 - 21 : Airborne infection probability for 'Filtration enhancement' scenario for Locker 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	0.380399	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	4.897326	1/hr	Measured recirculation value of 5.629110 ACH and MERV 13
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	1.098759	1/hr	Measured recirculation value of 5.629110 ACH and η_{UVduct} calculated in Table 3 - 18
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.932093	1/hr	Calculations shown in Table 3 - 19
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.11281**		Solved using equation (3 - 3)

For the scenario 'Filtration enhancement', Site A's Cafeteria 1 has an airborne infection probability of 12.86% while Site A's Locker 1 has an airborne infection probability of 11.28%.

iv) Air cleaner use

This scene is also a modified version of the 'Actual' scenario, with just the use of air cleaners. This scenario will provide the change in airborne infection probability on the use of air cleaners. For the scenario 'Air cleaner use', the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 22 for Cafeteria 1 Site A and Table 3 - 23 for Locker 1 Site A.

Table 3 - 22 : Airborne infection probability for 'Air cleaner use' scenario for Cafeteria 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)
p	0.120625	m^3/hr	Adult average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	0.715312	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	0.832225	1/hr	Measured recirculation value of 1.89142 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%

k_{UVduct}	0.753161	1/hr	Measured recirculation value of 1.89142 ACH and η_{UVduct} calculated in Table 3 - 2
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	2.688834	1/hr	Calculations shown in Table 3 - 8
k_{mask}	0.737724	1/hr	Calculations shown in Table 3 - 5
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.08842**		Solved using equation (3 - 3)

Table 3 - 23 : Airborne infection probability for ‘Air cleaner use’ scenario for Locker 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	0.380399	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.476808	1/hr	Measured recirculation value of 5.629110 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%

k_{UVduct}	1.098759	1/hr	Measured recirculation value of 5.629110 ACH and η_{UVduct} calculated in Table 3 - 18
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	2.650659	1/hr	Calculations shown in Table 3 - 4
k_{mask}	0.932093	1/hr	Calculations shown in Table 3 - 19
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.10957**		Solved using equation (3 - 3)

For the scenario 'Air cleaner use', Site A's Cafeteria 1 has an airborne infection probability of 8.84% while Site A's Locker 1 has an airborne infection probability of 10.96%.

v) Ventilation enhancement

This scene is also a modified version of the 'Actual' scenario, with the use of standard ventilation rates and design total airflow rates. ASHRAE Std. 62.1 (2019) is used, as explained in the experimental results section, to calculate the air changes per hour required for the spaces. The design total airflow rate is provided by the administration team. This scenario will provide the change in airborne infection probability by enhancing ventilation rates. For the scenario 'Ventilation enhancement', the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 24 for Cafeteria 1 Site A and Table 3 - 25 for Locker 1 Site A.

Table 3 - 24 : Airborne infection probability for 'Ventilation enhancement' scenario for Cafeteria 1 Site A

Variable	Value	Unit	Assumption
q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)
p	0.120625	m^3/hr	Adult average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	2.926929	1/hr	ASHRAE Std. 62.1 (2019) ventilation rate
$k_{filtration}$	2.316502	1/hr	Design recirculation value of 5.264778 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0.785598	1/hr	Design recirculation value of 5.264778 ACH and η_{UVduct} calculated in Table 3 - 7
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.737724	1/hr	Calculations shown in Table 3 - 5
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.07537**		Solved using equation (3 - 3)

Table 3 - 25 : Airborne infection probability for 'Ventilation enhancement' scenario for Locker 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	3.316359	1/hr	ASHRAE Std. 62.1 (2019) ventilation rate
$k_{filtration}$	2.984723	1/hr	Design recirculation value of 6.783462 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0.822215	1/hr	Design recirculation value of 6.783462 ACH and η_{UVduct} calculated in Table 3 - 26
k_{UVGI}	0	1/hr	No use of upper air UVGI
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.932093	1/hr	Calculations shown in Table 3 - 19
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.10291**		Solved using equation (3 - 3)

Table 3 - 26 : Calculating η_{UVduct} for Locker 1 Site A.

Variables	Values	Units
Irradiance, I	576	μW/cm^2
‘k' for Sars-Cov-2	0.002074	cm^2/μJ
Duct area	9	ft^2
Airflow	9983	cfm
“Effective” distance	2	feet
Exposure time, t	0.108184	secs
η_{UVduct}	0.121209	

For the scenario ‘Ventilation enhancement’, Site A’s Cafeteria 1 has an airborne infection probability of 7.54% while Site A’s Locker 1 has an airborne infection probability of 10.29%.

vi) UVGI use

This scenario is also a modified version of the ‘Actual’ scenario, with the installations of upper air ultraviolet systems. This scenario will provide the change in airborne infection probability on the use of upper air ultraviolet germicidal irradiation (UVGI). For the scenario ‘UVGI use’, the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 27 for Cafeteria 1 Site A and Table 3 - 28 for Locker 1 Site A.

Table 3 - 27 : Airborne infection probability for ‘UVGI use’ scenario for Cafeteria 1 Site A

Variable	Value	Unit	Assumption

q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)
p	0.120625	m^3/hr	Adult average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	0.715312	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	0.832225	1/hr	Measured recirculation value of 1.89142 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0.753161	1/hr	Measured recirculation value of 1.89142 ACH and η_{UVduct} calculated in Table 3 - 2
k_{UVGI}	21.32743	1/hr	Calculations shown in Table 3 - 3
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.737724	1/hr	Calculations shown in Table 3 - 5
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.02153**		Solved using equation (3 - 3)

Table 3 - 28 : Airborne infection probability for 'UVGI use' scenario for Locker 1 Site A

Variable	**Value**	**Unit**	**Assumption**

q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	0.380399	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.476808	1/hr	Measured recirculation value of 5.629110 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	1.098759	1/hr	Measured recirculation value of 5.629110 ACH and η_{UVduct} calculated in Table 3 - 18
k_{UVGI}	21.32743	1/hr	Calculations shown in Table 3 - 3
$\lambda_{aircleaner}$	0	1/hr	No air cleaners used
k_{mask}	0.932093	1/hr	Calculations shown in Table 3 - 19
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.03282**		Solved using equation (3 - 3)

For the scenario ‘UVGI use’, Site A’s Cafeteria 1 has an airborne infection probability of 2.15% while Site A’s Locker 1 has an airborne infection probability of 3.28%.

vii) Ideal

This scenario refers to the ideal situation when all of the above engineering strategies are used together. This means that the space should have occupants using masks, enhanced filtration, use of cleaners, proper ventilation, and upper air UVGI systems installed. Ideally, every occupant should be vaccinated as well but due to lack of vaccine efficiency data the research team is treating 'Vaccination' as a separate scenario for now. For the scenario 'Ideal', the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 29 for Cafeteria 1 Site A and Table 3 - 30 for Locker 1 Site A.

Table 3 - 29 : Airborne infection probability for 'Ideal' scenario for Cafeteria 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	28	-	10% of 280 (total occupants)
p	0.120625	m^3/hr	Adult average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1656	m^3	Provided by administration
$\lambda_{ventilation}$	2.926929	1/hr	ASHRAE Std. 62.1 (2019) ventilation rate
$k_{filtration}$	4.580357	1/hr	Design recirculation value of 5.264778 ACH and MERV 13
k_{RH}	0.00125	1/hr	Relative humidity of 30%

k_{UVduct}	0.785598	1/hr	Design recirculation value of 5.264778 ACH and η_{UVduct} calculated in Table 3 - 7
k_{UVGI}	21.32743	1/hr	Calculations shown in Table 3 - 3
$\lambda_{aircleaner}$	2.688834	1/hr	Calculations shown in Table 3 - 8
k_{mask}	0.737724	1/hr	Calculations shown in Table 3 - 5
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.01592**		Solved using equation (3 - 3)

Table 3 - 30 : Airborne infection probability for ‘Ideal’ scenario for Locker 1 Site A

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	3.316359	1/hr	ASHRAE Std. 62.1 (2019) ventilation rate
$k_{filtration}$	5.901612	1/hr	Design recirculation value of 6.783462 ACH and MERV 13

k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0.822215	1/hr	Design recirculation value of 6.783462 ACH and η_{UVduct} calculated in Table 3 - 26
k_{UVGI}	21.32743	1/hr	Calculations shown in Table 3 - 3
$\lambda_{aircleaner}$	2.650659	1/hr	Calculations shown in Table 3 - 4
k_{mask}	0.932093	1/hr	Calculations shown in Table 3 - 19
$v_{adjusted}$	1	-	No vaccinations available
Probability of infection, *P*	**0.02472**		Solved using equation (3 - 3)

For the scenario 'Ideal', Site A's Cafeteria 1 has an airborne infection probability of 1.59% while Site A's Locker 1 has an airborne infection probability of 2.47%.

viii) Vaccination

This scenario refers to the ideal situation explained above along with every occupant vaccinated. The average vaccination efficiency considered is 82.145% and every occupant is considered vaccinated. This scenario is a hypothetical situation imagined in order to understand the effect of vaccination since neither the vaccination details of workers nor the vaccination efficiencies are available at the point of these calculations. For the scenario, 'Vaccination', the airborne infection probability from SARS-CoV-2 is shown in Table 3 - 6 for Cafeteria 1 Site A and Table 3 - 31 for Locker 1 Site A.

Table 3 - 31 : Airborne infection probability for 'Vaccination' scenario for Locker 1 Site A

Variable	Value	Unit	Assumption
q	1190	quanta/hr	High shedder, moderate activity
I	60	-	10% of 600 (total occupants)
p	0.094166	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.5	hr	Observed from schedules
V	1679	m^3	Provided by administration
$\lambda_{ventilation}$	3.316359	1/hr	ASHRAE Std. 62.1 (2019) ventilation rate
$k_{filtration}$	5.901612	1/hr	Design recirculation value of 6.783462 ACH and MERV 13
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{UVduct}	0.822215	1/hr	Design recirculation value of 6.783462 ACH and η_{UVduct} calculated in Table 3 - 26
k_{UVGI}	21.32743	1/hr	Calculations shown in Table 3 - 3
$\lambda_{aircleaner}$	2.650659	1/hr	Calculations shown in Table 3 - 4
k_{mask}	0.932093	1/hr	Calculations shown in Table 3 - 19

$v_{adjusted}$	0.17855	-	All occupants vaccinated and average vaccination efficiency is 82.145%
Probability of infection, *P*	**0.00441**		Solved using equation (3 - 3)

For the scenario, 'Vaccination', Site A's Cafeteria 1 has an airborne infection probability of 0.28% while Site A's Locker 1 has an airborne infection probability of 0.44%.

The overall risk analysis results for Cafeteria 1 Site A and Locker 1 Site A are provided in Table 3 - 32 and Table 3 - 33 respectively.

