BARC0168: SENSE, SENSING AND CONTROLS

COURSEWORK 1 : Data Analysis and Control Strategies

MEng Engineering and Architectural Design
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1. INTRODUCTION

This report investigates the indoor environmental air quality (IAQ) and energy use of a hospital ward in Berlin through various ventilation strategies. Initially, ventilation has been modelled to a fixed occupancy schedule, and further investigations based on levels of CO2, indoor pollutants and occupancy illustrate the factors affecting this model. To determine the most accurate and efficient ventilation strategy, these methods can be comparatively assessed and presented through this report.

2. THE MODEL

2.1 HOSPITAL WARD

In relation to the issue of bed spacing for multi-bedded rooms, the current advice remains unchanged. That is, taking account of ergonomic criteria, primarily the space required for patient handling and other activities which take place in the immediate vicinity of the bed, it is recognised that the minimum bed space should not be less than 3.6m wide x 3.7m deep. (Atkins, 2010)

Assuming a ward with 6 beds, the following plan can be assumed of the hospital ward. This has a maximum of 18 people, assuming that for each patient there may be 2 extra people, either visitors or doctors/nurses.

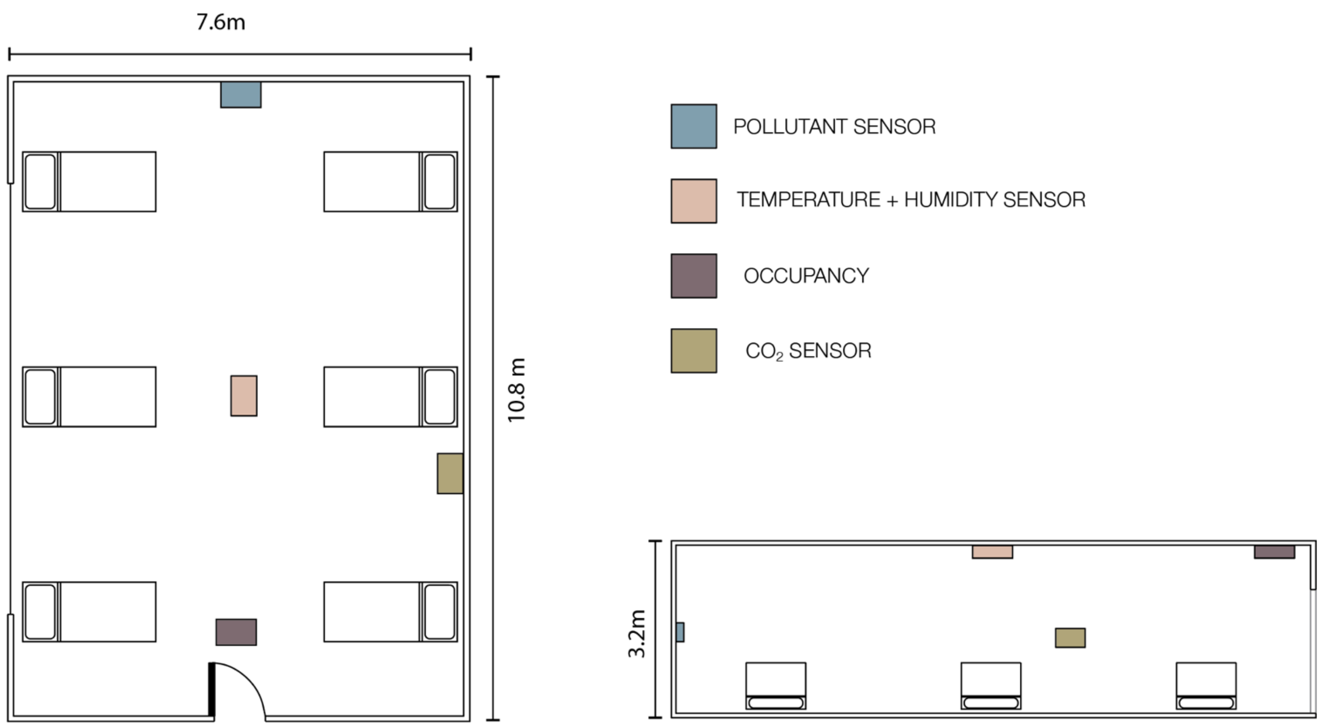

Figure 1 PLAN AND SECTION OF MODELLED HOSPITAL WARD WITH POSITIONED SENSORS

2.2 INPUT PARAMETERS (CIBSE, 2015)

DIMENSIONS		
Floor Area	82.08	m^2
Volume	262.66	m^3
Total Surface Area	281.92	m^2
OCCUPANCY		
Maximum Occupancy	18	ppl
Intermediate Occupancy	14	ppl
Minimum Occupancy	6	ppl
Fresh Air	10	l/s/p
Infiltration	0.4	h^{-1}
Emission Rate	5.56	$m^3/h\ m^2$
TIME		
Timesteps	900	seconds
PARTICULATES		
Filtration Efficiency	0.8	
Resuspension rate of particles	0.000015	h^{-1}
L_{f1}	500000	mg/m^2
Deposition velocity ($PM_{2.5}$)	1.2	m/h
Deposition velocity (NO_2)	0.72	m/h
CO_2 Generation Rate	20	ppm

Table 1 INPUT PARAMETERS

3. THE METHOD

The analysis is conducted for only 2 weeks due to aid technical efficiency. The time period selected have been from Monday, 19 May until Sunday, 1 June.

Analysis of ventilation and IAQ was chosen because the room type was a hospital ward which has the good health of patients and workers as a priority. Extended exposure to CO_2 can cause dizziness, difficulty breathing, increased heart rate, and high blood pressure (Health and Safety Executive, n.d.). Exposure to NO_2 can lead to respiratory symptoms, airway inflammation, decreased immune defence, and susceptibility to respiratory infection. $PM_{2.5}$ exposure has short-term effects on respiratory health and can hinder the healing ability of hospital patients. We will compare different ventilation control methods to find the most energy-efficient and balanced approach to improving indoor air quality. (WHO, n.d.)

The model aims to develop an appropriate ventilation strategy for the most optimized internal air quality.

3.1 DESCRIPTION OF ITERATIONS

1. BASELINE : Baseline simulations are run with the initial Berlin weather data and a basic occupancy schedule for a hospital ward.
2. ITERATION 1 : The ventilation schedule (ACH-Air change rate per hour) is altered with respect to the set occupancy schedule.
3. ITERATION 2 : CO_2 demand control ventilation is applied wherein the ACH is increased with reference to high internal CO_2 values.
4. ITERATION 3 : Previously increased ventilation may lead to increased particulates within the space; hence, ventilation strategy is altered to lower AER at high particulate concentration in the space.
5. ITERATION 4 : Re-adjusted ventilation strategy may result in elevated CO_2 levels which is controlled by increasing ACH with reference to high internal CO_2 values.
6. Real Occupant Profiles

4. BASELINE MODEL

A baseline model is first set-up to study and analyze the building natural interaction with the environment and then subsequently evaluate appropriate strategies for the further optimization of the model.

The baseline model uses a basic occupancy set-up for a hospital ward with 6 beds.

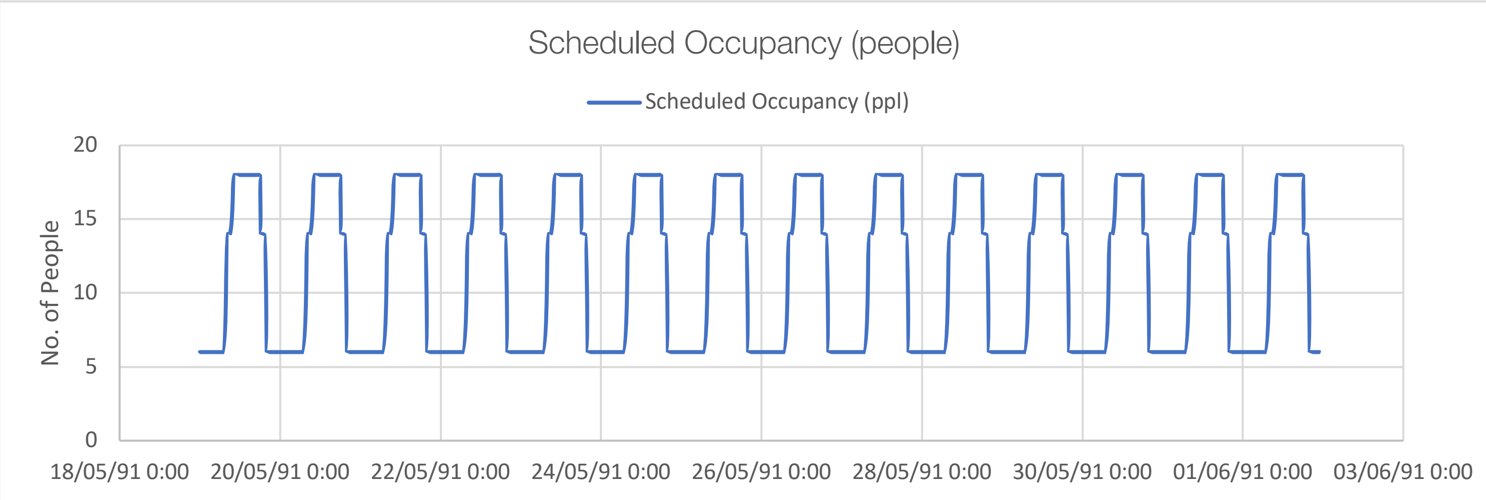

Figure 2 OCCUPANCY SCHEDULE SET UP

No. of People	6	14	18	14	6
Time	12 am – 8 am	8 am – 10 am	10 am – 6 pm	6 pm – 8 pm	8 pm – 12 am

Table 2 OCCUPANCY SCHEDULE

Volumetric Ventilation Rate, **q** (m^3/s)

$$q = (ACH \cdot Volume)/3600$$

where,
ACH: Air Change Rate per hour (h^{-1})

Rate of CO_2 generation, **G**

$$G = \text{occupancy} \times \text{emission rate}$$

Internal CO_2 concentration at time 'n', **$C_i(n)$** (ppm)

$$C_i(n) = C_e(n) + (G/q) + (C_i(n-1) - C_e(n) - (G/q))e^{-(q/volume)t}$$

where,
$C_e(n)$: External Concentration at time 'n'(ppm)
t: Timestep

The volumetric ventilation rate is calculated based on the set occupancy schedule which is then used to model internal CO_2 concentrations.

