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Placing VOC Sensors for Assessing Air Quality

A CFD Study of Indoor VOC Distribution

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Abstract

The Swedish Obligatory Ventilation Control (OVK) was established to ensure that ventilation systems are clean and work according to design. The control system of today is however not perfect, and there are many aspects of OVK which could be approached differently for improved efficiency and occupant health. A current project in Stockholm is looking at the possibility to use sensors, continuously metering volatile organic compounds (VOC), temperature, and relative humidity, in place of the airflow metering of the traditional OVK solution. One of the first issues encountered was sensor placement, as the sensors must be discreetly installed on available surfaces while the collected air quality data must represent the air in the occupied zone. A second challenge concerns how the sensor outputs should be interpreted in terms of indoor air quality.

The main purpose of this thesis is to suggest a model that can evaluate the suitability of different placements of sensors (such as the ceiling, walls, or lamp fixtures) from a VOC perspective. The idea is to evaluate what areas of the room best represent the average air quality of the occupied zone. This part of the study was approached by combining literature review and computational fluid dynamics (CFD) in two case studies; one office and one apartment. The intent behind the iterated method is to present a general CFD model that can be easily interpreted and adapted to accommodate new objects (e.g. building types or rooms). A secondary objective is to discuss how temperature and relative humidity can be included in the spatial position evaluation. Thirdly, the thesis aims to develop a base for further discussion regarding a method for how the sensor outputs can be combined into a single indoor environment quality index. The two last parts were primarily based on literature review.

The conclusions drawn in this study include a general CFD model that can be modified to evaluate different spatial location of VOC sensors, and general guidelines regarding placement of VOC meters in offices or apartments. Also provided in this report is a base for further discussion concerning indoor air quality estimations by combining the provided sensor-outputs, i.e. total VOC, temperature, and relative humidity.

Sammanfattning

Den obligatoriska ventilationskontrollen (OVK) infördes i Sverige för att säkerställa att ventilationssystem är rena och fungerar som de är designade att göra. Dagens system är dock inte perfekt och det finns många aspekter av OVK som skulle kunna göras annorlunda för att främja effektivitet och personers hälsa. Ett pågående projekt i Stockholm vill undersöka möjligheten att ersätta eller komplettera den luftflödesmätning som ingår i dagens OVK med kontinuerlig mätning av flyktiga organiska gaser (VOC), temperatur och relativ luftfuktighet med hjälp av sensorer. En av de första utmaningarna för projektet är placeringen av sensorer eftersom att de måste vara diskret installerade på befintliga ytor, samtidigt som det som uppmäts bör vara representativt för hur luften upplevs av personer i byggnaden. En annan utmaning för projektet är hur signalerna från sensorn ska kombineras för att utvärdera luftkvalitén.

Det huvudsakliga syftet med den här studien är att utveckla en modell som kan användas för att utvärdera lämpligheten av olika sensorplaceringar, till exempel tak, väggar och lamparmaturer, utifrån ett VOC-perspektiv. Idén är att ge en uppfattning om vilka placeringar som bäst representerar medelkvalitén på luften i vistelsezonen. Denna del av arbetet baserades på litteraturstudier och numeriska beräkningar med CFD (Computational Fluid Dynamics). Den föreslagna modellen applicerades i två fallstudier, ett kontor och en lägenhet. Avsikten med modellen är att den enkelt ska kunna tolkas och anpassas för olika rumstyper. Ett annat syfte med rapporten är att diskutera hur temperatur och relativ luftfuktighet kan inkluderas i utvärderingen av sensorplacering. Slutligen är ett tredje syfte med studien att påbörja en diskussion för hur de tre mätvärdena från sensorn kan kombineras i ett gemensamt inomhusklimatindex. De två sistnämnda delarna baserades främst på litteraturstudier.

Slutsatserna inkluderar en generell CFD-modell och metod som kan modifieras för att utvärdera olika placeringar av sensorn, samt riktlinjer för var VOC-sensorer bör placeras i kontor eller lägenheter baserat på två fallstudier. Också inkluderade i rapporten är en diskussionsbas för hur en utvärdering av luftkvalitet kan göras utifrån de tre värdena från sensorn (VOC, temperatur och relativ luftfuktighet).

Acknowledgements

I would like to thank my supervisor, Joachim Claesson, for providing feedback and suggestions over the course of the semester. Another sincere thank you goes to Annika Haglund who has provided me with information and welcomed me to the large-scale project from which the idea of this thesis derives. At last, my work would not have been possible without the collaboration with Marie Cabau who collected the sensor measurements in the reference rooms of my case studies.