Table 3 - 32 : Airborne infection probabilities for different scenarios for Cafeteria 1 Site A

Rank	**Scenarios**	**Estimated probability of airborne infection**
1	Vaccination	0.28%
2	Ideal	1.59%
3	UVGI use	2.15%
4	Ventilation enhancement	7.54%
5	Air cleaner use	8.84%
6	Filtration enhancement	12.86%
7	Actual	16.01%
8	Pre-Covid	54.32%

Table 3 - 33 : Airborne infection probabilities for different scenarios for Locker 1 Site A

Rank	**Scenarios**	**Estimated probability of airborne infection**
1	Vaccination	0.44%
2	Ideal	2.47%
3	UVGI use	3.28%
4	Ventilation enhancement	10.29%
5	Air cleaner use	10.96%
6	Filtration enhancement	11.28%
7	Actual	16.39%
8	Pre-Covid	50.36%

As evident from Table 3 - 32 and Table 3 - 33, the probability of airborne infection from SARS-CoV-2 can be significantly reduced. Ignoring the vaccination scenario, ideally, the probability of airborne infection from SARS-CoV-2 is reduced from 54.32% to 1.59% for Cafeteria 1 and from 50.36% to 2.47% in Locker 1. The use of upper air UVGI systems seems to be most effective in reducing the infection probability. The ventilation enhancement and use of portable air cleaners have almost similar effects and rightfully so because the portable cleaners also focus on delivering clean air to the space. The use of better filtration systems also brings down the airborne infection probabilities but may not be as effective as the other engineering strategies used here. It can be observed that the administration team of Site A has done quite well in bringing down the airborne infection probability from 54.32% in the pre-COVID scenario to 16.01% in the actual scenario for Cafeteria 1 and 50.36% in the pre-COVID scenario to 16.39% in the actual scenario. The reduction for the actual scenario is quite noteworthy and the administration team informed that the number of COVID-19 cases has reduced significantly since workers started wearing masks and ultraviolet lights were installed in the ducts to treat air. Wearing a mask increases the value of the mask removal factor, k_{mask} and decreases the value of the modified p scaling factor for masks, s and both in turn reduce the probability of airborne infection.

The risk analysis suggests that to reduce the probability of airborne infection from SARS-CoV-2, the administration team should ask the workers to wear masks, install upper air UVGI systems, use proper ventilation as per design standards, use portable air cleaners, enhance their filtration systems, and install in-duct ultraviolet lights. The probability of airborne infection is reduced by the use of any of the above and can be used in combination with each other as well.

3.4.2 Analysis of probability of airborne infection based on workers' schedule

The individual space risk analysis would provide the infection probability for a worker who would spend half an hour either in the locker room or the cafeteria. But in reality, the workers have a fixed schedule and they do not spend their entire shift in the locker or the cafeteria alone. Thus, this research further wanted to calculate the risk associated with a worker working in any of these meat processing plants for the entire day. This risk analysis was performed on the workers of the processing areas of Site C. With all the information gathered from Site C's administration team, the research team formed a hypothetical schedule and decided to perform a risk assessment for 1500 workers throughout their entire shift and see the changes in airborne infection probability from schedule changes and increased ventilation. Three different studies were conducted, Study I represents the actual settings with a typically followed schedule and measured ventilation, Study II represents a staggered schedule for all the workers with measured ventilation in spaces, and Study III demonstrates the use of enhanced ventilation along with a staggered schedule. Study I is the baseline study as it represents the original probability in the meat processing plant. Study II helps understand the advantage of using the administrative strategy of a staggered schedule. Study II provides inferences on the alternative way of mitigating airborne infections if an engineering solution is not applicable or available. Study III is the combination of using the administrative strategy of a staggered schedule and the engineering strategy of enhanced ventilation. Study III infers on the combined power of mitigating airborne infections when a combination of administrative strategies are used with engineering solutions.

The entire shift of the workers involves 4 spaces, namely men locker, women locker, cafeteria, processing area. All these spaces are of Site C and in the experimental results, men locker is referred to as Locker 4, women locker is defined as Locker 3, cafeteria is referred to as Cafeteria 5. Processing area was not involved in the experimental results as the research team did not have enough resources to carry out the required experiments, but the ventilation rates and total airflow involved in this risk analysis have been explained below. For simplicity and a better understanding of the risk analysis, the names of spaces used here are men locker, women locker, cafeteria, processing area. Also, since the use of different engineering strategies and their enhancements have already been demonstrated previously in the individual room analysis, the analysis based on schedule will omit some of them. The variables that would be ignored for these calculations are

k_{UVduct}, k_{UVGI}, $\lambda_{aircleaner}$ and $v_{adjusted}$. The schedule and the rest of the variables are explained in detail below.

The Site C processing area could not be measured for the ventilation rate and total airflow. However, to perform the risk analysis it was important to find out the actual and design ventilation rates of the Site C processing area. The Site C administration team was only able to provide that the design cfm for the processing area is 18000 cfm and since the research team was not able to measure for the outdoor air supply, it was assumed that 18000 cfm is the measured outdoor air. This might be an over-estimation of the supplied outdoor air but without any measurements, it would be unreasonable to underestimate the actual ventilation rate.

Site A's Processing Area 2 resembles to Site C's Processing Area and thus has been used here to deduce the design ventilation rates involved for the space. Site A's Processing Area 2 design ventilation information and total airflow, as provided by the administration team, is shown in Table 3 - 34. The cfm values are converted to their equivalent air changes per hour (ACH) using equation (3 - 5).

Table 3 - 34 : Design ventilation information for Site A Processing Area 2 provided by administration team

Units	**Design outdoor air**	**Recirculated air**	**Total airflow**
Cubic feet per minute (cfm)	30000	50000	80000
Air changes per hour (ACH)	9.51394	15.85657	25.37

It was assumed that the ACH values for Site C Processing Area were designed similarly. Thus, the design ventilation and total airflow for Site C is provided in Table 3 - 35.

Table 3 - 35 : Estimated design ventilation information for Site C Processing Area

Units	**Design outdoor air**	**Design Recirculated air**	**Design total airflow**
Air changes per hour (ACH)	9.51394	15.85657	25.37
Cubic feet per minute (cfm)	162271	270442	432713

Previously, it was assumed that 18000 cfm was the measured outdoor air, corresponding to 1.05534 ACH. It is also assumed that the processing area's total design airflow ACH of 25.37 does not change when measured and this corresponds to 432713 cfm. Thus, the measured ventilation and total airflow values are provided in Table 3 - 36.

Table 3 - 36 : Assumed measured ventilation information for Site C Processing Area

Units	**Measured outdoor air**	**Measured Recirculated air**	**Measured total airflow**
Air changes per hour (ACH)	1.05534	24.31466	25.37
Cubic feet per minute (cfm)	18000	414713	432713

As provided by the administration team, the design total airflow is 6 ACH for men locker, women locker, and cafeteria. The measured total airflow has been assumed to be 6 ACH as these spaces couldn't be measured for their total airflows. All the ventilation details, total airflow and room details have been provided for all the spaces in Table 3 - 37.

Table 3 - 37 : Details of parameters of Site C's men and women locker, cafeteria, and processing area

Space name	**Occupancy**	**Volume (ft^3)**	**Measured Outdoor air (ACH)**	**ASHRAE/ Design Outdoor air (ACH)**	**Design/ measured total airflow (ACH)**	**Filter Used**
Cafeteria	420	141680	0.31465	2.00861	6	MERV 7
Men Locker	823	52490	0.93618	5.06382	6	MERV 7
Women Locker	417	26350	0.88805	5.10740	6	MERV 7
Processing area	1500	1023366	1.05534	9.51394	25.37	MERV 13

The probability of airborne infection from SARS-CoV-2 can hereby be calculated for the mentioned schedules and the available information. The probabilities of 4 different spaces are calculated separately and then the overall scene's probability is calculated based on the weighted average population of individual spaces.

Study I

The schedule for Study I is shown in Figure 3 - 1. The table format of the schedule is also shown in Table A - 1 for a better understanding of the occupancy and time durations. A group of 1500 workers is selected since the processing area capacity is 1500 workers and the schedule is broken into a total of 10 scenes named from A-J. These workers enter the meat processing plants at two different timings. Scene A resembles the entry of 750 workers who enter at 5:30 AM and head toward their respective locker rooms. Scene B resembles the entry of the rest of the 750 workers into their locker rooms, while the workers who entered during Scene A enter the processing area at 5:45 AM. At 6 AM, all 1500 workers are in the processing area resembling Scene C. The lunch break starts at 9:00 AM when 400 of the workers visit the cafeteria for 15 minutes as shown in Scene D. These set of workers come back to the processing area and a new set of 400 workers take their break at 9:15 AM for Scene E. Then this is repeated for Scene F at 9:30 AM where 400 new workers replace them and, in the end, the remaining 300 workers for Scene G take their break at 9:45 AM. Scene H represents all 1500 workers back in the processing areas where they work for 5 hours. Lastly, similar to the shift start, the first set of 750 workers head back to their locker rooms at 3:00 PM denoting Scene I, and then the next set of workers enter their locker rooms at 3:15 PM for Scene J. At 3:30 PM, all 1500 workers ended their shifts and vacated those areas.

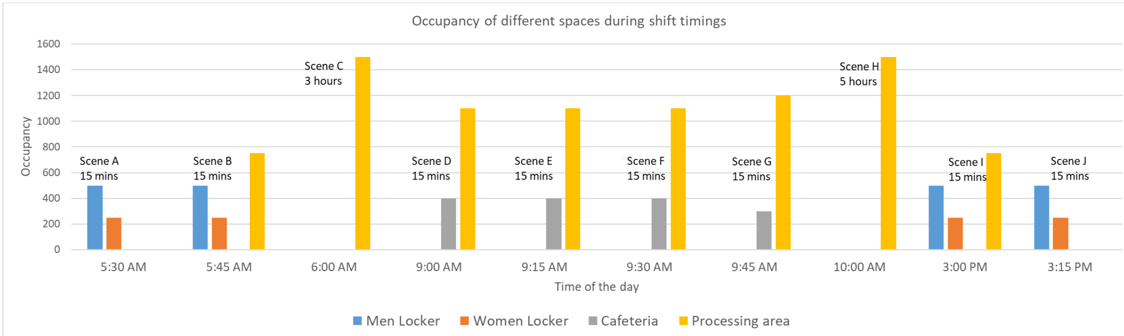


Figure 3 - 1 : The schedule formed for 1500 workers working in the processing area.

The calculations of Scene A would involve calculating the probability of infection for 500 workers in Men Locker and 250 workers in Women Locker for a time period of 15 mins. The Scene A's Men locker calculations are shown in Table 3 - 38 and Women Locker in Table 3 - 39. Scene A's probability of infection for cafeteria and processing area is 0, since there are no occupants in them for Scene A.

Table 3 - 38 : Airborne infection probability Scene A's men locker

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	50	-	10% of 500 (total occupants)
p	0.14708	m^3/hr	Male average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene A duration
V	1486	m^3	Provided by administration
$\lambda_{ventilation}$	0.93618	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.22808	1/hr	Measured recirculation value of 5.06382 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%

k_{mask}	0.91052	1/hr	Calculations shown in Table A - 2
Probability of infection, *P*	**0.14602**		Solved using equation (3 - 3)

Table 3 - 39 : Airborne infection probability Scene A's women locker

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	25	-	10% of 250 (total occupants)
p	0.09417	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene A duration
V	746	m^3	Provided by administration
$\lambda_{ventilation}$	0.88805	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.24926	1/hr	Measured recirculation value of 5.11195 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0.90913	1/hr	Calculations shown in Table A - 3
Probability of infection, *P*	**0.09639**		Solved using equation (3 - 3)

Thus, the overall probability of infection for Scene A is calculated using the weighted average of the population of 1500 workers. The occupancy fraction is calculated by equation (3 - 20) and overall probability is calculated by equation (3 - 21).

$$Occupancy\ fraction = \frac{Total\ occupants\ in\ space}{1500} \qquad (3 - 19)$$

$$Overall\ probability = \frac{(P_{ML}*OF_{ML})+(P_{WL}*OF_{WL})+(P_{CF}*OF_{CF})+(P_{PA}*OF_{PA})}{Total\ occupancy\ fraction} \qquad (3 - 20)$$

where,

P_{ML}= airborne infection probability of men locker,

P_{WL}= airborne infection probability of women locker,

P_{CF}= airborne infection probability of cafeteria,

P_{PA}= airborne infection probability of processing area,

OF_{ML}= Occupancy fraction of men locker,

OF_{WL}= Occupancy fraction of women locker,

OF_{CF}= Occupancy fraction of cafeteria,

OF_{PA}= Occupancy fraction of processing area,

$Total\ occupancy\ fraction$ = 1.