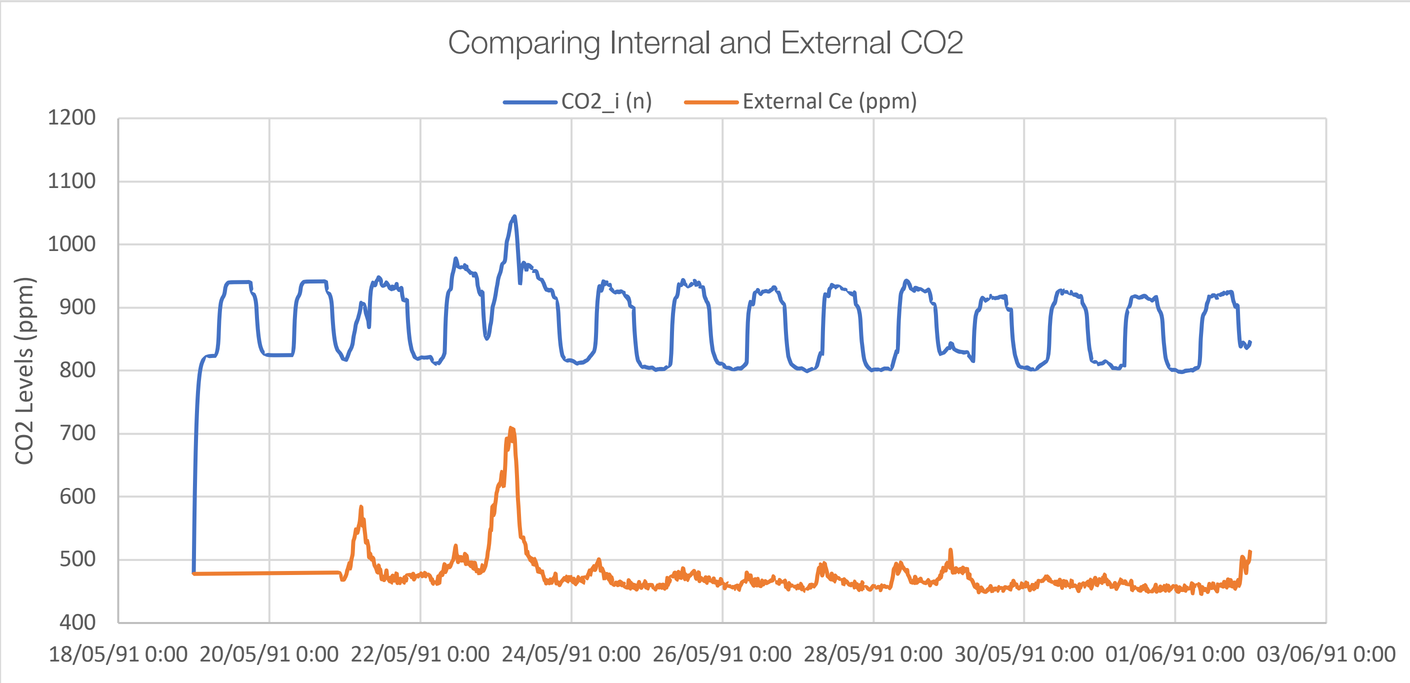

Figure 3 COMPARING INTERNAL AND EXTERNAL CO2 CONCENTRATIONS

BASELINE			
Category	Range	Frequency	%Simulated
IDA1	<400	621	24.0139211
IDA2	400-600	621	24.0139211
IDA3	600-1000	1344	51.9721578
IDA4	>1000	0	0

Table 3 ASSESSING CO2 CONCENTRATIONS

The internal CO_2 were calculated using the mean of external CO_2 concentration, and adding the stated concentration.

The internal CO_2 levels are at an average between 800-950 ppm and show a steady pattern of fluctuation in synergy with the occupancy schedule.

The external CO_2 levels are mostly steady but it is difficult to understand the yearly trend from just a time period of 2 weeks. In the plotted data, a peak in external CO_2 levels is observed and this peak is reflected in the internal CO_2 levels.

More than half of the modelled CO_2 concentrations lie in the 'moderate indoor air quality band'.

Calculating internal concetration of particulate matter, i.e., NO_2 and $PM_{2.5}$

Internal NO_2 concentration, **NO_2_in** (mg/m^3)

$$NO_2\_in = (\lambda_v\ f\ C_o) / ((v_d \times A/volume) + \lambda_v)$$

where,
A: Floor Area (m^2)
λ_v: Air Change Rate (h^{-1})
f: Filtration efficiency (taken 0.8 assuming little infiltration)
v_d: Deposition velocity (0.74 m/h)

Internal $PM_{2.5}$ concentration, **$PM_{2.5}$_in** (mg/m^3)

$$PM_{2.5}\_in = (L_{f1}A_{f1}R + \lambda_v .P.volume.C_o + G) / (A_d v_d + \lambda_v volume)$$

where,
L_{f1}: mass loading of particles on accessible floor surfaces (500000 mg/m^2)
A_{f1}: Floor Area (m^2)
R: Resuspension rate of particles from floor (0.000015h^{-1})
P: Penetration factor of outdoor particles
C_o: Outdoor concentration of particulates (mg/m3)
G: Indoor particle generation rate (µg/h).
A_d: Particle deposition surface area
v_d: Deposition velocity (1.2 m/h)

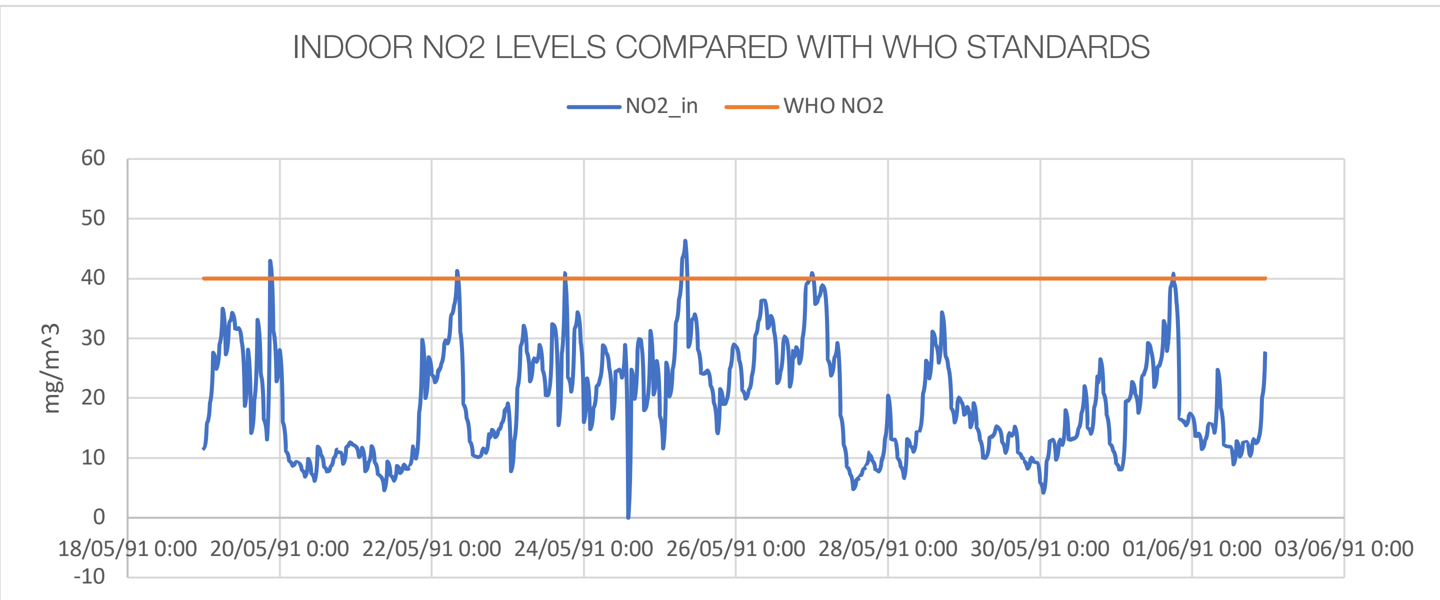

Figure 4 INDOOR NO2 LEVELS

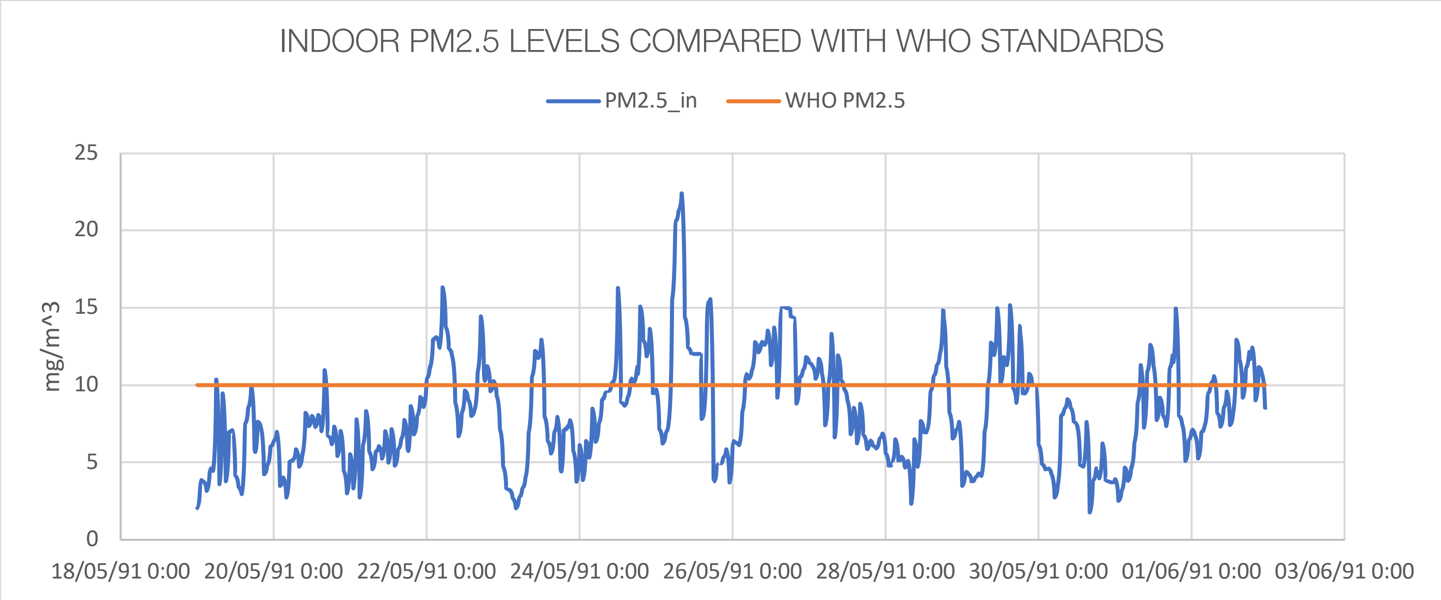

Figure 5 INDOOR PM2.5 LEVELS

The indoor NO_2 levels compared with the WHO standards illustrate that the internal NO_2 levels are for the majority within the safety limit except for a few peaked values.

The indoor $PM_{2.5}$ levels compared with the WHO standards illustrate that the internal $PM_{2.5}$ levels show some high peaks which can be unsafe

5. ITERATION 1 : ALTERATION IN VENTILATION SCHEDULE

The ventilation rates are changed with a slight step, i.e., the ventilation increases a little before the actual increase in the occupancy according to the set schedule. Additionally, it is generally improbable that occupancy sensors link to the ventilation control system of a building, hence altering the ventilation schedule according to the set expected occupancy schedule might be a useful strategy.