Content

Nomenclature

Abbreviations

API = Air Pollution Index
BBR = Boverkets byggregler (Eng: Swedish Building Code)
CFD = Computational Fluid Dynamics
CO_2 = Carbon Dioxide
DPM = Discrete Phase Modelling
e-CO_2 = Equivalent Carbon Dioxide
EPA = United States Environmental Protection Agency
IAQ = Indoor Air Quality
IDI = Indoor Discomfort Index
IEI = Indoor Environmental Index
OVK = Obligatorisk ventilationskontroll (Eng: Obligatory Ventilation Control)
OZCI = Occupied Zone Compliance Index
PD = Predicted Percentage Dissatisfied
PMV = Predicted Mean Vote
RH = Relative Humidity
SBS = Sick Building Syndrome
TVOC = Total Volatile Organic Compounds
VOC = Volatile Organic Compounds
WHO = World Health Organisation

Variables

$\bar{A}$ = Surface area vector
C_{dmc} = Concentration demarcation value
C_{max} = Maximum measured concentration
C_{min} = Minimum measured concentration
$\bar{C}_o$ = Mean TVOC concentration in the occupied zone
C_{obs} = Observed concentration
C_p = TVOC concentration as area average of subject surface
C_μ = Constant used to calculate turbulent viscosity
$\bar{F}$ = Force vector
$\boldsymbol{I}$ = Identity matrix
k = Turbulent kinetic energy
p = Pressure
RH_{lcl} = Lower comfort level relative humidity
RH_{opt} = Optimal relative humidity
RH_{obs} = Observed relative humidity
RH_{ucl} = Upper comfort level relative humidity
T_{lcl} = Lower comfort level temperature
$\bar{T}_o$ = Mean temperature in the occupied zone
T_{opt} = Optimal temperature
T_p = Temperature as area average of subject surface
T_{ucl} = Upper comfort level temperature
V = Volume
ϵ = Dissipation rate
μ_t = Turbulent viscosity
$\bar{v}$ = Velocity vector
ρ = Density
$\bar{\bar{\tau}}$ = Stress Tensor

1 Introduction

Sustaining adequate indoor air quality (IAQ) is crucial for occupant health. Throat issues, nausea, and headaches are common symptoms related to *Sick Building Syndrome (SBS)*, which is caused by bad indoor conditions such as unclean ventilation, wrong humidity levels, or odours. Governments and agencies have taken actions to prevent SBS by establishing general regulations and recommendations regarding building materials or ventilation control (United States Environmental Protection Agency, 2016).

The Swedish Obligatory Ventilation Control (OVK) was established in 1991 (Boverket, 2017), to ensure that ventilation systems are clean and work according to design. Swedish building regulations (BBR) state that all building owners (except owners of single or two-family houses) are obliged to make sure that OVK is performed by a certified professional every three to six years. It is mainly airflow rates that are measured during an OVK, although it also includes ensuring accessibility of ventilation instructions, checking that ventilation system are clean from pollutants, and suggesting recommendations for increased energy efficiency (Boverket, 2017).

While OVK exists to promote good IAQ, there are still many aspects of the current solution which could be improved. A Swedish survey conducted in 2017, found that 20% of the Swedish population are unsatisfied with the indoor environment in their homes (Folkhälsomyndigheten; Institutet för miljömedicin, Karolinska Institutet, 2017), which is a strong indication that there is a need for a better adapted method of controlling the IAQ. RISE (Research Institutes of Sweden Holding AB), an independent research institute, stated some issues with OVK in an article from 2017 (Fyhr, 2017). Some topics mentioned in that article were lack of economic support, lack of follow-up audits, no centralised systematic approach leading to inconsistency of quality regarding improvement recommendations, and the fact that the control is checked towards design conditions rather than the actual activity of the building. Another issue, brought up recently by Boverket (Boverket, 2017), was that there could be a significant risk of deficiency of certified auditors in the future, as the number of buildings is rising while many of the certified auditors are retiring. The solution proposed was to lower the certification criteria (for example lowering the number of years of experience) for auditors.

There is currently a project, involving multiple building owners in Stockholm[1] and REQS System AB, aiming at developing a better method of controlling IAQ. The idea is to use continuous metering by installing a small (and comparingly cheap) sensor, which can measure levels of VOC (volatile organic compounds), relative humidity, and temperature. VOC is many times overlooked when evaluating IAQ, although there are studies which argue that it could create a clearer picture of actual air quality than the traditional indicator carbon dioxide (CO_2) (Mølhave, et al., 1997) (Sun, et al., 2017). While traditional ventilation inspections only measure ventilation flow rate every few years, this other method could thus potentially increase both the efficiency and quality of the IAQ inspection. Carbon dioxide (CO_2) is strongly correlated to human activity in a building, one purpose of the project at large is thus also to determine how VOC levels relate to CO_2. An experimental pilot study is to be conducted in different types of buildings (hospitals, public buildings, offices, and apartments) (Haglund, 2018), where one initial issue concerns placement of sensors, as the sensors should preferably be discreetly mounted to existing surfaces while still providing data that is representative for the occupied zone. Another challenge for the project is determining how the sensor outputs should be interpreted.

The main purpose of this thesis is to develop a simple model that can evaluate different placements of sensors, such as the ceiling, lamp fixtures, or walls, to conclude potential measuring points for deriving

[1] Locum, SISAB, Stockholms stad, Vasakronan, and Förvaltaren Sundbyberg

signals representative for the indoor air quality in the occupied zone with respect to VOC. The intent is to provide a general model which can easily be interpreted and adapted to room types. A secondary objective of this study is to discuss how temperature and relative humidity can be included in the model. The third objective differs slightly from the first two, as the thesis aims to also develop a first draft for how the sensor outputs (VOC, temperature, and relative humidity) can be combined in a single indoor environment quality index. The suggested index is intended to provide a base for future work and function as a proposal for how building owners can interpret the observed air quality.