The total occupancy fraction is always 1 since the infection probability is determined for 1500 people at all times and thus, even if 1500 workers are not present inside the meat processing plant, the sample size still remains to be 1500 workers and the occupancy fraction becomes 1 (or 100%).

Scene A's overall probability calculation is shown in Table 3 - 40.

Table 3 - 40 : Scene A's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.14602	0.33333	**0.06474**
Women Locker	0.09639	0.16667	
Cafeteria	0	0	
Processing Area	0	0	

Similarly, Scene B-J are calculated for their airborne probability of infection from SARS-CoV-2. The calculations are listed in table formats and can be referred to using Table 3 - 41.

Table 3 - 41 : Table information for referring to calculations of Study I

Scene	**Men Locker**	**Women Locker**	**Cafeteria**	**Processing area**	**Overall probability**
Scene B	Same as Table 3 - 38	Same as Table 3 - 39	NA	Table A - 4	Table A - 6
Scene C	NA	NA	NA	Table A - 7	Table A - 9
Scene D	NA	NA	Table A - 10	Table A - 11	Table A - 13
Scene E	NA	NA	Same as Table A - 10	Same as Table A - 11	Same as Table A - 13

Scene F	NA	NA	Same as Table A - 10	Same as Table A - 11	Same as Table A - 13
Scene G	NA	NA	Table A - 14	Table A - 15	Table A - 17
Scene H	NA	NA	NA	Table A - 18	Table A - 19
Scene I	Same as Table 3 - 38	Same as Table 3 - 39	NA	Same as Table A - 4	Same as Table A - 6
Scene J	Same as Table 3 - 38	Same as Table 3 - 39	NA	NA	Same as Table 3 - 40

Table 3 - 42 : Probabilities of different spaces and the scenes for Study I

Scene	**Men Locker**	**Women Locker**	**Cafeteria**	**Processing area**	**Overall probability**
Scene A	0.14602	0.09639	0	0	**0.06474**
Scene B	0.14602	0.09639	0	0.0023	**0.06589**
Scene C	0	0	0	0.05365	**0.05365**
Scene D	0	0	0.11928	0.00337	**0.03427**
Scene E	0	0	0.11928	0.00337	**0.03427**
Scene F	0	0	0.11928	0.00337	**0.03427**
Scene G	0	0	0.09085	0.00367	**0.02111**

Scene H	0	0	0	0.08781	**0.08781**
Scene I	0.14602	0.09639	0	0.0023	**0.06589**
Scene J	0.14602	0.09639	0	0	**0.06474**

Thus, the 10 individual scenes had their probability of airborne infection calculated separately and in each of these calculations, the consolidation of the probabilities of different spaces was considered which depended upon the distribution of the occupants in different spaces. This is shown in Table 3 - 42. The overall probability of an individual scene represents the probability of a worker, out of 1500 workers, getting infected during an ongoing scene. But these individual scenes are not mutually exclusive events. This means that a worker has a probability of getting infected from Scene A as well as Scene B as well as Scene C and so on. Thus, in order to calculate the actual probability of infection for the 1500 workers it is necessary to calculate the probability of the union of the 10 sets (i.e., *P*(A U B U C U D U E U F U G U H U I U J)). The concept for calculating the probability of a union of 10 sets has been formulated using Taylor (2020) which states the following steps:

i) The probabilities of individual events are to be added.

ii) For every pair of events, the intersection of probabilities needs to be subtracted. The intersection of probabilities is calculated by multiplying the two probabilities.

iii) The intersection probabilities of every three events need to be added.

iv) The intersection probabilities of every four events need to be subtracted.

v) This process would continue until the last event is reached which corresponds to the total number of events and until then the intersection probabilities would be added and subtracted alternatively.

A Java code was written based on the above algorithm and executed to calculate the probability of these 'n' events which is shown in APPENDIX B. The variable 'arr[]' should contain all the probabilities of the 'n' events and this code would return the actual probability of the study.

After the code was executed, the SARS-CoV-2 airborne infection probability of Study I was found to be **0.41910**. This means that, on an average, every worker out of the selected 1500 workers would have 41.91% chance of getting infected from SARS-CoV-2 during their shift.

Study II

Study I was the base study that provided the actual probability of airborne infection for a group of selected workers. The next step was to identify methods of reducing the infection probability and one such step was identified during the research team's visit to Site B. Site B administration had restructured their schedules and divided the workforce into several groups such that for the majority of the time the maximum occupancy is not crossed in the common spaces and every group of workers work equal shift timings. With this concept in mind, a hypothetical staggered schedule is created for Study II which is shown in Figure 3 - 2. The table format of the schedule is also shown in Table A - 20 for a better understanding of the occupancy and time durations.

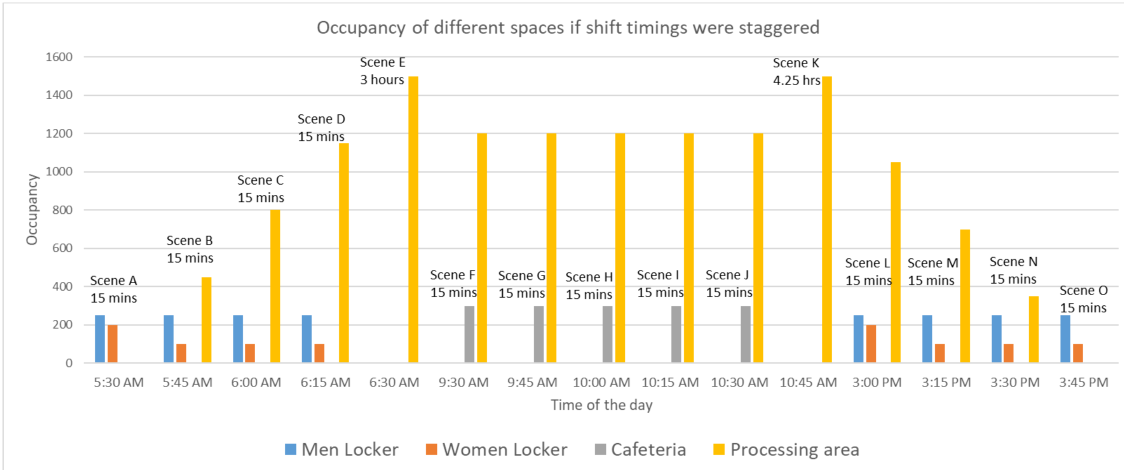


Figure 3 - 2 : The Study II staggered schedule for workers in the processing area.

In this Study II, similar to Study I, all Scenes A-O were calculated for the airborne infection probability from SARS-CoV-2. The calculations are listed in table formats and can be referred using Table 3 - 43.

Table 3 - 43 : Table information for referring to calculations of Study II

Scene	**Men Locker**	**Women Locker**	**Cafeteria**	**Processing area**	**Overall probability**
Scene A	Table A - 21	Table A - 23	NA	NA	Table A - 25
Scene B	Same as Table A - 21	Table A - 26	NA	Table A - 28	Table A - 30
Scene C	Same as Table A - 21	Same as Table A - 26	NA	Table A - 31	Table A - 33
Scene D	Same as Table A - 21	Same as Table A - 26	NA	Table A - 34	Table A - 36

Scene E	NA	NA	NA	Same as Table A - 7	Same as Table A - 9
Scene F	NA	NA	Same as Table A - 14	Same as Table A - 15	Same as Table A - 17
Scene G	NA	NA	Same as Table A - 14	Same as Table A - 15	Same as Table A - 17
Scene H	NA	NA	Same as Table A - 14	Same as Table A - 15	Same as Table A - 17
Scene I	NA	NA	Same as Table A - 14	Same as Table A - 15	Same as Table A - 17
Scene J	NA	NA	Same as Table A - 14	Same as Table A - 15	Same as Table A - 17
Scene K	NA	NA	NA	Table A - 37	Table A - 38
Scene L	Same as Table A - 21	Same as Table A - 23	NA	Table A - 39	Table A - 41
Scene M	Same as Table A - 21	Same as Table A - 26	NA	Table A - 42	Table A - 44
Scene N	Same as Table A - 21	Same as Table A - 26	NA	Table A - 45	Table A - 47

Scene O	Same as Table A - 21	Same as Table A - 26	NA	NA	Table A - 48

Table 3 - 44 : Probabilities of different spaces and the scenes for Study II

Scene	**Men Locker**	**Women Locker**	**Cafeteria**	**Processing area**	**Overall probability**
Scene A	0.07913	0.07919	0	0	**0.02375**
Scene B	0.07913	0.04184	0	0.00138	**0.01639**
Scene C	0.07913	0.04184	0	0.00245	**0.01729**
Scene D	0.07913	0.04184	0	0.00352	**0.01868**
Scene E	0	0	0	0.05365	**0.05365**
Scene F	0	0	0.09085	0.00367	**0.02111**
Scene G	0	0	0.09085	0.00367	**0.02111**
Scene H	0	0	0.09085	0.00367	**0.02111**
Scene I	0	0	0.09085	0.00367	**0.02111**
Scene J	0	0	0.09085	0.00367	**0.02111**
Scene K	0	0	0	0.07515	**0.07515**
Scene L	0.07913	0.07919	0	0.00322	**0.026**

Scene M	0.07913	0.04184	0	0.00215	**0.01698**
Scene N	0.07913	0.04184	0	0.00108	**0.01623**
Scene O	0.07913	0.04184	0	0	**0.01598**

The Study II probabilities are shown in Table 3 - 44. The code in APPENDIX B was executed and the SARS-CoV-2 airborne infection probability of Study II was found to be **0.3248**. This means that, on average, every worker out of the selected 1500 workers would have a 32.48% chance of getting infected from SARS-CoV-2 if their shift is staggered. Thus, it was seen that without any inclusion or use of technologies, the probability of airborne infection for Study II was reduced by almost 10%.

Study III

It was observed that the staggered schedule in Study II is a good administrative measure by which the probability of infection can be reduced. Study III was intended to further reduce the SARS-CoV-2 airborne infection probability by using the standard or design ventilation rates in conjunction with the staggered schedule. Thus, for Study III, the same schedule as Study II is used.

The only difference between Study II and Study III would be using design ventilation rates and recirculated air rates for the spaces and these design airflow rates are provided in Table 3 - 37. The changes in these two rates bring in changes to only two variables, $\lambda_{ventilation}$ and $k_{filtration}$, while the rest of the values of the variables would be the same as that in Study II. The standard airflow rates of Men Locker, Women Locker, and

Cafeteria are calculated using ASHRAE Std. 62.1 (2019) and is shown in the experimental results section of Test C. The design airflow rates of Site C's Processing Area are estimated by comparing it to Site A as shown in this section previously.

Thus, with all the information available for the variables used, the probabilities of airborne infection are calculated. Study III contains Scenes A-O, and their calculations are listed in table formats and can be referred to using Table 3 - 45.