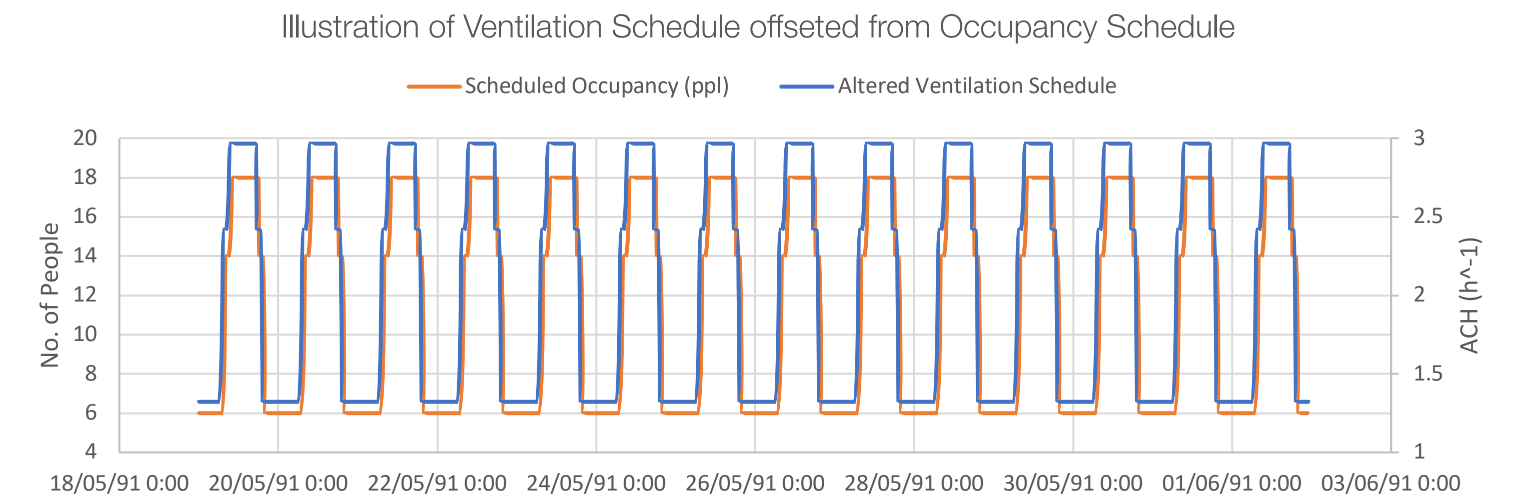

Figure 7 ALTERATION IN VENTILATION SCHEDULE

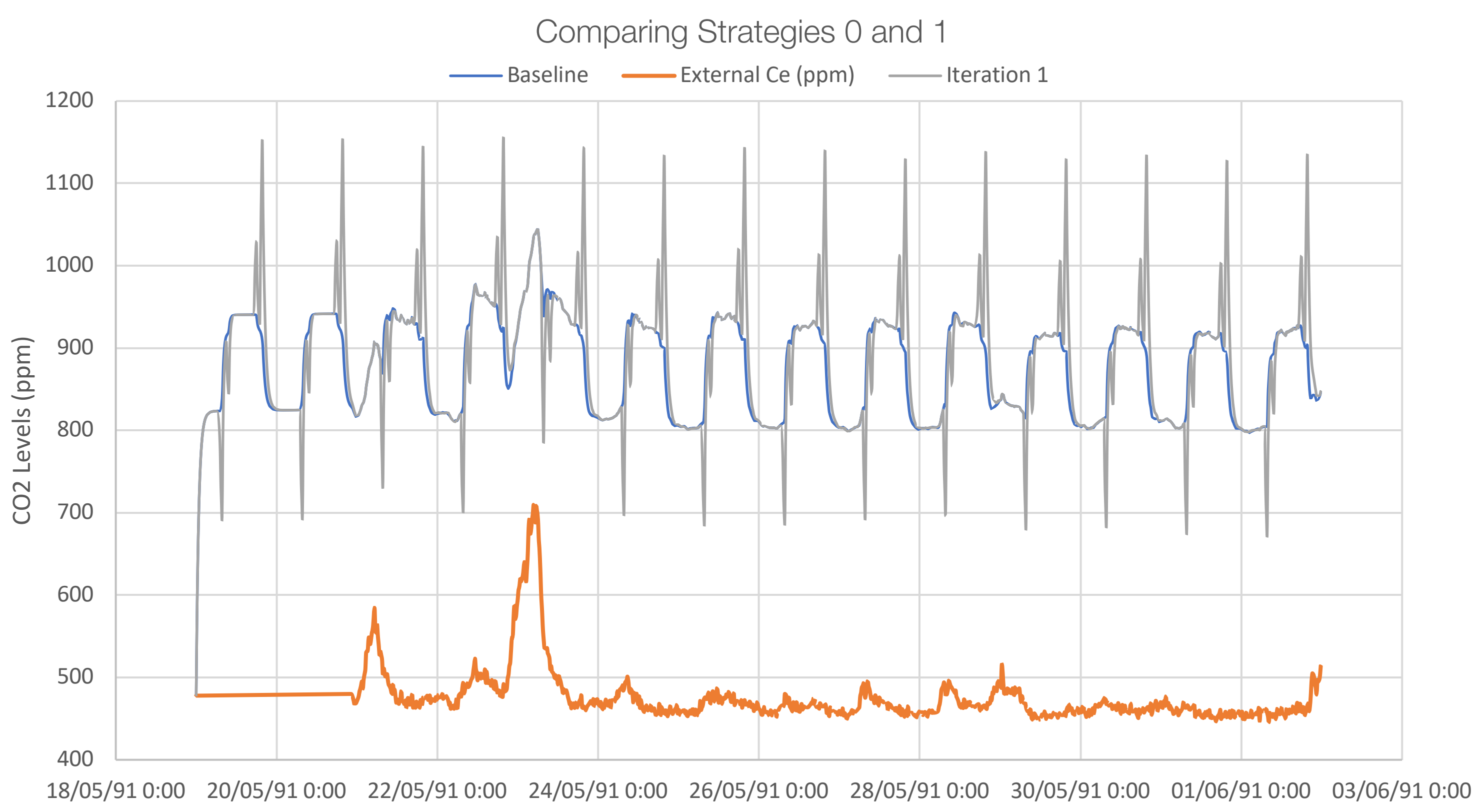

Figure 6 INTERNAL CO2 COMPARISONS

The changed schedule results in a sudden drop in CO_2 right before the increase in daily occupancy and a sudden peak right after the daily decrease in occupancy. There is however,an increase in the frequency of internal CO_2 in the high and medium IAQ band.

		BASELINE		ITERATION 1	
Category	Range	Frequency	%Simulated	Frequency	%Simulated
IDA1	<400	621	24.0139211	625	24.3569758
IDA2	400-600	621	24.0139211	625	24.3569758
IDA3	600-1000	1344	51.9721578	1316	51.2860483
IDA4	>1000	0	0	0	0

Table 4 ASSESSING CO2 CONCENTRATIONS

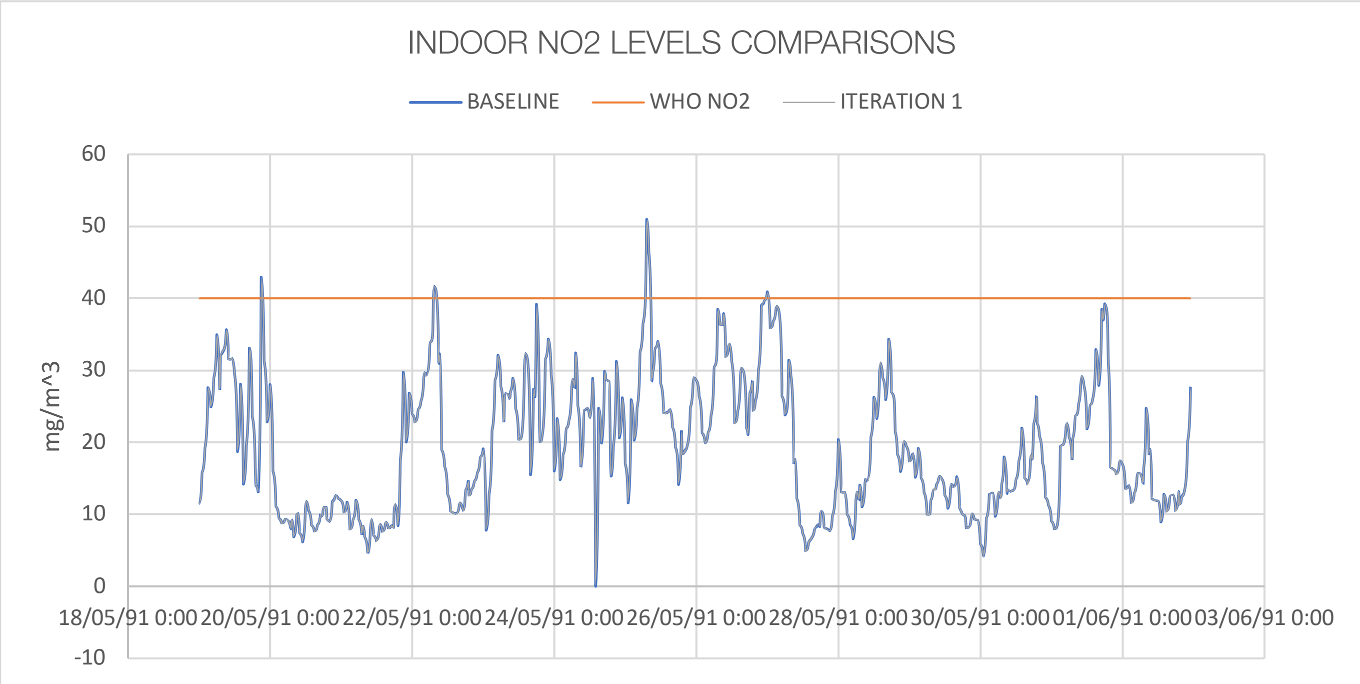

Figure 9 INDOOR NO2 LEVELS

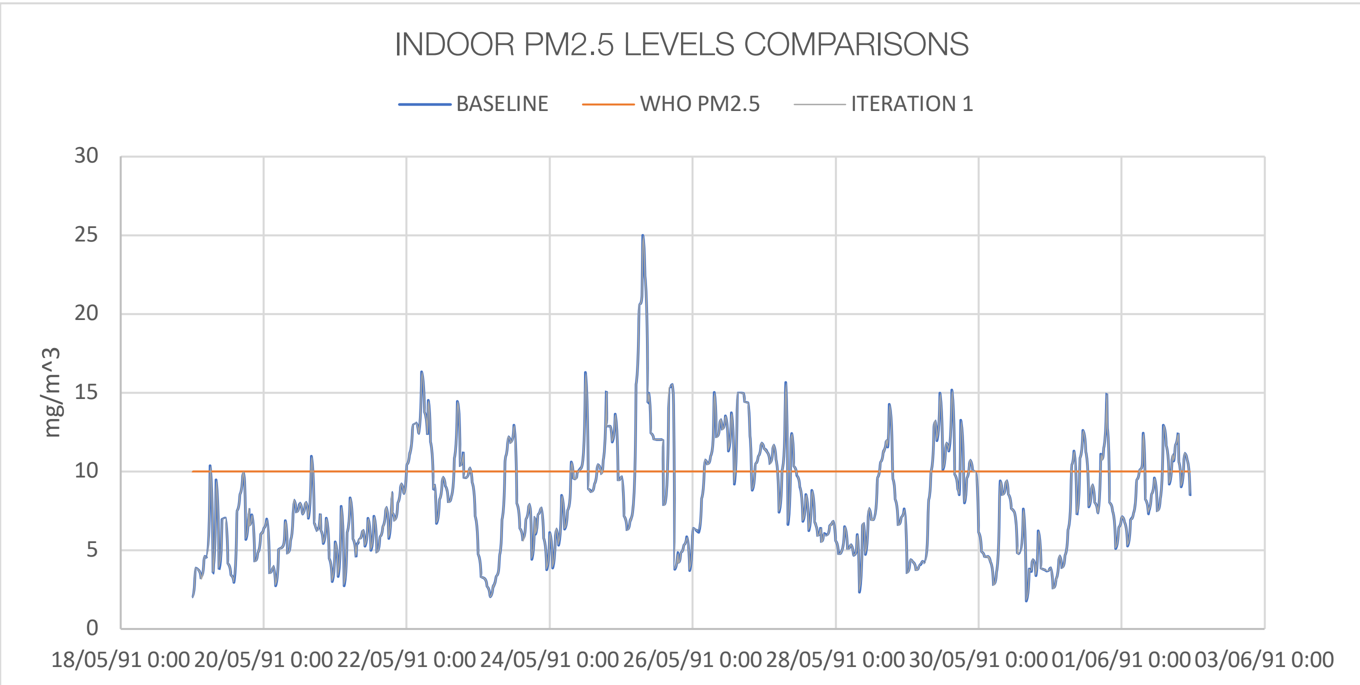

Figure 8 INDOOR PM2.5 LEVELS

The indoor particulate concentrations (NO_2 and $PM_{2.5}$) show very negligible change from the baseline model.