Table 3 - 45 : Table information for referring to calculations of Study III

Scene	**Men Locker**	**Women Locker**	**Cafeteria**	**Processing area**	**Overall probability**
Scene A	Table A - 49	Table A - 50	NA	NA	Table A - 51
Scene B	Same as Table A - 49	Table A - 52	NA	Table A - 53	Table A - 54
Scene C	Same as Table A - 49	Same as Table A - 52	NA	Table A - 55	Table A - 56
Scene D	Same as Table A - 49	Same as Table A - 52	NA	Table A - 57	Table A - 58
Scene E	NA	NA	NA	Table A - 59	Table A - 60
Scene F	NA	NA	Table A - 61	Table A - 62	Table A - 63
Scene G	NA	NA	Same as Table A - 61	Same as Table A - 62	Same as Table A - 63

Scene H	NA	NA	Same as Table A - 61	Same as Table A - 62	Same as Table A - 63
Scene I	NA	NA	Same as Table A - 61	Same as Table A - 62	Same as Table A - 63
Scene J	NA	NA	Same as Table A - 61	Same as Table A - 62	Same as Table A - 63
Scene K	NA	NA	NA	Table A - 64	Table A - 65
Scene L	Same as Table A - 49	Same as Table A - 50	NA	Table A - 66	Table A - 67
Scene M	Same as Table A - 49	Same as Table A - 52	NA	Table A - 68	Table A - 69
Scene N	Same as Table A - 49	Same as Table A - 52	NA	Table A - 70	Table A - 71
Scene O	Same as Table A - 49	Same as Table A - 52	NA	NA	Table A - 72

Table 3 - 46 : Probabilities of different spaces and the scenes for Study III

Scene	**Men Locker**	**Women Locker**	**Cafeteria**	**Processing area**	**Overall probability**
Scene A	0.05046	0.05044	0	0	**0.01513**

Scene B	0.05046	0.02611	0	0.001	**0.01045**
Scene C	0.05046	0.02611	0	0.00177	**0.0111**
Scene D	0.05046	0.02611	0	0.00255	**0.0121**
Scene E	0	0	0	0.03909	**0.03909**
Scene F	0	0	0.06877	0.00266	**0.01588**
Scene G	0	0	0.06877	0.00266	**0.01588**
Scene H	0	0	0.06877	0.00266	**0.01588**
Scene I	0	0	0.06877	0.00266	**0.01588**
Scene J	0	0	0.06877	0.00266	**0.01588**
Scene K	0	0	0	0.05493	**0.05493**
Scene L	0.05046	0.05044	0	0.00233	**0.01676**
Scene M	0.05046	0.02611	0	0.00155	**0.01087**
Scene N	0.05046	0.02611	0	0.00078	**0.01033**
Scene O	0.05046	0.02611	0	0	**0.01015**

The Study II probabilities are shown in Table 3 - 46. The code in APPENDIX B was executed again and the SARS-CoV-2 airborne infection probability of Study III was found to be **0.2396**. This means that, on average, every worker out of the selected 1500 workers would have a 23.96% chance of getting infected from SARS-CoV-2 if their shift is staggered and required ventilation is provided. Thus, the probability of airborne infection for Study III was reduced by almost 9% from Study II by including proper ventilation in these spaces.

The overall results of the three studies evaluating the probability of airborne infection based on workers' daily schedule are shown in Table 3 - 47.

Table 3 - 47: Overall airborne infection probabilities from Study I, Study II, and Study III

Study name	**Overall probability**
Study I	41.91%
Study II	32.48%
Study III	23.96%

3.4.3 Sensitivity tests using low shedding infectious workers - Studies I-L, II-L, and III-L

The values of quanta generation rate 'q' in Studies I, II, and III were all high shedders. However, this might not be true in a real scenario. Studies I, II, and III can be treated as the worst-case scenarios for airborne infection probability for a worker's entire shift. Studies I-L, II-L, and III-L were constructed as exact replicas of Studies I, II, and III, with the only difference in quanta generation rate. Studies I-L, II-L, and III-L used the quanta generation rates based on low shedders. The difference in quanta generation rates between low shedders and high shedders have been provided in Table 3 - 48 for the selected activity of loudly speaking [Harmon and Lau (2021)]. Studies I-L, II-L, and III-L together with

Studies I, II, and III will provide a range of airborne infection probabilities for two different types of SARS-CoV-2 viral shedding.

Table 3 - 48: SARS-CoV-2 Quanta generation rates for low and high shedders

Activity type	**SARS-CoV-2 quanta generation rate (quanta/hr)**	
	Low shedder	**High Shedder**
Loudly speaking/ moderate activity	170	1190
Loudly speaking/ heavy activity	408	2856

Using the quanta values for low shedders, the airborne infection probabilities for Study I-L, Study II-L, and Study III-L were calculated. The probabilities for Study I-L, Study II-L, and Study III-L are shown in Table 3 - 49.

Table 3 - 49: Overall airborne infection probabilities for Study I-L, Study II-L, and Study III-L

Study name	**Overall probability**
Study I-L	7.64%
Study II-L	5.54%
Study III-L	3.88%

Study I-L, Study II-L, and Study III-L act as a sensitivity test for the ‘q’ quanta generation rate variable. These studies were conducted because high shedder quanta values were 7 times higher than the low shedder values.

3.5 Conclusions and discussions

Several risk analyses were performed to calculate the probability of airborne infection from SARS-CoV-2 for different spaces. Risk analysis in a single room provides insights into the additional use of engineering technologies in reducing the probability of infection, whereas the risk analysis based on the workers’ schedules helped in evaluating the overall probability of infection during their full shift.

The two spaces tested in the individual room risk analysis were Site A’s Cafeteria 1 and Locker 1. Both these spaces demonstrated similar results in the risk analysis. Different hypothetical situations were considered for analyzing the risk of these different scenarios. The Pre-Covid scenario had a very high probability of airborne infection from SARS-CoV-2 for these two spaces, 54.32% for Cafeteria 1 and 50.36% for Locker 1. It can be anticipated that the meat processing plants initially had a very high number of daily COVID-19 cases because of a such high probability of infection. It was later in the pandemic that the workers started using masks, and the plants used ultraviolet lights for disinfection. This situation, denoted as ‘actual’, would essentially reduce the airborne infection probability to 16.01% in Cafeteria 1 and 16.39% in Locker 1. The tests and experiments in Chapter 3 of the thesis were conducted during the ‘actual’ situation and the administration teams mentioned a reduction in the number of daily COVID-19 cases in their plants. The study further showcased that, in an ‘ideal’ situation, using more engineering solutions could reduce the airborne infection probability to 1.59% in Cafeteria 1 and 2.47% in Locker 1. Thus, it is highly suggestive that the meat processing plants start using technologies like portable air cleaners, upper-air ultraviolet germicidal irradiation, and in-duct ultraviolet lights. Risk reductions are also considerable when these engineering solutions and technologies are enhanced, such as using higher quality filters and increased ventilation rates. The workers wearing a mask is quite significant in risk reduction as it partially prevents the spread of viral loads from the infected person as well as reduces the chances of intake of the viral loads by the non-infected person. This study should help the meat processing plant administrations understand the benefits of using these technologies and they should plan on installing them in the plants so that in case of a future pandemic or sudden outbreak of COVID-19-like disease, the chances of a worker getting infected can be significantly reduced.

The next risk analysis was done following a worker's daily schedule considering all the infective individuals inside a space are high shedders. This risk analysis consisted of three different studies. Study I represented the actual schedule and conditions prevailing inside the meat processing plant for a set of 1500 workers. The overall probability of airborne infection from SARS-CoV-2 was found to be 41.91% for the selected 1500 workers. The next scenario of Study II was imagined as having a staggered schedule. Study II's staggered schedule would mean that the spaces are often less crowded than usual in Study I. It was observed that by not changing any other parameters except the schedule of the workers, the airborne infection probability was reduced to 32.48% for Study II. Study III aimed to show the additional effect of the staggered schedule and use of standard or design ventilation rates. The processing area was supplied with design total airflow rates and design ventilation rates. For the rest of the spaces, the ASHRAE Std. 62.1 (2019) rates were used for ventilation and the administration-decided design airflow rates were used for total airflow. This study established that using the required ventilation along with the staggered schedule would lead to an airborne infection probability of 23.96%.

Similar to the above, Study I-L, Study II-L, and Study III-L were conducted to analyze the airborne infection probabilities for 1500 workers when the infective persons inside the space are considered to be low shedders. Study I-L represented the actual schedule and conditions prevailing inside the meat processing plant for a set of 1500 workers. The overall probability of airborne infection from SARS-CoV-2 was found to be 7.64% for the selected 1500 workers. The next scenario of Study II-L had a staggered schedule. Study II's staggered schedule would mean that the spaces are often less crowded than usual in Study I. It was observed that by not changing any other parameters except the schedule of the workers, the airborne infection probability was reduced to 5.54% for Study II. Study III aimed to show the additional effect of the staggered schedule and use of standard or design ventilation rates. The processing area was supplied with design total airflow rates and design ventilation rates. For the rest of the spaces, the ASHRAE Std. 62.1 (2019) rates were used for ventilation and the administration-decided design airflow rates were used for total airflow. This study established that using the required ventilation along with the staggered schedule would lead to an airborne infection probability of 3.88%.

Thus, the baseline study being Study I, the relative reduction in airborne probabilities was calculated for Study II and Study III. Similarly, Study I-L being the baseline study, the relative reductions in airborne probabilities were calculated for Study II-L and Study III-L. The relative reduction percentages of the studies when compared to the baseline study are provided in Table 3 - 50.

Table 3 - 50 : Relative reduction in airborne infection probabilities across the studies

Shedder type	**Study Name**	**Overall airborne infection probability**	**Relative reduction percentage**
High shedder	**Study I**	41.91%	**NA**
	Study II	32.48%	**22.5%**
	Study III	23.96%	**42.83%**
Low shedder	**Study I-L**	7.64%	**NA**
	Study II-L	5.54%	**27.49%**
	Study III-L	3.88%	**49.21%**

As evident in Table 3 - 50, the relative reduction percentages for both high shedders and low shedders are similar to each other. Thus, these risk analyses would help the administration teams of the meat processing plants in deciding the use of various engineering techniques in mitigating the airborne infection risks from SARS-CoV-2 and can be used in ranking these different solutions.

CHAPTER 4 CONCLUSION

The research team visited the three meat processing plants multiple times and interviewed the respective administration teams. The research team then conducted three tests to measure the spaces for ventilation rates and total airflow.

Test A was conducted in Site A and Site B for some spaces. It was seen that the common spaces of Site A, like Locker I and Cafeteria I had very low ventilation rates when compared to similar spaces in ASHRAE Std. 62.1 (2019). There are no comparable standards for processing areas, and the administration of the plant decides the mechanical ventilation rate in those spaces. Site B had better-measured ventilation rates when compared to the ASHRAE Std. 62.1 (2019), but the experimental measurements might have been overestimated due to unforeseen circumstances. It was impossible to conduct Test A in many spaces due to limited human resources and the challenges in scheduling spaces to stay unoccupied for 3-4 hours during Test A. Hence, Test C was sought as an alternative way to estimate the in-situ ventilation rates.

Test B was conducted in all three sites to measure the total airflow of the spaces. It was observed that, for most spaces in Site B, the measured total airflow rates were close to the documented design total airflow rates. However, for common areas of Site A and Site C, such as cafeterias and locker rooms, the measured supply airflow rates were very low when compared to the documented design supply airflow rates. The office areas of Site A and Site C had measured total airflow rates similar to the design values.

Test C was conducted in several spaces for all three sites to measure their ventilation rates. The measured results of Test C indicated that Site A and Site C had insufficient ventilation rates when compared to the required ASHRAE Std. 62.1 (2019) ventilation rates. The locker rooms and cafeterias of Site A and Site C need to be addressed immediately for their poor ventilation rates. The office spaces of Site A and Site C had better ventilation rates than the other common areas. Site B had satisfactory results for Test C except for the cafeteria areas. However, the administration team stated that the cafeterias do not reach their designed occupancy due to the implementation of a staggered schedule in Site B.

After all these site visits and Tests A to C were conducted, the research team decided to perform a risk analysis to study the airborne infection probability from SARS-CoV-2 using the data from these tests. A literature review was conducted on the existing Wells-Riley models, and a modified version of the Wells-Riley model was selected. The risk analysis was done in two stages; one assessed the risks for workers in individual rooms, and the other one evaluated the risks for workers during their whole shift as they moved from room to room.

The individual room risk analysis considered different scenarios and engineering technologies that can be employed to reduce the airborne infection probability. As per rank, the airborne infection probability reduces significantly upon the use of upper-air ultraviolet germicidal irradiation, enhanced ventilation, portable air cleaner, and enhanced filter quality. The mask intercepts and blocks viral aerosols from the infective person as well as prevents the non-infected person from intaking the infectious viral aerosols. Thus, wearing a mask would always reduce airborne infection probability. Also, using in-duct ultraviolet lights also helps inactivate the virus particles and offers additional protection in risk reduction. This individual room analysis can help the meat processing plant administration to understand the importance of all these technologies as this analysis compares the infection probabilities before the onset of COVID-19 and the using all these technologies together.

The other simulation studies, based on the workers' schedules during their entire shift, were developed to study the airborne infection probability as workers move from room to room. Six different studies were conducted for these analyses. Three studies were conducted considering the infective workers as high shedders and the other three studies assumed the workers as low shedders. For the high shedding scenarios, Study I was the "baseline" study that involved the workers' actual schedules and actual airflow and ventilation rates. Study II was a hypothetical situation that used a staggered schedule and actual airflow and ventilation rates. The airborne infection probability for Study II decreased by about 23% of the baseline study even though no additional engineering solution was employed. Study III used Study II's staggered schedule and design or standard airflow and ventilation rates. Study III points out that the use of proper ventilation can make a difference in reducing infection risks and the airborne infection probability is reduced by about 43%.

For the low shedding scenarios, Study I-L was the "baseline" study that involved the workers' typical schedules and measured supply airflow and ventilation rates. Study II-L and Study III-L were the exact schedules and same ventilation rate arrangements as those in Study II and Study III correspondingly. The airborne infection probability for Study II-L and Study III-L decreased by about 27% and 49% respectively when compared to the baseline study with low shedders.

To conclude, there is a lack of guidance on the required ventilation rates in the meat processing plants for the worker's health and safety. This research can also provide insights into the importance of different engineering techniques in reducing airborne infection probabilities in meat processing plants. The Wells-Riley model demonstrates the reduction in airborne infection probabilities when these engineering technologies are used. The administrative strategy of using the staggered schedule can also cause a significant decrease in infection risks. Thus, in cases where engineering techniques cannot be implemented or installed, the staggered schedule can be implemented to bring a difference.

Overall, this research determines that the administrative strategy of staggered schedule and engineering technologies like the portable air cleaner, upper-air ultraviolet germicidal irradiation, in-duct ultraviolet lights, enhanced filtration systems, enhanced ventilation, and wearing masks, would all contribute to the reduction in the spread of COVID-19 or similar virus in the meat processing plants.

LIST OF REFERENCES

Addleman, S., Leung, V., Asadi, L., Sharkawy, A., and McDonald, J. (2021). "Mitigating airborne transmission of SARS-CoV-2." *Cmaj*, 193(26), E1010–E1011.

Aganovic, A., Bi, Y., Cao, G., Drangsholt, F., Kurnitski, J., and Wargocki, P. (2021). "Estimating the impact of indoor relative humidity on SARS-CoV-2 airborne transmission risk using a new modification of the Wells-Riley model." *Building and Environment*, Elsevier Ltd, 205(August), 108278.

ASHRAE Std. 62.1 (2019). ANSI/ASHRAE Standard 62.1- 2019 User's Manual, Ventilation for Acceptable Indoor Air Quality. Atlanta: ASHRAE.

ASHRAE Handbook-HVAC Applications (2019). "Ultraviolet Air and Surface Treatment." *ASHRAE Handbook-HVAC Applications*, (2), 62.1-62.17.

ASTM D6245 (2018). American Society of Testing and Materials International's Standard D6245-18 Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation. Available at: https://doi.org/10.1520/D6245-18. (Accessed: February 14, 2023)

ASTM E741 (2019). American Society of Testing and Materials International's Standard E741-11, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. Available at: https://doi.org/10.1520/E0741-11R17. (Accessed: February 12, 2023)

Azimi, P., and Stephens, B. (2013). "HVAC filtration for controlling infectious airborne disease transmission in indoor environments: Predicting risk reductions and operational costs." *Building and Environment*, Elsevier Ltd, 70, 150–160.

Baloch, S., Baloch, M. A., Zheng, T., and Pei, X. (2020). "La pandemia de la enfermedad por coronavirus 2019 (COVID-19)." *La revista Tohoku de medicina experimental*, 250(4), 271–278.

Buonanno, G., Stabile, L., and Morawska, L. (2020). "Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment." *Environment International*, Pergamon, 141, 105794.

Burridge, H. C., Fan, S., Jones, R. L., Noakes, C. J., and Linden, P. F. (2021). "Predictive and retrospective modelling of airborne infection risk using monitored carbon dioxide." *Indoor and Built Environment*.

Cai, C., Peng, Y., Shen, E., Huang, Q., Chen, Y., Liu, P., Guo, C., Feng, Z., Gao, L., Zhang, X., Gao, Y., Liu, Y., Han, Y., Zeng, S., and Shen, H. (2021). "A comprehensive analysis of the efficacy and safety of COVID-19 vaccines." *Molecular Therapy*, Elsevier Ltd., 29(9), 2794–2805.

CDC (2009) "*Centers for Disease Control and Prevention's Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for*

Healthcare Settings." Available at: https://www.cdc.gov/niosh/docs/2009-105/default.html. (Accessed: February 03, 2023).

CDC (2021) *Centers for Disease Control and Prevention's Global Resources Pivot to address COVID-19.* Available at: https://www.cdc.gov/globalhealth/resources/reports/annual/2021/global-resources-pivot.html. (Accessed: February 20, 2023).

Chakraborti, R. K., and Kaur, J. (2014). "Noninvasive Measurement of Particle-Settling Velocity and Comparison with Stokes' Law." *Journal of Environmental Engineering*, 140(2), 1–9.

Clapp, P. W., Sickbert-Bennett, E. E., Samet, J. M., Berntsen, J., Zeman, K. L., Anderson, D. J., Weber, D. J., and Bennett, W. D. (2021). "Evaluation of Cloth Masks and Modified Procedure Masks as Personal Protective Equipment for the Public during the COVID-19 Pandemic." *JAMA Internal Medicine*, 181(4), 463–469.

Clements-Croome, D., and Baizhan, L. (2000). "Productivity and Indoor Environment." *Proceedings of Healthy Buildings*, 1(September), 629–634.

Code of Federal Regulations (1999) *"Establishment Grounds and facilities - Ventilation" Title 9 Chapter III Subchapter E Part 416.2(d),* Available at: https://www.ecfr.gov/current/title-9/chapter-III/subchapter-E/part-416#p-416.2(d). (Accessed: February 20, 2023).

Dai, H., and Zhao, B. (2020). "Association of the infection probability of COVID-19 with ventilation rates in confined spaces." *Building Simulation*, 13(6), 1321–1327.

Department of Homeland Security (2021) *DHS's Estimated Airborne Decay of SARS-CoV-2 (virus that causes covid-19)*. Available at: https://www.dhs.gov/science-and-technology/sars-airborne-calculator (Accessed: February 5, 2023).

Dineen, K. K., Lowe, A., Kass, N. E., Lee, L. M., Wynia, M. K., Voo, T. C., Mohapatra, S., Lookadoo, R., Ramos, A. K., Herstein, J. J., Donovan, S., Lawler, J. V., Lowe, J. J., Schwedhelm, S., and Sederstrom, N. O. (2022). "Treating Workers as Essential Too: An Ethical Framework for Public Health Interventions to Prevent and Control COVID-19 Infections among Meat-processing Facility Workers and Their Communities in the United States." *Journal of Bioethical Inquiry*, Journal of Bioethical Inquiry, 19(2), 301–314.

Environmental Protection Agency (2011). *EPA's Exposure factors handbook 2011 edition (final report)*. Available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=236252. (Accessed: February 2, 2023).

Escombe, A. R., Oeser, C. C., Gilman, R. H., Navincopa, M., Ticona, E., Pan, W., Martínez, C., Chacaltana, J., Rodríguez, R., Moore, D. A. J., Friedland, J. S., and Evans, C. A. (2007). "Natural ventilation for the prevention of airborne contagion." *PLoS Medicine*, 4(2), 0309–0317.

Fennelly, K. P., and Edward, A. N. (1998). “The Relative Efficacy of Respirators and Room Ventilation in Preventing Occupational Tuberculosis.” *Infection Control and Hospital Epidemiology* 19, no. 10: 754–59. https://doi.org/10.2307/30141420.

Finci, I., Siebenbaum, R., Richtzenhain, J., Edwards, A., Rau, C., Ehrhardt, J., Koiou, L., Joggerst, B., and Brockmann, S. O. (2022). "Risk factors associated with an outbreak of COVID-19 in a meat processing plant in southern Germany , April to June 2020." *Eurosurveillance*, European Centre for Disease Prevention and Control (ECDC), 27(13).

Fisk, B., Energy, E., Division, T., Berkeley, L., Seppanen, O., and Huang, J. (2004). “Economic Benefits of an Economizer System :” (June), 1–10.

Foster, A., and Kinzel, M. (2021). “Estimating COVID-19 exposure in a classroom setting: A comparison between mathematical and numerical models.” *Physics of Fluids*, AIP Publishing LLC, 33(2).

Günther, T., Czech-Sioli, M., Indenbirken, D., Robitaille, A., Tenhaken, P., Exner, M., Ottinger, M., Fischer, N., Grundhoff, A., Brinkmann, M. M. (2020). SARS-CoV-2 outbreak investigation in a German meat processing plant. *EMBO molecular medicine*, 12(12), e13296.

Guo, Y., Qian, H., Sun, Z., Cao, J., Liu, F., Luo, X., Ling, R., Weschler, L. B., Mo, J., and Zhang, Y. (2021). “Assessing and controlling infection risk with Wells-Riley model and spatial flow impact factor (SFIF).” *Sustainable Cities and Society*, Elsevier, 67, 102719.

Harmon, M., and Lau, J. (2021). “The Facility Infection Risk Estimator™: A web application tool for comparing indoor risk mitigation strategies by estimating airborne transmission risk.” *Indoor and Built Environment*, 0(0), 1–24.

He, X., Lau, E. H. Y., Wu, P., Deng, X., Wang, J., Hao, X., Lau, Y. C., Wong, J. Y., Guan, Y., Tan, X., Mo, X., Chen, Y., Liao, B., Chen, W., Hu, F., Zhang, Q., Zhong, M., Wu, Y., Zhao, L., Zhang, F., Cowling, B. J., Li, F., and Leung, G. M. (2020). “Temporal dynamics in viral shedding and transmissibility of COVID-19.” *Nature Medicine*, 26(5), 672–675.