6. ITERATION 2 : CO_2 DEMAND CONTROL VENTILATION

Iteration 1 yielded dangerously high peaks of internal CO_2 concentrations which may cause issues. To normalize these peaks, the ventilation (ACH) is increased by 0.5 h^{-1} whenever to internal CO_2 concentration exceeds 800 ppm. 800 ppm was taken as a cut off mean value after analysing data from iteration 1.

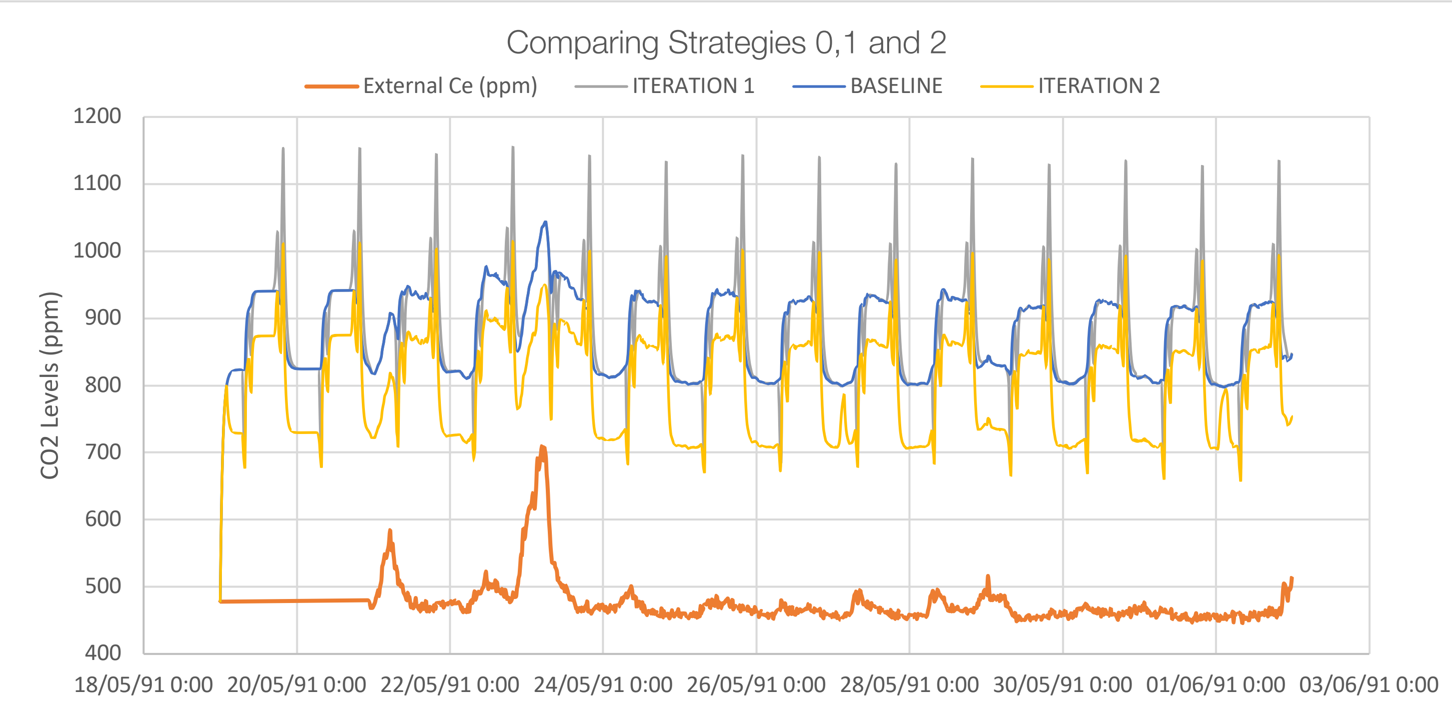

Figure 10 INTERNAL CO2 COMPARISONS

		BASELINE		ITERATION 1		ITERATION 2	
Category	Range	Frequency	%Simulated	Frequency	%Simulated	Frequency	%Simulated
IDA1	<400	621	24.01	625	24.36	1161	31.67
IDA2	400-600	621	24.01	625	24.36	1161	31.67
IDA3	600-1000	1344	51.97	1316	51.29	1344	36.67
IDA4	>1000	0	0	0	0	0	0

Table 5 ASSESSING CO2 CONCENTRATIONS

After Iterating, it is evident that the peaks from the previous iteration have considerably normalized, and the general trend of internal CO_2 concentrations are now lower than both the baseline and iteration 1.

This is more evidently observed as the internal CO_2 concentrations have reduced by nearly 20% in the moderate IAQ band and increased by over 5% in the high and medium IAQ bands.

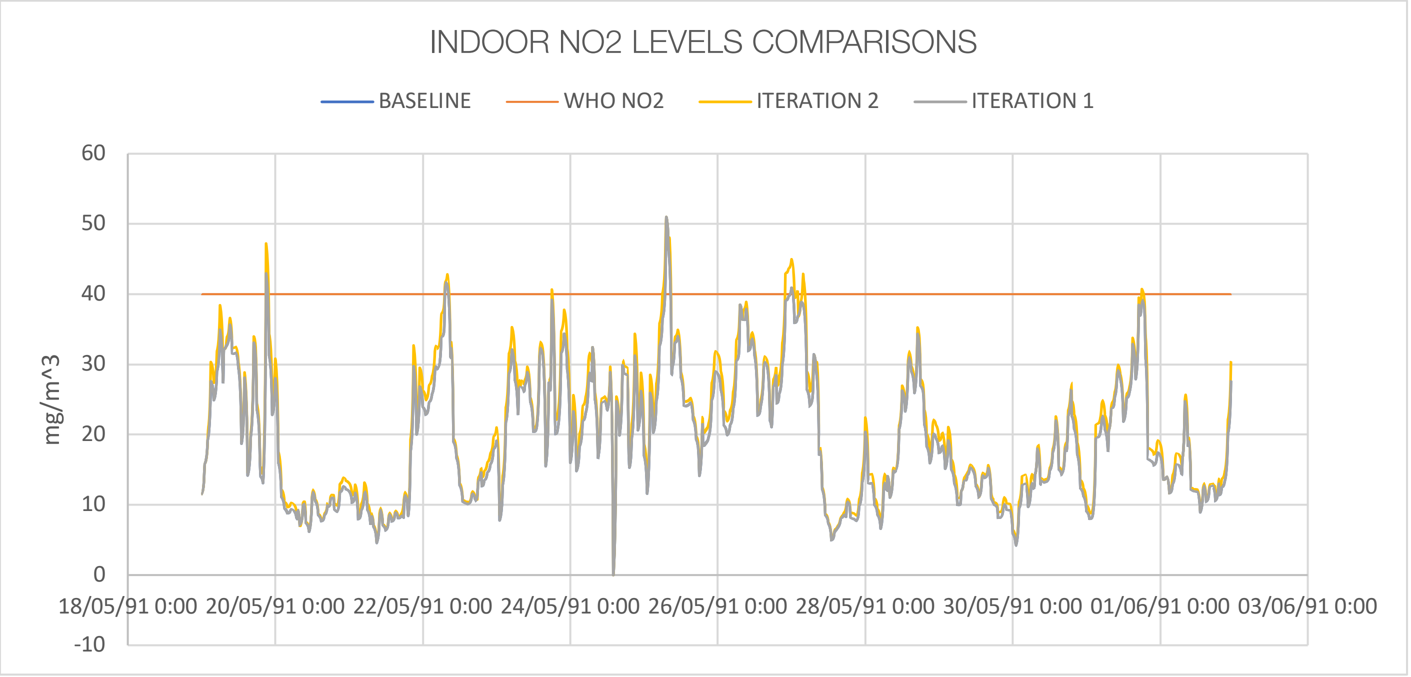

Figure 12 INDOOR NO2 LEVELS

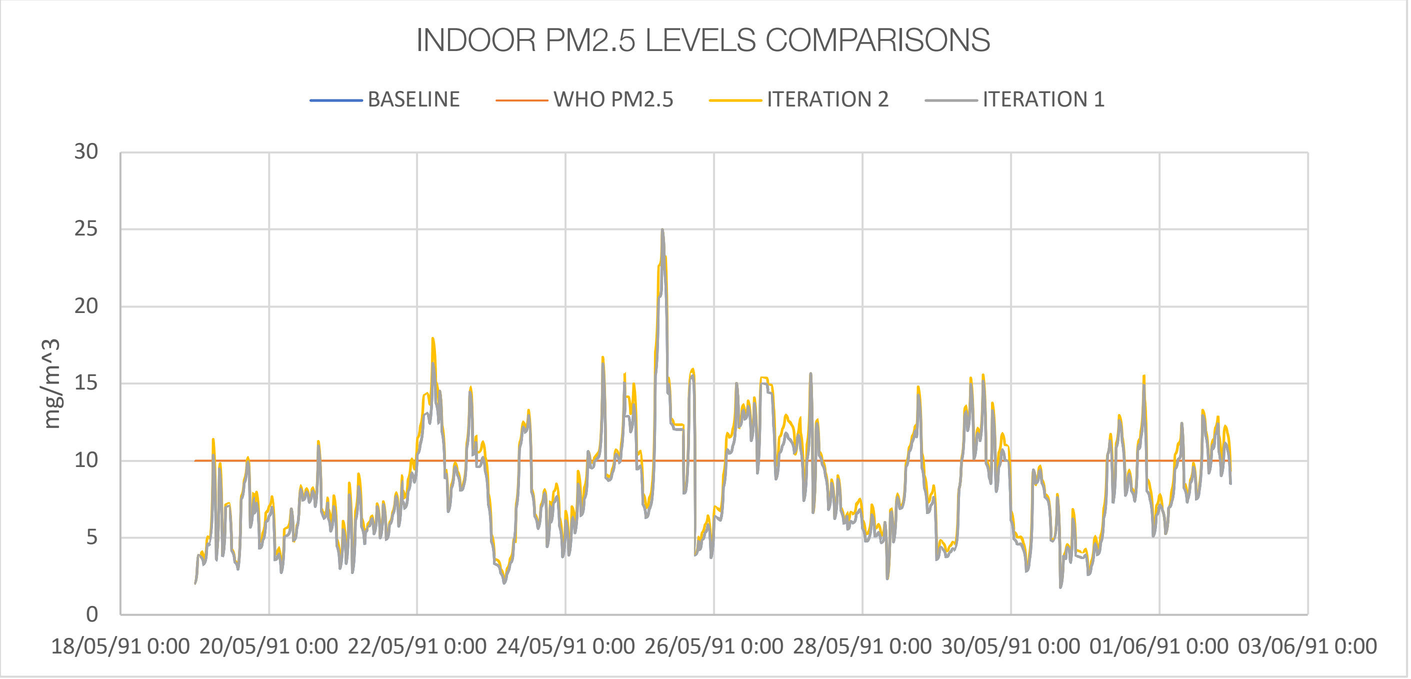

Figure 11 INDOOR PM2.5 LEVELS

However, due the increased ventilation rates, the particulate concentration has seen a slight increase. This is clearly evident from the above graphs wherein the yellow line is demonstrating the concentrations of the present iteration.