Herstein, J. J., Degarege, A., Stover, D., Austin, C., Schwedhelm, M. M., Lawler, J. V., Lowe, J. J., Ramos, A. K., and Donahue, M. (2021). "Characteristics of SARS-CoV-2 transmission among meat processing workers in Nebraska, USA, and effectiveness of risk mitigation measures." *Emerging Infectious Diseases*, 27(4), 1032–1039.

Khankari, Kishor. (2021). "Analysis of spread of airborne contaminants and risk of infection." *ASHRAE Journal,* 63(7), 14–20.

Kirkman, S., Zhai, J., and Miller, S. L. (2020). *"Effectiveness of air cleaners for removal of virus-containing respiratory droplets: recommendations for air cleaner selection for campus spaces."* Available at: https://shellym80304.files.wordpress. com/2020/06/air-cleaner-report.pdf. (Accessed: February 09, 2023)

Lau, J., Bahnfleth, W., and Freihaut, J. (2009). “Estimating the effects of ambient conditions on the performance of UVGI air cleaners.” *Building and Environment*, Elsevier Ltd, 44(7), 1362–1370.

Lau, J., Bahnfleth, W., Mistrick, R., and Kompare, D. (2012). “Ultraviolet irradiance measurement and modeling for evaluating the effectiveness of in-duct ultraviolet germicidal irradiation devices.” *HVAC and R Research*, 18(4), 626–642.

Li, C., and Tang, H. (2021). “Study on ventilation rates and assessment of infection risks of COVID-19 in an outpatient building.” *Journal of Building Engineering*, Elsevier, 42, 103090.

Li, X., Lester, D., Rosengarten, G., Aboltins, C., Patel, M., and Cole, I. (2022). “A spatiotemporally resolved infection risk model for airborne transmission of COVID-19 variants in indoor spaces.” *Science of the Total Environment*, Elsevier B.V., 812, 152592.

Liao, C. M., Chang, C. F., and Liang, H. M. (2005). “A probabilistic transmission dynamic model to assess indoor airborne infection risks.” *Risk Analysis*, 25(5), 1097–1107.

Liu, Z., Zhuang, W., Hu, X., Zhao, Z., Rong, R., Li, J., Li, N., and Ding, W. (2021). “Potential infection risk assessment of improper bioaerosol experiment operation in one BSL-3 laboratory based on the improved Wells-Riley method.” *Building and Environment*, Pergamon, 201, 107974.

Martin Jr, S. B., Dunn, C., Freihaut, J. D., Bahnfleth, W. P., Lau, J., & Nedeljkovic-Davidovic, A. (2008). “Ultraviolet germicidal irradiation: current best practices”. *Ashrae Journal*, 50(8), 28.

Middleton, J., Reintjes, R., and Lopes, H. (2020). “Meat plants-a new front line in the covid-19 pandemic.” *The BMJ*, 370, 1–2.

Miller, S. L., Hernandez, M., Fennelly, K., Martyny, J., and Macher, J. (2002). “*Efficacy of ultraviolet irradiation in controlling the spread of tuberculosis.*” Available at: https://stacks.cdc.gov/view/cdc/11285. (Accessed: February 12, 2023).

Mphaphlele, M., A. S. Dharmadhikari, P. A. Jensen, S. N. Rudnick, T. H. van Reenen, M. A. Pagano, W. Leuschner, T. A. Sears, S. P. Milonova, M. van der Walt, A. C. Stoltz, K. Weyer, and E. A. Nardell. (2015). “Institutional Tuberculosis Transmission. Controlled Trial of Upper Room Ultraviolet Air Disinfection: A Basis for New Dosing Guidelines.” *Am J Respir Crit Care Med*, 192 (4): 477–484. https://doi.org/10.1164/rccm.201501-0060OC.

Nardell, E.A., Keegan, J., Cheney, S.A., and Etkind, S.C. (1991) “Airborne infection: theoretical limits of protection achievable by building ventilation.” *Am. Rev. Respir. Dis.*, 144, 302–306.

Nazaroff, W. W., Nicas, M., and Miller, S. L. (1998). “Framework for evaluating measures to control nosocomial tuberculosis transmission.” *Indoor Air*, 8(4), 205–218.

Neisi, A., Goudarzi, G., Babaei, A., Hamid, V., and Mousavi, S. K. (2022). “Meta-Analysis of COVID-19 Spread in Meat Processing Plants and Recommended Practical Actions.” *Avicenna Journal of Environmental Health Engineering*, 9(2).

Noakes, C. J., and Sleigh, P. A. (2008). “Applying the Wells-Riley equation to the risk of airborne infection in hospital environments : The importance of stochastic and proximity effects.” *Indoor Air*, 17–22.

Noakes, C. J., Beggs, C. B., Sleigh, P. A., and Kerr, K. G. (2006). “Modelling the transmission of airborne infections in enclosed spaces.” *Epidemiology and Infection*, 134(5), 1082–1091.

Park, S., Choi, Y., Song, D., and Kim, E. K. (2021). “Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building.” *Science of The Total Environment*, Elsevier, 789, 147764.

Peng, Z., and Jimenez, J. L. (2021). “Exhaled CO2as a COVID-19 infection risk proxy for different indoor environments and activities.” *Environmental Science and Technology Letters*, 8(5), 392–397.

Pokora, R., Kutschbach, S., Weigl, M., Braun, D., Epple, A., Lorenz, E., Grund, S., Hecht, J., Hollich, H., Rietschel, P., Schneider, F., Sohmen, R., Taylor, K., and Dienstbuehl, I. (2021). "Investigation of superspreading COVID-19 outbreak events in meat and poultry processing plants in Germany: A cross-sectional study." *PLoS ONE*, 16(6): e0242456.

Qian, H., Li, Y., Nielsen, P. V., and Huang, X. (2009). “Spatial distribution of infection risk of SARS transmission in a hospital ward.” *Building and Environment*, Pergamon, 44(8), 1651–1658.

Ramos, A. K., Lowe, A. E., Herstein, J. J., Schwedhelm, S., Dineen, K. K., and Lowe, J. J. (2020). “Invisible No More: The Impact of COVID-19 on Essential Food Production Workers.” *Journal of Agromedicine*, 25(4), 378–382.

Riley, C.E., Murphy, G. and Riley, R. L. (1978). “Airborne spread of measles in a suburban elementary school.” *American Journal of Epidemiology*, 107(5), 421–432.

Rudnick, S. N., and Milton, D. K. (2003). “Risk of indoor airborne infection transmission estimated from carbon dioxide concentration.” *Indoor Air*, 13(3), 237–245.

Saitone, T. L., K. Aleks Schaefer, and D. P. Scheitrum. (2021). “COVID-19 morbidity and mortality in U.S. meatpacking counties.” *Food Policy*, 101: 102072. Available at: https://doi.org/10.1016/j.foodpol.2021.102072.

Sha, H., Zhang, X., and Qi, D. (2021). “Optimal control of high-rise building mechanical ventilation system for achieving low risk of COVID-19 transmission and ventilative cooling.” *Sustainable Cities and Society*, Elsevier, 74, 103256.

Shao, X., and Li, X. (2020). “COVID-19 transmission in the first presidential debate in 2020.” *Physics of Fluids*, AIP Publishing, LLC, 32(11).

Stephens, B. (2013). “HVAC filtration and the Wells-Riley approach to assessing risks of infectious airborne diseases.” *NAFA foundation report*, (March), 44.

Sun, C., and Zhai, Z. (2020). “The efficacy of social distance and ventilation effectiveness in preventing COVID-19 transmission.” *Sustainable Cities and Society*, Elsevier, 62, 102390.

Sze-To, G. N., and Chao, C. Y. H. (2010). “Review and comparison between the Wells-Riley and dose-response approaches to risk assessment of infectious respiratory diseases.” *Indoor Air*, 20(1), 2–16.

Taylor, C. A., Boulos, C., and Almond, D. (2020). “Livestock plants and COVID-19 transmission.” *Proceedings of the National Academy of Sciences of the United States of America*, 117(50), 31706–31715.

Taylor, Courtney (2020). *"Probability of the Union of 3 or More Sets".* Available at https://www.thoughtco.com/probability-union-of-three-sets-more-3126263. (Accessed: February 19, 2023).

USDA (1997). *USDA’s Facility guidelines for meat processing plants*. Available at: https://ncagr.gov/MeatPoultry/pdf/Facility%20Guidelines.pdf. (Accessed: February 17, 2023).

VanOsdell, D., and Foarde, K. (2002). “Defining the effectiveness of UV lamps installed in circulating air ductwork.” *(No. DOE/OR22674/610-40030-01),* Air-Conditioning and Refrigeration Technology Institute, Arlington, VA (US); RTI International, Research Triangle Park, NC (US).

Walshe, N., Fennelly, M., Hellebust, S., Wenger, J., Sodeau, J., Prentice, M., Grice, C., Jordan, V., Comerford, J., Downey, V., Perrotta, C., Mulcahy, G., and Sammin, D. (2021). “Assessment of Environmental and Occupational Risk Factors for the Mitigation and Containment of a COVID-19 Outbreak in a Meat Processing Plant.” *Frontiers in Public Health*, 9(October), 1–12.

Wang, Y., Xu, G., and Huang, Y. W. (2020). “Modeling the load of SARS-CoV-2 virus in human expelled particles during coughing and speaking.” *PLoS ONE*, 15(10 October), 1–12.

Wang, Z., Galea, E. R., Grandison, A., Ewer, J., and Jia, F. (2022). “A coupled Computational Fluid Dynamics and Wells-Riley model to predict COVID-19 infection probability for passengers on long-distance trains.” *Safety Science*, Elsevier, 147, 105572.

Wells, W.F. (1955). “Airborne Contagion and Air Hygiene.” *Cambridge MA, Cambridge University Press*. 117–122.

WHO COVID-19 dashboard (2023) *World Health Organization’s coronavirus (COVID-19) dashboard*. Available at: https://covid19.who.int/ (Accessed: February 15, 2023).

Xu, C., Liu, W., Luo, X., Huang, X., and Nielsen, P. V. (2022). “Prediction and control of aerosol transmission of SARS-CoV-2 in ventilated context: from source to receptor.” *Sustainable Cities and Society*, Elsevier, 76, 103416.

Yan, Y., Li, X., Shang, Y., and Tu, J. (2017). “Evaluation of airborne disease infection risks in an airliner cabin using the Lagrangian-based Wells-Riley approach.” *Building and Environment*, Pergamon, 121, 79–92.

Zhang, S., and Lin, Z. (2021). “Dilution-based evaluation of airborne infection risk - Thorough expansion of Wells-Riley model.” *Building and Environment*, Elsevier Ltd, 194(February), 107674.

Zhu, S., Srebric, J., Spengler, J. D., and Demokritou, P. (2012). “An advanced numerical model for the assessment of airborne transmission of influenza in bus microenvironments.” *Building and Environment*, Pergamon, 47(1), 67–75.