7. ITERATION 3 : INDOOR PARTICULATE CONTROLLED VENTILATION

Iteration 2 yielded elevated levels of indoor particulate concentrations (both NO_2 and $PM_{2.5}$) due to increased ventilation as a strategy to reduce internal CO_2 concentrations. Additionally, the internal $PM_{2.5}$ concentrations are considerably over the WHO health standards for indoor $PM_{2.5}$. Hence, in this iteration the ACH from iteration 2 is further iterated to reduce by half its value whenever the internal $PM_{2.5}$ concentrations from iteration 2 exceed 10 ppm (WHO standard).

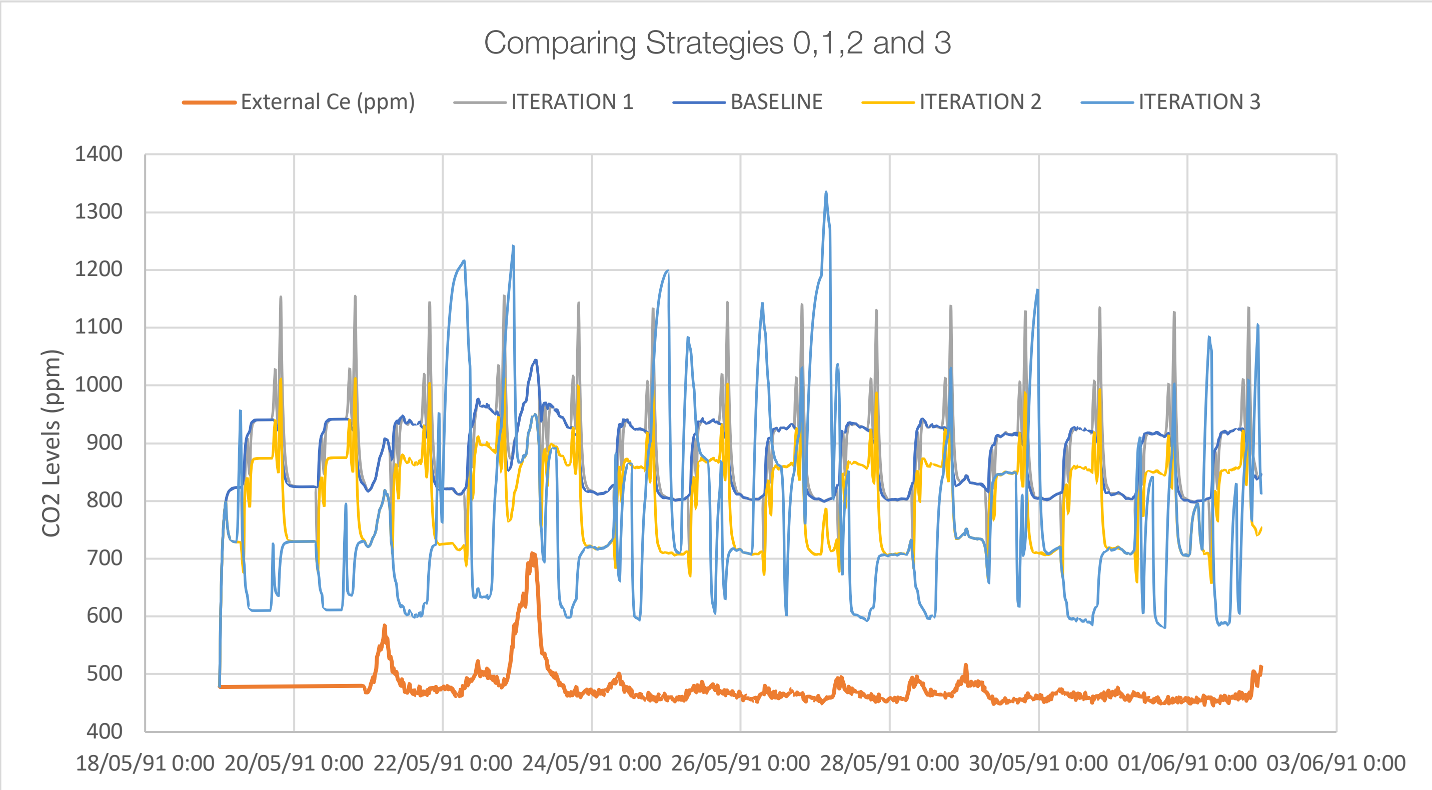

Figure 13 INTERNAL CO2 COMPARISONS

		BASELINE		ITERATION 1		ITERATION 2		ITERATION 3	
Category	Range	Frequency	%Simulated	Frequency	%Simulated	Frequency	%Simulated	Frequency	%Simulated
IDA1	<400	621	24.01	625	24.36	1161	31.67	1056	31.48
IDA2	400-600	621	24.01	625	24.36	1161	31.67	1056	31.48
IDA3	600-1000	1344	51.97	1316	51.29	1344	36.67	1242	37.03
IDA4	>1000	0	0	0	0	0	0	0	0

Table 6 ASSESSING CO2 CONCENTRATIONS

The general trend of CO_2 concentrations has reduced the most during this iteration, however, extremely high peaks can also be noticed. These values are probably due to the reduced ventilation at timestamps wherein the particulate concentration was a dangerous level.

Given the high peaks, there is a slight increase in the percentage of moderate IAQ even though the overall trend is much lower than the previous iterations.