APPENDIX A : Calculation tables for airborne infection probability

Table A - 1 : Schedule for 1500 workers and occupancy of spaces in Study I

Scene	Time	Occupancy			
		Men Locker	Women Locker	Cafeteria	Processing area
Scene A	5:30 AM – 5:45 AM	500	250	0	0
Scene B	5:45 AM – 6:00 AM	500	250	0	750
Scene C	6:00 AM – 9:00 AM	0	0	0	1500
Scene D	9:00 AM – 9:15 AM	0	0	400	1100
Scene E	9:15 AM – 9:30 AM	0	0	400	1100
Scene F	9:30 AM – 9:45 AM	0	0	400	1100
Scene G	9:45 AM – 10:00 AM	0	0	300	1200
Scene H	10:00 AM – 3:00 PM	0	0	0	1500
Scene I	3:00 PM – 3:15 PM	500	250	0	750
Scene J	3:15 PM – 3:30 PM	500	250	0	0

Table A - 2 : Study I Scene A’s Men Locker calculations for k_{mask}

Variables	Values	Units
Total occupants	500	
Infective occupants	50	
Non-infected occupants	450	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	52490	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.34752	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.91052	1/hr

Table A - 3 : Study I Scene A’s Women Locker calculations for k_{mask}

Variables	Values	Units
Total occupants	250	
Infective occupants	25	

Non-infected occupants	225	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	26350	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.34613	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.90913	1/hr

Table A - 4 : Study I's airborne infection probability for Scene B's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	75	-	10% of 750 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene B duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.58974	1/hr	Calculations shown in Table A - 5
Probability of infection, *P*	**0.0023**		Solved using equation (3 - 3)

Table A - 5 : Study I Scene B's Processing area calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	750	
Infective occupants	75	
Non-infected occupants	675	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.02673	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.58974	1/hr

Table A - 6 : Study I Scene B's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.14602	0.33333	**0.06589**
Women Locker	0.09639	0.16667	
Cafeteria	0	0	
Processing Area	0.0023	0.5	

Table A - 7 : Study I's airborne infection probability for Scene C's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	150	-	10% of 1500 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	3	hr	Scene C duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.61647	1/hr	Calculations shown in Table A - 8
Probability of infection, P	**0.05365**		Solved using equation (3 - 3)

Table A - 8 : Study I Scene C's Processing area calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	1500	
Infective occupants	150	
Non-infected occupants	1350	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.05347	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.61647	1/hr

Table A - 9 : Study I Scene C's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0	0	**0.05365**
Women Locker	0	0	
Cafeteria	0	0	
Processing Area	0.05365	1	

Table A - 10 : Study I's airborne infection probability Scene D's cafeteria

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	40	-	10% of 400 (total occupants)
p	0.12063	m^3/hr	Adult average, moderate activity
s	1	-	Workers having lunch without mask
t	0.25	hr	Scene D duration
V	4012	m^3	Provided by administration
$\lambda_{ventilation}$	0.31465	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.50155	1/hr	Measured recirculation value of 5.68535 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0	1/hr	No mask during lunch time
Probability of infection, *P*	**0.11928**		Solved using equation (3 - 3)

Table A - 11 : Study I's airborne infection probability for Scene D's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	110	-	10% of 1100 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene D duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.60221	1/hr	Calculations shown in Table A - 12
Probability of infection, *P*	**0.00337**		Solved using equation (3 - 3)

Table A - 12 : Study I Scene D's Processing area calculations for k_{mask}

Variables	Values	Units
Total occupants	1100	
Infective occupants	110	
Non-infected occupants	990	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.03921	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.60221	1/hr

Table A - 13 : Study I Scene D's overall probability of infection

Space Name	Probability Value	Occupancy fraction	Overall Probability
Men Locker	0	0	**0.03427**
Women Locker	0	0	
Cafeteria	0.11928	0.26667	
Processing Area	0.00337	0.73333	

Table A - 14 : Study I's airborne infection probability for Scene G's cafeteria

Variable	Value	Unit	Assumption
q	1190	quanta/hr	High shedder, moderate activity
I	30	-	10% of 300 (total occupants)
p	0.12063	m^3/hr	Adult average, moderate activity
s	1	-	Workers having lunch without mask
t	0.25	hr	Scene G duration
V	4012	m^3	Provided by administration
$\lambda_{ventilation}$	0.31465	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.50155	1/hr	Measured recirculation value of 5.68535 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0	1/hr	No mask during lunch time
Probability of infection, $\boldsymbol{P}$	**0.09085**		Solved using equation (3 - 3)

Table A - 15 : Study I's airborne infection probability for Scene G's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	120	-	10% of 1200 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene G duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.60578	1/hr	Calculations shown in Table A - 16
Probability of infection, P	**0.00367**		Solved using equation (3 - 3)

Table A - 16 : Study I Scene G's Processing area calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	1200	
Infective occupants	120	
Non-infected occupants	1080	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.04278	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.60578	1/hr

Table A - 17 : Study I Scene G's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0	0	**0.02111**
Women Locker	0	0	
Cafeteria	0.09085	0.2	
Processing Area	0.00367	0.8	

Table A - 18 : Study I's airborne infection probability for Scene H's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	150	-	10% of 1500 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	5	hr	Scene H duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.61647	1/hr	Calculations shown in Table A - 8
Probability of infection, *P*	**0.08781**		Solved using equation (3 - 3)

Table A - 19 : Study I Scene H's overall probability of infection

Space Name	Probability Value	Occupancy fraction	Overall Probability
Men Locker	0	0	**0.08781**
Women Locker	0	0	
Cafeteria	0	0	
Processing Area	0.08781	1	

Table A - 20 : Staggered schedule for Study II

Scene	Time	Occupancy			
		Men Locker	Women Locker	Cafeteria	Processing area
Scene A	5:30 AM – 5:45 AM	250	200	0	0
Scene B	5:45 AM – 6:00 AM	250	100	0	450
Scene C	6:00 AM – 6:15 AM	250	100	0	800
Scene D	6:15 AM – 6:30 AM	250	100	0	1150
Scene E	6:30 AM – 9:30 AM	0	0	0	1500
Scene F	9:30 AM – 9:45 AM	0	0	300	1200
Scene G	9:45 AM – 10:00 AM	0	0	300	1200
Scene H	10:00 AM – 10:15 AM	0	0	300	1200

Scene I	10:15 AM – 10:30 AM	0	0	300	1200
Scene J	10:30 AM – 10:45 AM	0	0	300	1200
Scene K	10:45 AM – 3:00 PM	0	0	0	1500
Scene L	3:00 PM – 3:15 PM	250	200	0	1050
Scene M	3:15 PM – 3:30 PM	250	100	0	700
Scene N	3:30 PM – 3:45 PM	250	100	0	350
Scene O	3:45 PM – 4:00 PM	250	100	0	0

Table A - 21 : Study II's airborne infection probability for Scene A's Men locker

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	25	-	10% of 250 (total occupants)
p	0.14708	m^3/hr	Male average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene A duration
V	1486	m^3	Provided by administration
$\lambda_{ventilation}$	0.93618	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.22808	1/hr	Measured recirculation value of 5.06382 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0.73676	1/hr	Calculations shown in Table A - 22
Probability of infection, P	**0.07913**		Solved using equation (3 - 3)

Table A - 22 : Study II Scene A's Men locker calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	250	
Infective occupants	25	
Non-infected occupants	225	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	52490	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.17376	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.73676	1/hr

Table A - 23 : Study II's airborne infection probability for Scene A's Women locker

Variable	Value	Unit	Assumption
q	1190	quanta/hr	High shedder, moderate activity
I	20	-	10% of 200 (total occupants)
p	0.09417	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene A duration
V	746	m^3	Provided by administration
$\lambda_{ventilation}$	0.88805	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.24926	1/hr	Measured recirculation value of 5.11195 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0.83991	1/hr	Calculations shown in Table A - 24
Probability of infection, *P*	**0.07919**		Solved using equation (3 - 3)

Table A - 24 : Study II Scene A's Women locker calculations for k_{mask}

Variables	Values	Units
Total occupants	200	
Infective occupants	20	
Non-infected occupants	180	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	26350	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.27691	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.83991	1/hr

Table A - 25 : Study II Scene A's overall probability of infection

Space Name	Probability Value	Occupancy fraction	Overall Probability
Men Locker	0.07913	0.16667	**0.02375**
Women Locker	0.07919	0.13333	
Cafeteria	0	0	
Processing Area	0	0	

Table A - 26 : Study II's airborne infection probability for Scene B's Women locker

Variable	Value	Unit	Assumption
q	1190	quanta/hr	High shedder, moderate activity
I	10	-	10% of 100 (total occupants)
p	0.09417	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene B duration
V	746	m^3	Provided by administration
$\lambda_{ventilation}$	0.88805	1/hr	Measured ventilation rate from Test C
$k_{filtration}$	2.24926	1/hr	Measured recirculation value of 5.11195 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0.70145	1/hr	Calculations shown in Table A - 27
Probability of infection, P	**0.04184**		Solved using equation (3 - 3)

Table A - 27 : Study II Scene B's Women locker calculations for k_{mask}

Variables	Values	Units
Total occupants	100	
Infective occupants	10	
Non-infected occupants	90	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	26350	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.13845	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.70145	1/hr

Table A - 28 : Study II's airborne infection probability for Scene B's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	45	-	10% of 450 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene B duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration

$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.57904	1/hr	Calculations shown in Table A - 29
Probability of infection, *P*	**0.00138**		Solved using equation (3 - 3)

Table A - 29 : Study II Scene B's Processing area calculations for k_{mask}

Variables	Values	Units
Total occupants	450	
Infective occupants	45	
Non-infected occupants	405	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.01604	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.58904	1/hr

Table A - 30 : Study II Scene B's overall probability of infection

Space Name	Probability Value	Occupancy fraction	Overall Probability
Men Locker	0.07913	0.16667	**0.01639**
Women Locker	0.04184	0.06667	
Cafeteria	0	0	
Processing Area	0.00138	0.3	

Table A - 31 : Study II's airborne infection probability for Scene C's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	80	-	10% of 800 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene C duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration

$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.59152	1/hr	Calculations shown in Table A - 32
Probability of infection, *P*	**0.00245**		Solved using equation (3 - 3)

Table A - 32 : Study II Scene C's Processing area calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	800	
Infective occupants	80	
Non-infected occupants	720	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.02852	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.59152	1/hr

Table A - 33 : Study II Scene C's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.07913	0.16667	**0.01729**
Women Locker	0.04184	0.06667	
Cafeteria	0	0	
Processing Area	0.00245	0.53333	

Table A - 34 : Study II's airborne infection probability for Scene D's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	115	-	10% of 1150 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene D duration
V	28798	m^3	Provided by administration

$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.60400	1/hr	Calculations shown in Table A - 35
Probability of infection, *P*	**0.00352**		Solved using equation (3 - 3)

Table A - 35 : Study II Scene D's Processing area calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	1150	
Infective occupants	115	
Non-infected occupants	1035	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.041	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.60400	1/hr

Table A - 36 : Study II Scene D's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.07913	0.16667	**0.01868**
Women Locker	0.04184	0.06667	
Cafeteria	0	0	
Processing Area	0.00352	0.76667	

Table A - 37 : Study II's airborne infection probability for Scene K's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	150	-	10% of 1500 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	4.25	hr	Scene K duration
V	28798	m^3	Provided by administration

$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.61647	1/hr	Calculations shown in Table A - 8
Probability of infection, *P*	**0.07515**		Solved using equation (3 - 3)

Table A - 38 : Study II Scene K's overall probability of infection

Space Name	Probability Value	Occupancy fraction	Overall Probability
Men Locker	0	0	**0.07515**
Women Locker	0	0	
Cafeteria	0	0	
Processing Area	0.07515	1	

Table A - 39 : Study II's airborne infection probability for Scene L's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	105	-	10% of 1050 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene L duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.60043	1/hr	Calculations shown in Table A - 40
Probability of infection, *P*	**0.00322**		Solved using equation (3 - 3)

Table A - 40 : Study II Scene L's Processing area calculations for k_{mask}

Variables	Values	Units
Total occupants	1050	
Infective occupants	105	
Non-infected occupants	945	
% Non-infected wearing mask	100%	

% Infected wearing mask	100%	
Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.03743	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.60043	1/hr

Table A - 41 : Study II Scene L's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.07913	0.16667	**0.026**
Women Locker	0.07919	0.13333	
Cafeteria	0	0	
Processing Area	0.00322	0.7	

Table A - 42 : Study II's airborne infection probability for Scene M's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	70	-	10% of 700 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene M duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.588	1/hr	Calculations shown in Table A - 43
Probability of infection, $\boldsymbol{P}$	**0.00215**		Solved using equation (3 - 3)

Table A - 43 : Study II Scene M's Processing area calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	700	
Infective occupants	70	
Non-infected occupants	630	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	

Room volume	1023366	ft^3
Mask Efficiency	56.3%	
Non-infected mask removal factor	0.025	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.588	1/hr

Table A - 44 : Study II Scene M's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.07913	0.16667	**0.01698**
Women Locker	0.04184	0.06667	
Cafeteria	0	0	
Processing Area	0.00215	0.46667	

Table A - 45 : Study II's airborne infection probability for Scene N's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	35	-	10% of 350 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene N duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	1.05534	1/hr	Measured ventilation rate from administration
$k_{filtration}$	10.69845	1/hr	Measured recirculation value of 24.31466 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.57548	1/hr	Calculations shown in Table A - 46
Probability of infection, *P*	**0.00108**		Solved using equation (3 - 3)

Table A - 46 : Study II Scene M's Processing area calculations for k_{mask}

Variables	**Values**	**Units**
Total occupants	350	
Infective occupants	35	
Non-infected occupants	315	
% Non-infected wearing mask	100%	
% Infected wearing mask	100%	
Room volume	1023366	ft^3

Mask Efficiency	56.3%	
Non-infected mask removal factor	0.01248	1/hr
Source reduction	0.563	1/hr
$\boldsymbol{k_{mask}}$	0.57548	1/hr

Table A - 47 : Study II Scene N's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.07913	0.16667	**0.01623**
Women Locker	0.04184	0.06667	
Cafeteria	0	0	
Processing Area	0.00108	0.23333	

Table A - 48 : Study II Scene O's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.07913	0.16667	**0.01598**
Women Locker	0.04184	0.06667	
Cafeteria	0	0	
Processing Area	0	0	

Table A - 49 : Study III's airborne infection probability for Scene A's Men locker

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	25	-	10% of 250 (total occupants)
p	0.14708	m^3/hr	Male average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene A duration
V	1486	m^3	Provided by administration
$\lambda_{ventilation}$	5.06382	1/hr	ASHRAE Std 62.1 ventilation rate
$k_{filtration}$	0.41192	1/hr	Design recirculation value of 0.93618 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0.73676	1/hr	Calculations shown in Table A - 22
Probability of infection, $\boldsymbol{P}$	**0.05046**		Solved using equation (3 - 3)

Table A - 50 : Study III's airborne infection probability for Scene A's Women locker

Variable	Value	Unit	Assumption
q	1190	quanta/hr	High shedder, moderate activity
I	20	-	10% of 200 (total occupants)
p	0.09417	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene A duration
V	746	m^3	Provided by administration
$\lambda_{ventilation}$	5.1074	1/hr	ASHRAE Std 62.1 ventilation rate
$k_{filtration}$	0.39274	1/hr	Design recirculation value of 0.8926 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0.83991	1/hr	Calculations shown in Table A - 24
Probability of infection, *P*	**0.05044**		Solved using equation (3 - 3)

Table A - 51 : Study III Scene A's overall probability of infection

Space Name	Probability Value	Occupancy fraction	Overall Probability
Men Locker	0.05046	0.16667	**0.01514**
Women Locker	0.05044	0.13333	
Cafeteria	0	0	
Processing Area	0	0	

Table A - 52 : Study III's airborne infection probability for Scene B's Women locker

Variable	Value	Unit	Assumption
q	1190	quanta/hr	High shedder, moderate activity
I	10	-	10% of 100 (total occupants)
p	0.09417	m^3/hr	Female average, moderate activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene B duration
V	746	m^3	Provided by administration
$\lambda_{ventilation}$	5.1074	1/hr	ASHRAE Std 62.1 ventilation rate
$k_{filtration}$	0.39274	1/hr	Design recirculation value of 0.8926 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0.70145	1/hr	Calculations shown in Table A - 27
Probability of infection, *P*	**0.02611**		Solved using equation (3 - 3)

Table A - 53 : Study III's airborne infection probability for Scene B's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	45	-	10% of 450 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene B duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.57904	1/hr	Calculations shown in Table A - 29
Probability of infection, *P*	**0.001**		Solved using equation (3 - 3)

Table A - 54 : Study III Scene B's overall probability of infection

Space Name	Probability Value	Occupancy fraction	Overall Probability
Men Locker	0.05046	0.16667	**0.01045**
Women Locker	0.02611	0.06667	
Cafeteria	0	0	
Processing Area	0.001	0.3	

Table A - 55 : Study III's airborne infection probability for Scene C's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	80	-	10% of 800 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene C duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.59152	1/hr	Calculations shown in Table A - 32
Probability of infection, *P*	**0.00177**		Solved using equation (3 - 3)

Table A - 56 : Study III Scene C's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.05046	0.16667	**0.0111**
Women Locker	0.02611	0.06667	
Cafeteria	0	0	
Processing Area	0.00177	0.53333	

Table A - 57 : Study III's airborne infection probability for Scene D's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	115	-	10% of 1150 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene D duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.604	1/hr	Calculations shown in Table A - 35
Probability of infection, *P*	**0.00255**		Solved using equation (3 - 3)

Table A - 58 : Study III Scene D's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.05046	0.16667	**0.0121**
Women Locker	0.02611	0.06667	
Cafeteria	0	0	
Processing Area	0.00255	0.76667	

Table A - 59 : Study III's airborne infection probability for Scene E's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	150	-	10% of 1500 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	3	hr	Scene E duration

V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.61647	1/hr	Calculations shown in Table A - 8
Probability of infection, *P*	**0.0391**		Solved using equation (3 - 3)

Table A - 60 : Study III Scene E's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0	0	**0.0391**
Women Locker	0	0	
Cafeteria	0	0	
Processing Area	0.0391	1	

Table A - 61 : Study III's airborne infection probability for Scene F's cafeteria

Variable	**Value**	**Unit**	**Assumption**
q	1190	quanta/hr	High shedder, moderate activity
I	30	-	10% of 300 (total occupants)
p	0.12063	m^3/hr	Adult average, moderate activity
s	1	-	Workers having lunch without mask
t	0.25	hr	Scene G duration
V	4012	m^3	Provided by administration
$\lambda_{ventilation}$	2.00861	1/hr	ASHRAE Std 62.1 ventilation rate
$k_{filtration}$	1.75621	1/hr	Design recirculation value of 3.99139 ACH and MERV 7
k_{RH}	0.00125	1/hr	Relative humidity of 30%
k_{mask}	0	1/hr	No mask during lunch time
Probability of infection, *P*	**0.06877**		Solved using equation (3 - 3)

Table A - 62 : Study III's airborne infection probability for Scene F's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	120	-	10% of 1200 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask

t	0.25	hr	Scene F duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.60578	1/hr	Calculations shown in Table A - 16
Probability of infection, *P*	**0.00266**		Solved using equation (3 - 3)

Table A - 63 : Study III Scene F's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0	0	**0.01588**
Women Locker	0	0	
Cafeteria	0.06877	0.2	
Processing Area	0.00266	0.8	

Table A - 64 : Study III's airborne infection probability for Scene K's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	150	-	10% of 1500 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	4.25	hr	Scene K duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.61647	1/hr	Calculations shown in Table A - 8
Probability of infection, *P*	**0.05493**		Solved using equation (3 - 3)

Table A - 65 : Study III Scene K's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0	0	**0.05493**
Women Locker	0	0	

Cafeteria	0	0	
Processing Area	0.05493	1	

Table A - 66 : Study III's airborne infection probability for Scene L's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	105	-	10% of 1050 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene L duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.60043	1/hr	Calculations shown in Table A - 40
Probability of infection, *P*	**0.00233**		Solved using equation (3 - 3)

Table A - 67 : Study III Scene L's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.05046	0.16667	**0.01676**
Women Locker	0.05044	0.13333	
Cafeteria	0	0	
Processing Area	0.00233	0.7	

Table A - 68 : Study III's airborne infection probability for Scene M's processing area

Variable	Value	Unit	Assumption
q	2856	quanta/hr	High shedder, heavy activity
I	70	-	10% of 700 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene M duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%

k_{mask}	0.588	1/hr	Calculations shown in Table A - 43
Probability of infection, *P*	**0.00155**		Solved using equation (3 - 3)

Table A - 69 : Study III Scene M's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.05046	0.16667	**0.01087**
Women Locker	0.02611	0.06667	
Cafeteria	0	0	
Processing Area	0.00155	0.46667	

Table A - 70 : Study III's airborne infection probability for Scene N's processing area

Variable	**Value**	**Unit**	**Assumption**
q	2856	quanta/hr	High shedder, heavy activity
I	35	-	10% of 350 (total occupants)
p	0.03521	m^3/hr	Adult average, heavy activity
s	0.437	-	All occupants wearing mask
t	0.25	hr	Scene N duration
V	28798	m^3	Provided by administration
$\lambda_{ventilation}$	9.51394	1/hr	Estimated design ventilation rate
$k_{filtration}$	6.97689	1/hr	Estimated design recirculation value of 15.85657 ACH and MERV 13
k_{RH}	0.00395	1/hr	Relative humidity of 50%
k_{mask}	0.57548	1/hr	Calculations shown in Table A - 46
Probability of infection, *P*	**0.00078**		Solved using equation (3 - 3)

Table A - 71 : Study III Scene N's overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.05046	0.16667	**0.01033**
Women Locker	0.02611	0.06667	
Cafeteria	0	0	
Processing Area	0.00078	0.23333	

Table A - 72 : Study III Scene O’s overall probability of infection

Space Name	**Probability Value**	**Occupancy fraction**	**Overall Probability**
Men Locker	0.05046	0.16667	**0.01015**
Women Locker	0.02611	0.06667	
Cafeteria	0	0	
Processing Area	0	0	

APPENDIX B : Code to find actual probability of combined scenes

```
import java.util.*;
import java.lang.*;
import java.io.*;
class Codechef {
        static double sum = 0;
        static void combinationUtil(double arr[], double data[], int start, int end, int
        index, int r)
        {
            if (index == r)
            {
                    double prod = 1;
                    for (int j=0; j<r; j++) {
                            prod = prod * data[j];
                    }
                    if(r%2 == 1)
                            sum += prod;
                    else
                            sum -= prod;
                    return;
            }
            for (int i=start; i<=end && end-i+1 >= r-index; i++)
            {
                    data[index] = arr[i];
                    combinationUtil(arr, data, i+1, end, index+1, r);
            }
        }
        static void printCombination(double arr[], int n, int r)
        {
            double data[]=new double[r];

            combinationUtil(arr, data, 0, n-1, 0, r);
        }
        public static void main (String[] args) {
            double arr[] = { 0.06474, 0.06589, 0.05365, 0.03427, 0.03427, 0.03427,
        0.02111, 0.08781, 0.06589, 0.06474};
            int r = 1;
            int n = arr.length;
            for(int i=1;i<=arr.length;i++)
                    printCombination(arr, n, i);
            System.out.println(sum);
        }
}
```