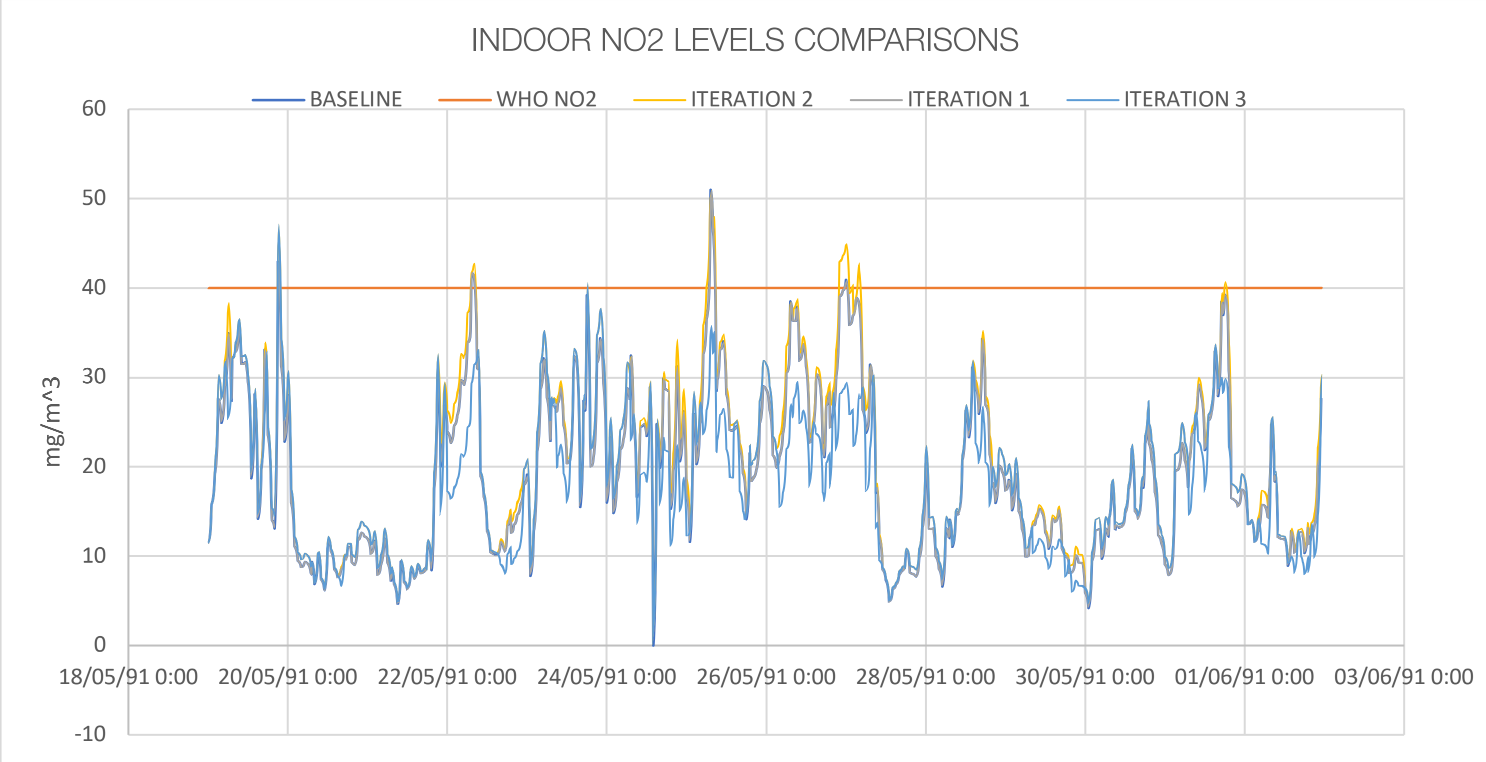

Figure 15 INDOOR NO2 LEVELS

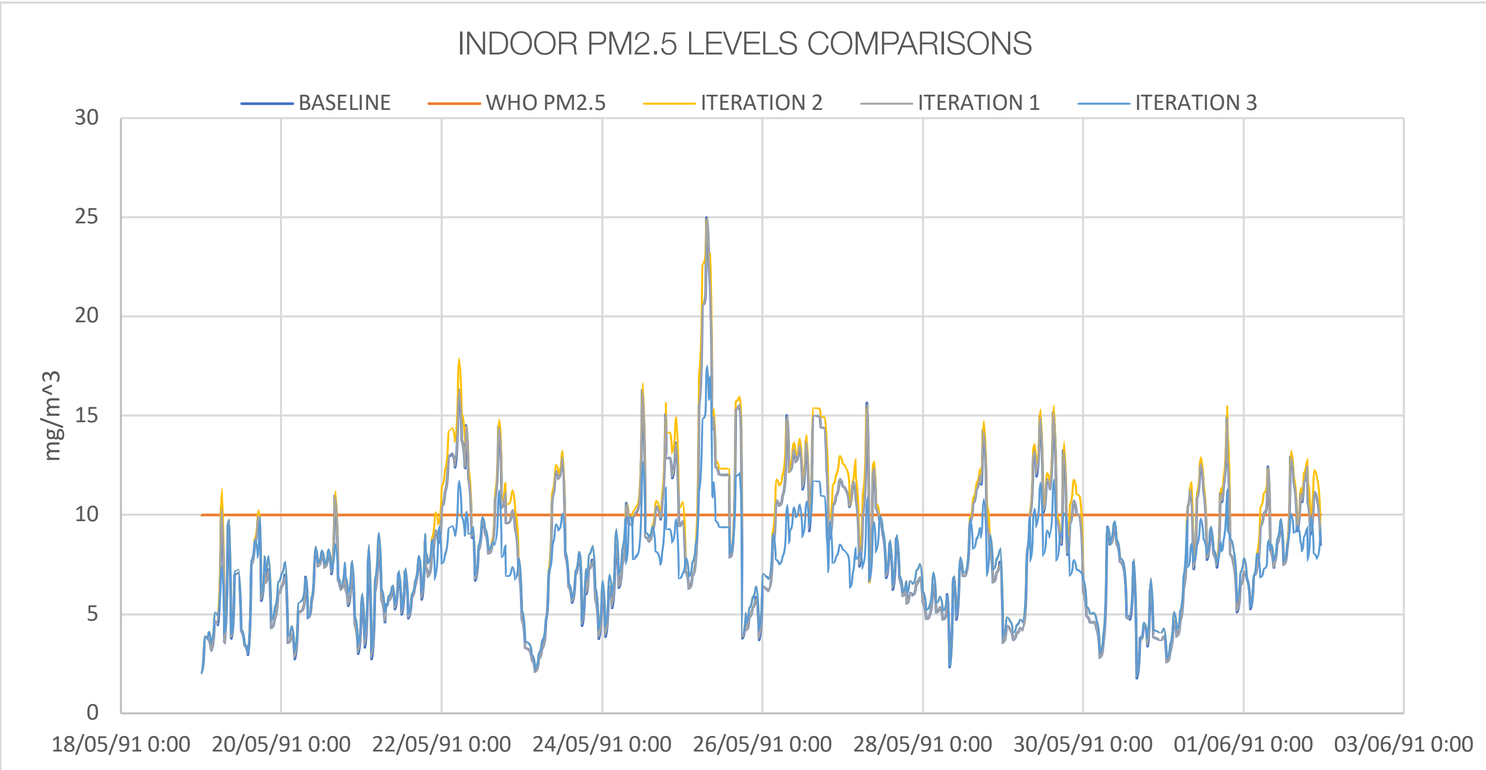

Figure 14 INDOOR PM2.5 LEVELS

Since the strategy focused on reducing indoor particulate concentration, it has succeeded and there is a visible reduction in both the NO_2 and the $PM_{2.5}$ values.

8. ITERATION 4 : COMBINING CO_2 AND PARTICULATE CONTROLLED VENTILATION

Iteration 3 yielded a generally lowered internal CO_2 levels with the exception of certain high peaks that predictably occur at points of previously elevated $PM_{2.5}$ concentrations. In order to normalize these peaks on internal CO_2 concentrations while also maintaining the lowered particulate matter concentrations, in iteration 4, the ACH from iteration 3 is further iterated to reduce by 0.5 h^{-1} at points where the internal CO_2 from iteration 3 exceeds 700 ppm. 700 ppm was taken as a cut off mean value after analyzing data from iteration 3.

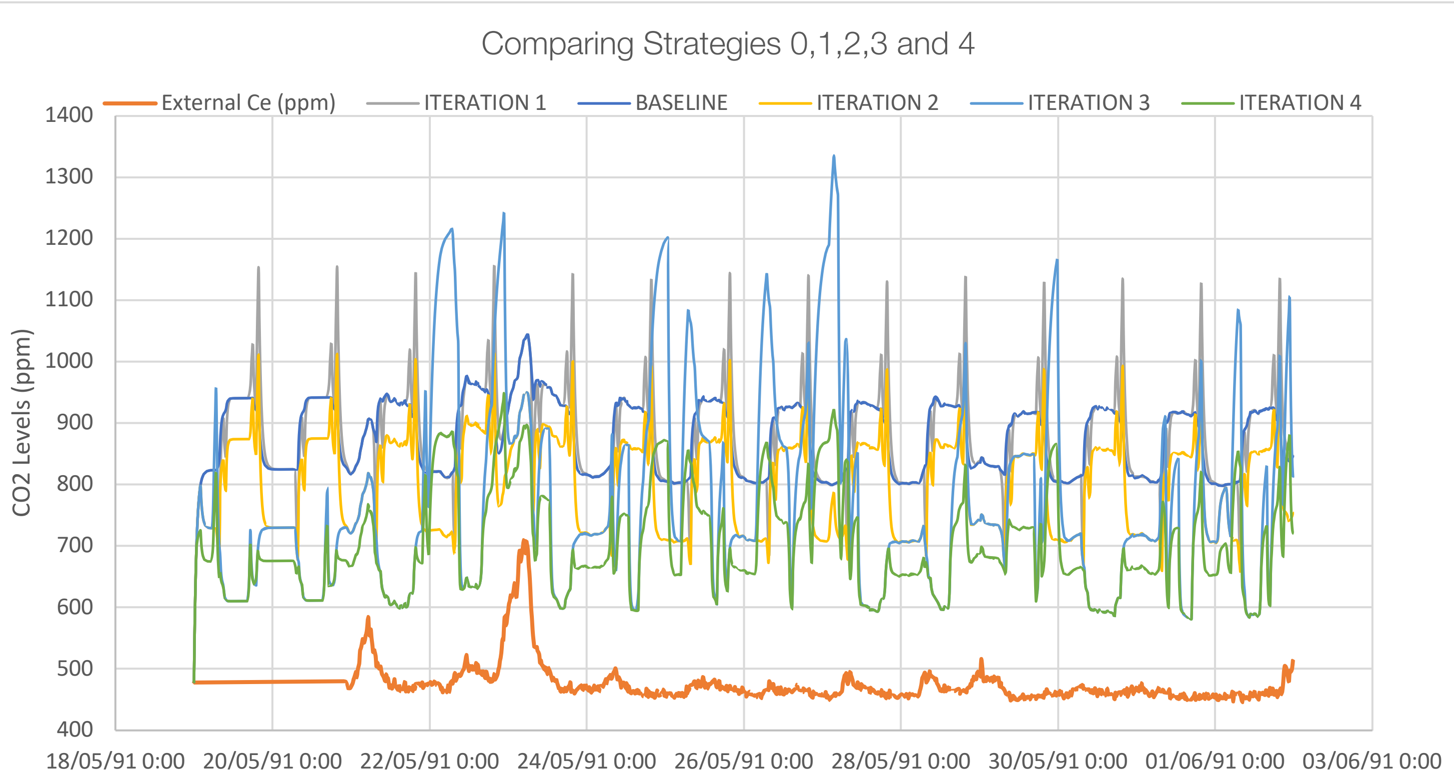

Figure 16 INTERNAL CO2 COMPARISONS

		BASELINE		ITERATION 1		ITERATION 2	
Category	Range	Frequency	%Simulated	Frequency	%Simulated	Frequency	%Simulated
IDA1	<400	621	24.01	1161	31.67	625	24.36
IDA2	400-600	621	24.01	1161	31.67	625	24.36
IDA3	600-1000	1344	51.97	1344	36.67	1316	51.29
IDA4	>1000	0	0	0	0	0	0
		ITERATION 3		ITERATION 4			
Category	Range	Frequency	%Simulated	Frequency	%Simulated		
IDA1	<400	1056	31.48	1295	32.92		
IDA2	400-600	1056	31.48	1295	32.92		
IDA3	600-1000	1242	37.03	1344	34.16		
IDA4	>1000	0	0	0	0		

Table 7 ASSESSING CO2 CONCENTRATIONS

This iteration yields the best results in terms of internal CO_2 concentrations. The general trend is the lowest from all other iterations and it presents itself with no particularly high peaking values of internal CO_2.

Its also shows the highest percentage within the high and medium IAQ bands out of all the iterations.

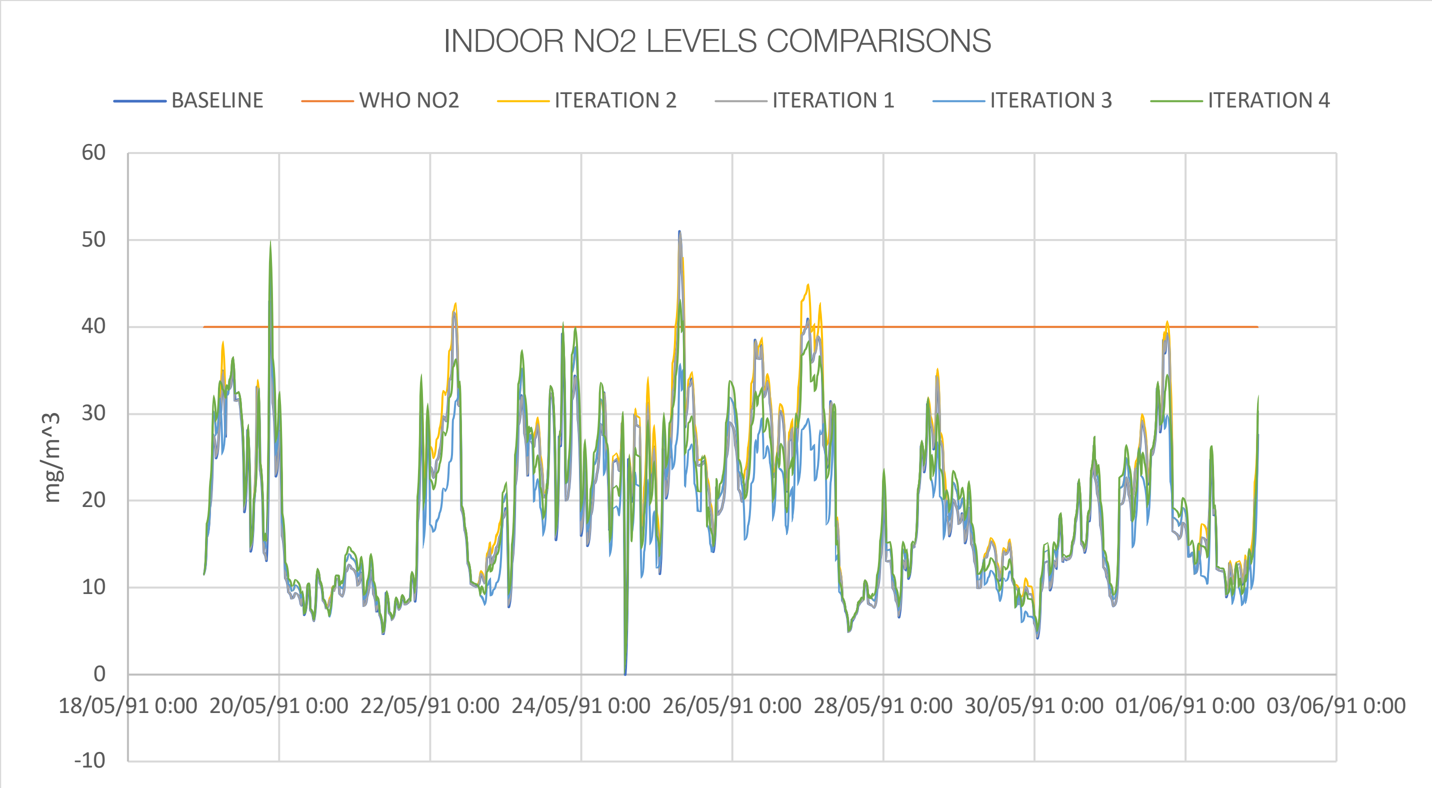

Figure 18 INDOOR NO2 LEVELS

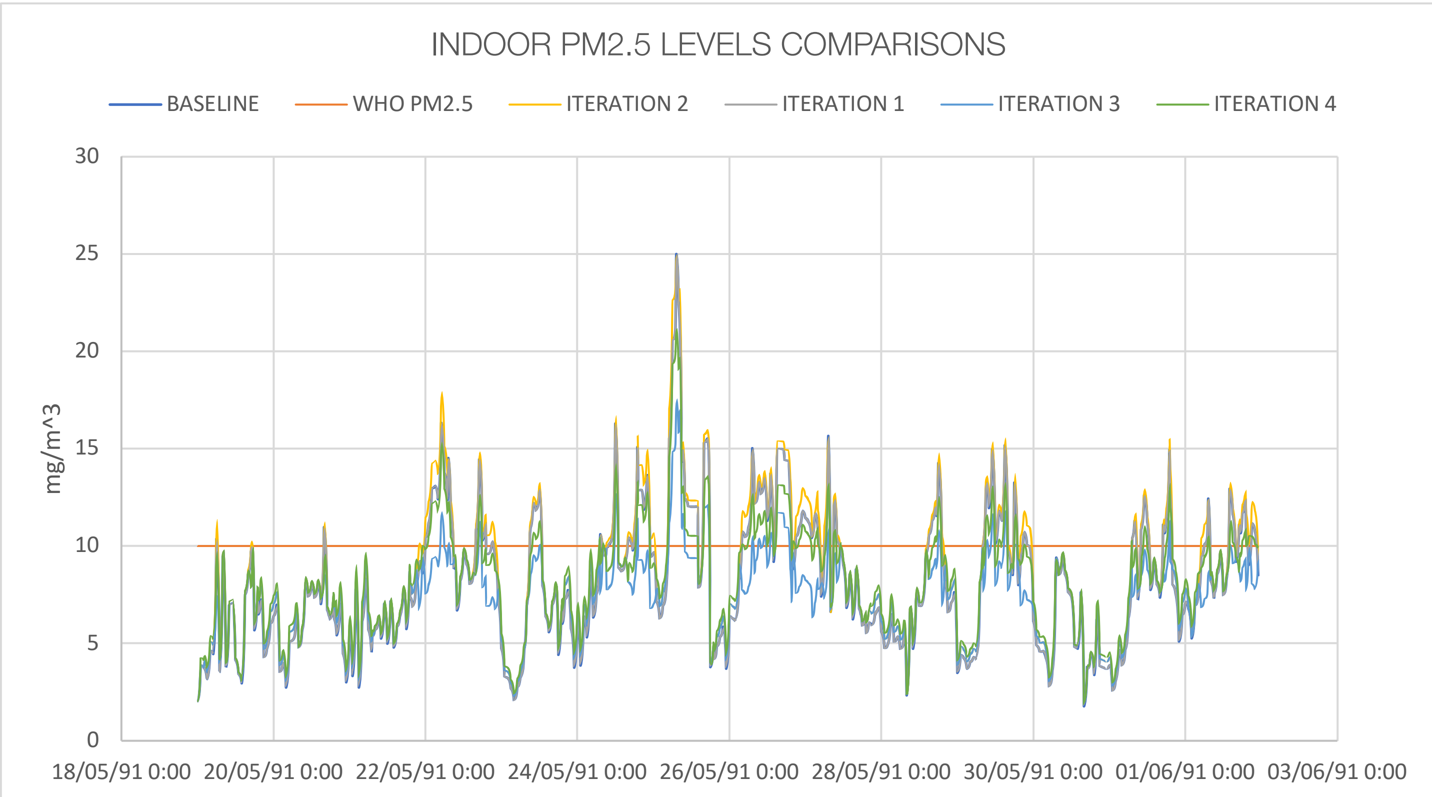

Figure 17 INDOOR PM2.5 LEVELS

The particulate concentrations are not lower than iteration 3 but are considerably lower than all other iterations.

9. ITERATION 5 : REAL OCCUPANCY BEHAVIOUR

The previous iterations are all repeated with a new random occupancy instead of a fixed occupancy schedule. However, the new 'real occupancy' is created from the occupancy schedule and it a random number between the minimum occupancy and the occupancy in each slot of the schedule. This gives a more real idea of a predicted occupancy withing the ward.

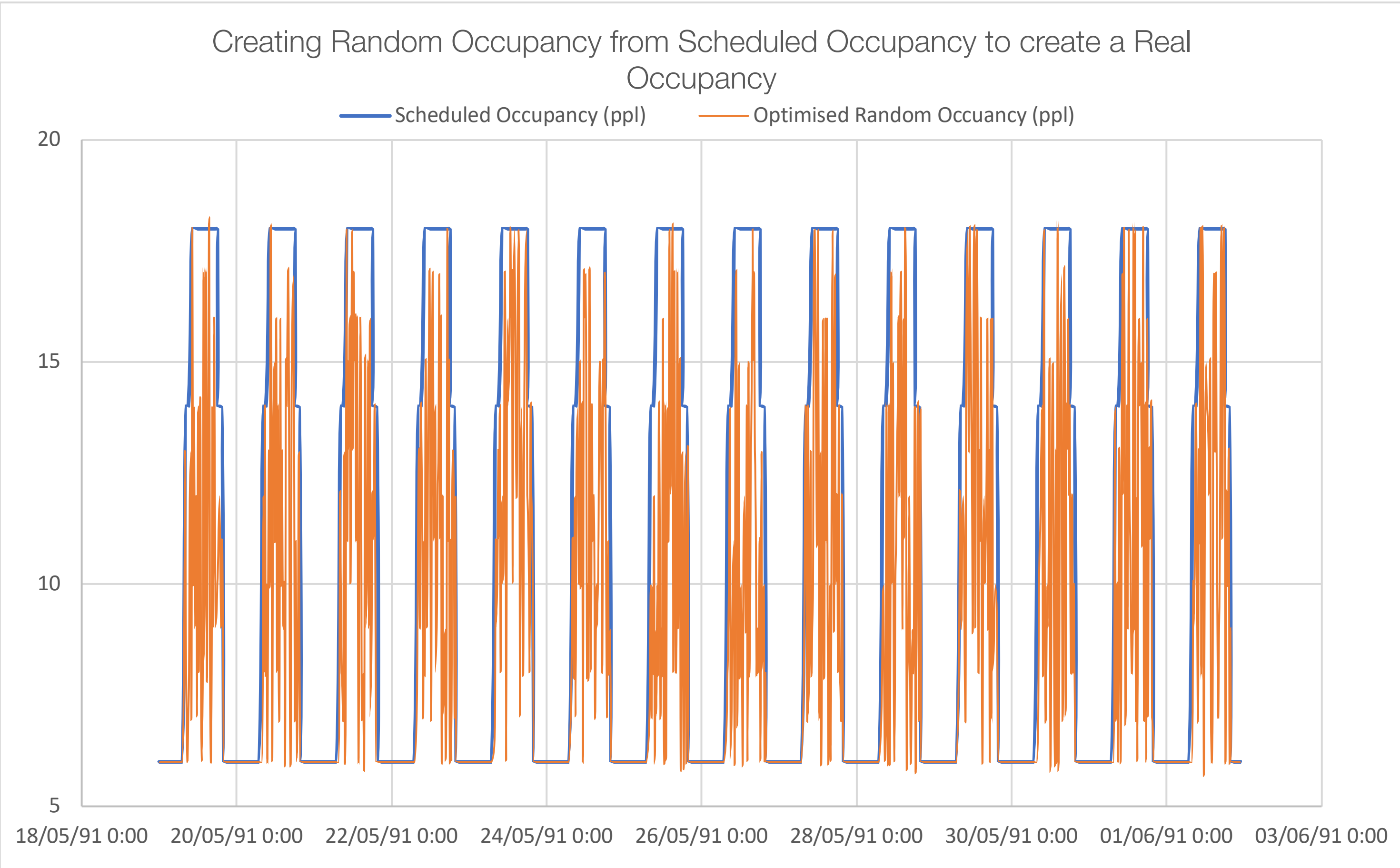

Figure 19 CREATING REAL OCCUPANCY

Using real occupancy schedules provides more randomness to the model and this models a more comfortable internal environment since the occupancy does not often reach 100%, so the methods used are more efficient in removing internal CO_2 while also keeping out particulates.

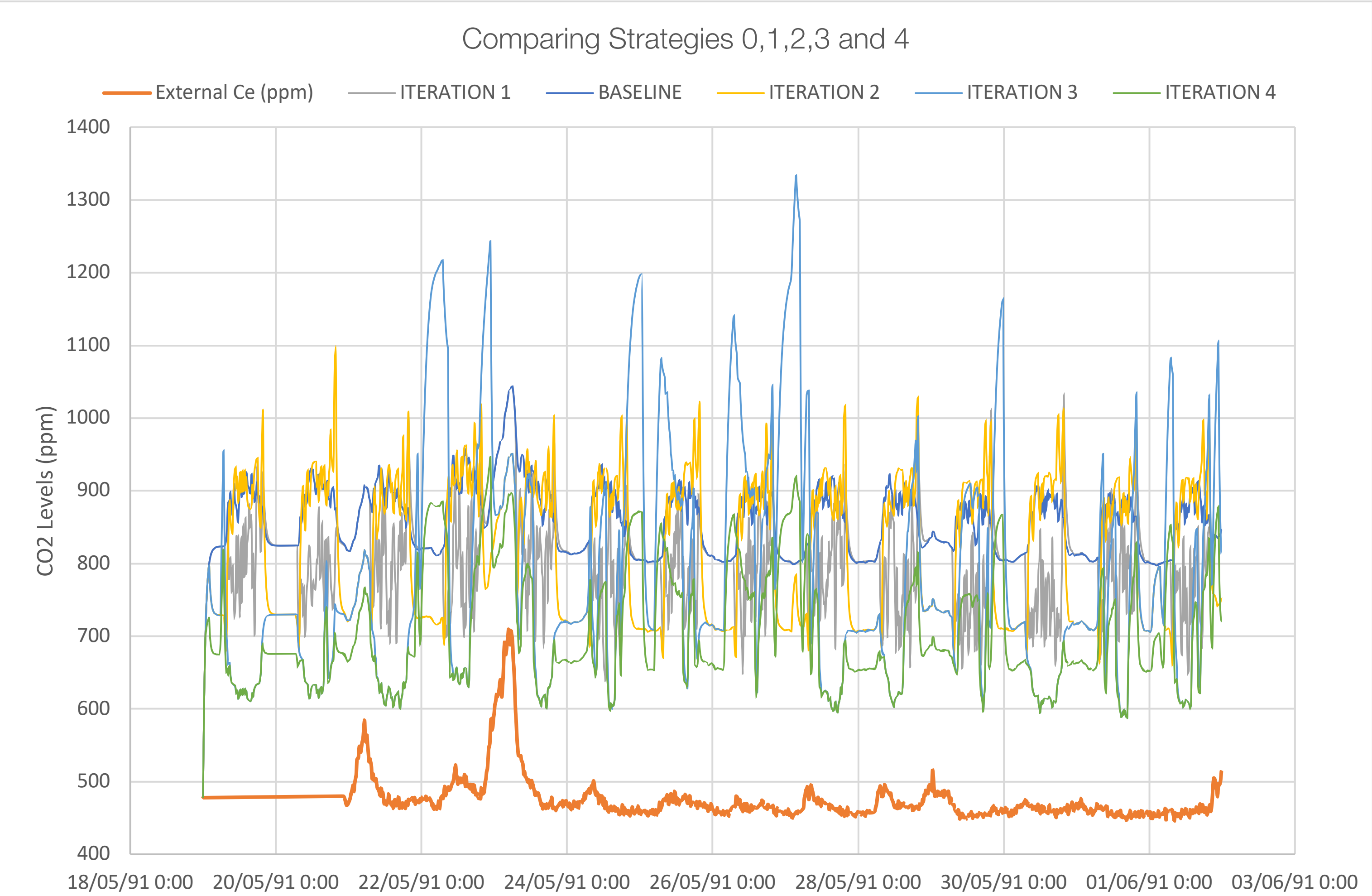

Figure 20 INTERNAL CO2 COMPARISONS

		BASELINE		ITERATION 1		ITERATION 2	
Category	Range	Frequency	%Simulated	Frequency	%Simulated	Frequency	%Simulated
IDA1	<400	810	27.33	1219	32.23	801	27.21
IDA2	400-600	810	27.33	1219	32.23	801	27.21
IDA3	600-1000	1344	45.34	1344	35.54	1342	45.58
IDA4	>1000	0	0	0	0	0	0

		ITERATION 3		ITERATION 4	
Category	Range	Frequency	%Simulated	Frequency	%Simulated
IDA1	<400	1002	30.91	1294	32.91
IDA2	400-600	1002	30.91	1294	32.91
IDA3	600-1000	1238	38.19	1344	34.18
IDA4	>1000	0	0	0	0

Table 8 ASSESSING CO2 CONCENTRATIONS

As in the scheduled occupancy case, iteration 4 yields the best results in terms of internal CO_2 concentrations and has the highest percentages in the high and medium IAQ bands.

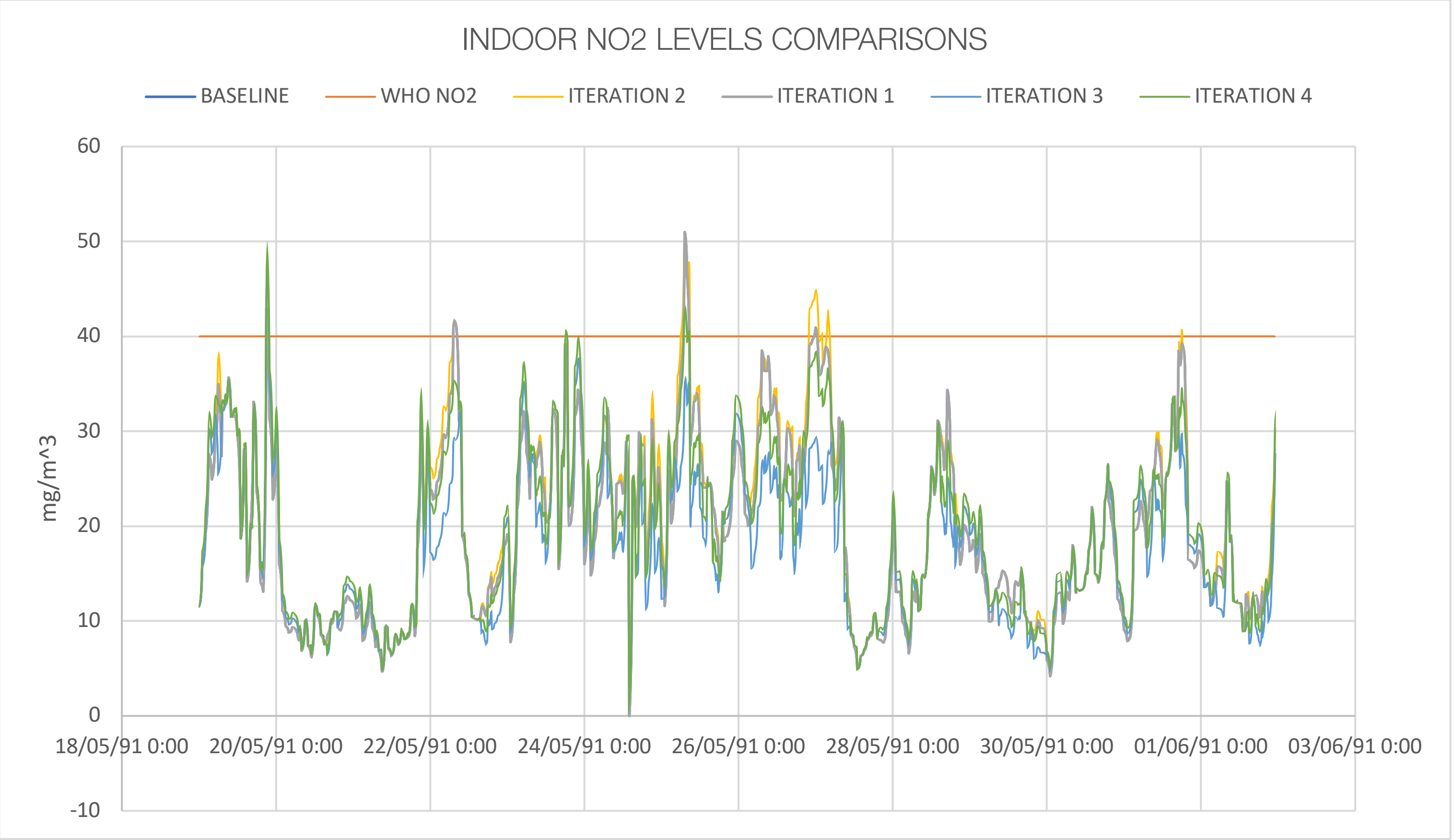

Figure 22 INDOOR NO2 LEVELS

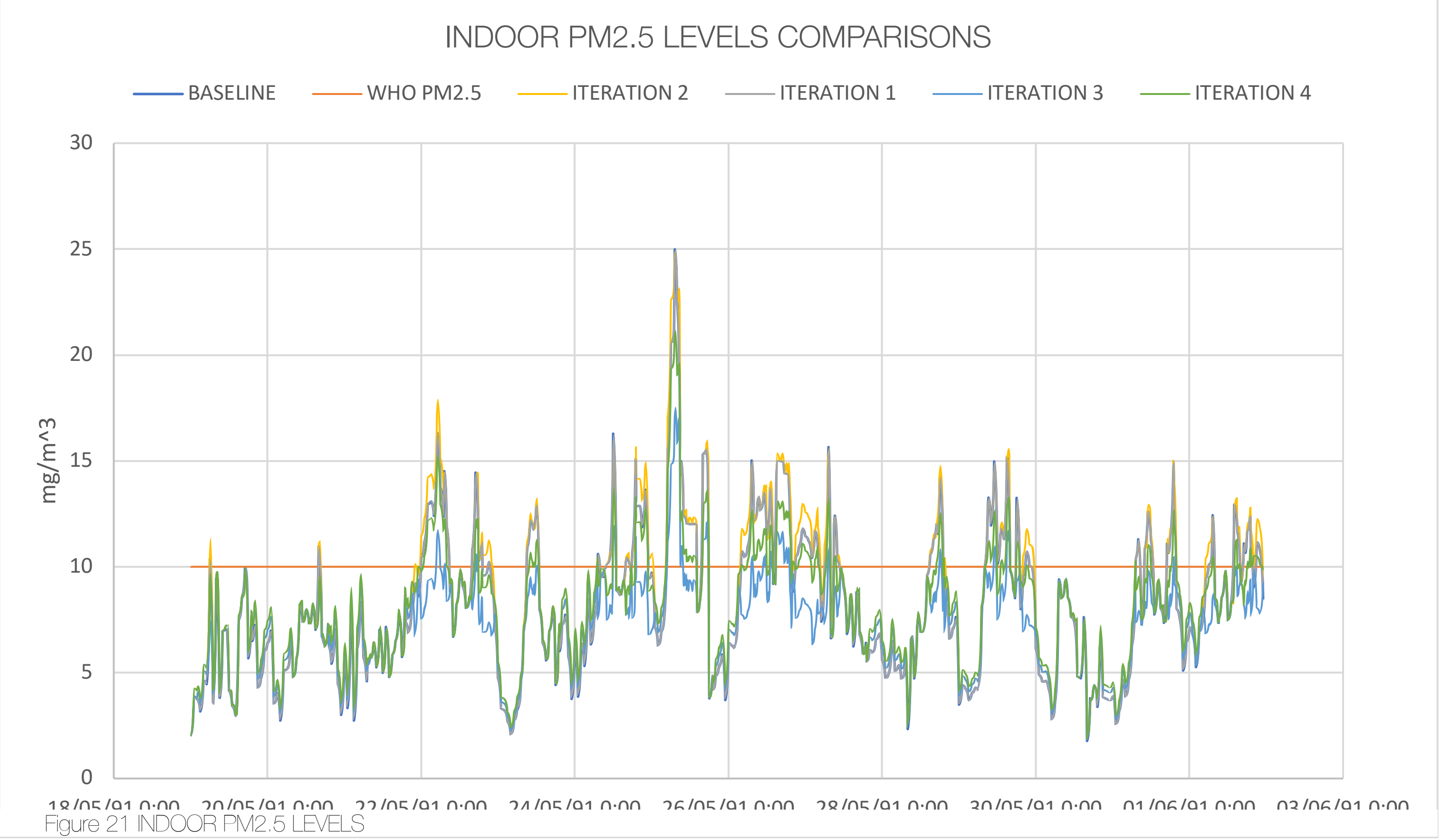

Figure 21 INDOOR PM2.5 LEVELS

10. ENERGY CONSUMPTION

Lastly, alterations to the ventilation lead to changes in the energy use and consumption, below displays the total heat loss due to ventilation, this is calculated by:

$$H\_vent = 1/3*ACH*volume$$

Scheduled Occupancy

Strategy	Baseline	Iteration 1	Iteration 2	Iteration 3	Iteration 4
H_vent	242290.944	242290.944	297842.688	228419.712	269175.168

Random Occupancy

Strategy	Baseline	Iteration 1	Iteration 2	Iteration 3	Iteration 4
H_vent	199486.944	242290.944	280376.064	217905.92	269175.168

Table 9 COMPARATIVE ENERGY CONSUMTIONS

The maximum energy consumption occurs during Iteration 2, i.e. CO_2 demand control ventilation whereas the baseline along with Iteration 3, i.e. particulate controlled ventilation use lower energy. Iteration 1, schedule change, followed by Iteration 4, combined strategy, are moderate in terms of energy consumption.

11. CONCLUSION

In conclusion, iteration 4 provides the most realistic and comfortable IAQ, even though it also leads to the higher energy consumption and is very dependent on the occupancy behaviour, showing that even though extensive modelling can be done to optimise conditions and energy consumption, the occupants have the biggest impact. Having only been modelled over two weeks in the moderate weather, this model would show very different results in the extreme heat and cold temperatures, therefore if this were being used to implement different strategies in the building control it would need to be completed at least over each season, looking at summer and winter design weeks as well. Furthermore, although this provides an insight into the IAQ, there are other factors and pollutants that would impact the indoor air quality, which can be assumed to follow the same patterns as CO2 and outdoor pollutants.

12. REFERENCES

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