2 Literature Review

Information regarding volatile organic compounds, carbon dioxide, and existing recommendations for indoor air quality and sensors can be found in this chapter.

2.1 Definition of VOC and TVOC

Volatile Organic Compounds (VOC) is an umbrella term for several organic compounds. Occupants might notice VOC as bad odour or generally “bad indoor air quality”. Bad odour can be reported from certain VOCs even at low (or undetectable) quantities (Mølhave, et al., 1997).

Total VOC (or TVOC) is a way of measuring the combined levels of present VOCs, but what VOCs are included in TVOC can vary depending on the method of measurement, and the application or context. No single instrument can measure all types of VOC, and TVOC is thus always a selection which should be clearly defined by the study (United States Environmental Protection Agency, 2017). ISO Standard 16000-6:2012 approaches the issue of defining TVOC, but primarily emphasises that it can vary depending on the method and application.

In general, American GPO (U.S. Government Publishing Office (GPO), 2018), and EPA (United States Environmental Protection Agency) define VOCs as:

> *“Volatile organic compounds (VOC) means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions.” (U.S. Government Publishing Office (GPO), 2018)*

EPA however, also states another definition specifically for indoor air. The main difference is that indoor air VOC does not exclude compounds that fulfil the criteria of evaporating at normal indoor temperature and pressure:

> *“Volatile organic compounds, or VOCs are organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure.” (United States Environmental Protection Agency, 2017)*

Australian NPI (National Pollutant Inventory (NPI), 2009) defines volatile organic compounds as:

> *“Total VOC are defined as any chemical compound based on carbon chains or rings with a vapour pressure greater than 0.01 kPa at 293.15 K (i.e. 20°C), that participate in atmospheric photochemical reactions.” (National Pollutant Inventory (NPI), 2009)*

NPI then proceeds with listing a few exceptions from the rule; carbon monoxide, methane, acrylamide, benzene hexachloro, biphenyl, chlorophenols, n-dibutyl phthalate, ethylene glycol, di-(2-ethylhexyl) phthalate (DEHP), 4,4-methylene bis 2,4 aniline (MOCA), methylenebis, phenol, and toluene-2,4-diisocyanate.

The World Health Organization defines VOCs of different levels of volatility (semi-volatile, volatile, and very volatile) (United States Environmental Protection Agency, 2017).

There are different ways to divide VOC into sub categories. Common divisions are based on their physical properties, potential health effects, or chemical character (Mølhave, et al., 1997). Many studies mention the problems associated with an unstandardized definition for TVOC (Mølhave, et al., 1997) (Berglund, et al., 1997), and some suggestions have been developed on how to standardise the reported TVOC. One suggestion is to add a suffix to symbolise the type of reading instrument, while Mølhave, et al. ultimately propose that TVOC should be as representative as possible for indoor air quality, include the most abundant types of VOC (but as many as possible), and be transparent with what range of VOC is included. Shortly put, TVOC should be as close to the actual indoor air total VOC as possible, which was also put through as a standardisation proposal for the European Comission (Berglund, et al., 1997).

Some likely sources of VOC are wall paint, floor coating, furniture, printers, computers, cleaning products, perfumes, and clothes. Newly built houses may show larger concentrations of VOC than older buildings, with certain types of VOC declining rapidly for the first one or a half year (Shin, 2013). Although VOC levels are higher during the first year(s) of operation, better indoor air quality than old buildings can still be reached by following proper building standards (Tuomainen, et al., 2003).

In Table 1, common indoor air compounds are listed according to chemical subgroup.

Table 1. Common indoor air compounds divided by chemical subgroup (Mølhave, et al., 1997)

Chemical Subgroup	Common VOCs
Alcohols	2-propanol, 1-butanol, 2-ethyl-1-hexanol, methanol, ethanol
Aldehydes	Butanal, pentanal, hexanal, nonanal, benzaldehyde, acetaldehyde, hexanal
Ketones	Methylethylketone, methylisobutylketone, cyclohexanone, acetophenone, acetone
Organic Acids	Hexanoic acid, acetic acid, formic acid, acid fragment
Amines	[triethylamine, pyrrolidine, di-iso-butylamine, 2-ethyl-hexylamine, n-octylamine]*
Alphatic Hydrocarbons	n-C6 to n-C16; n-Hexane, n-heptane, n-octane, n-nonane, n-decane, n-undercane, n-dodecane, n-tridecane, n-tetradecan, n-pentadecane, n-hexadecane, 2-methylpentane, 3-methylpentane, 1-actane, 1-decene
Aromatic Hydrocarbons	Benzene; toluene; ethylbenzene; m/p-xylene; o-xylene; n-propylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; 2-ethyltoluene; styrene; naphthalene; 4-phenylcyclohexene

* (Karlsson, et al., 1989)

2.2 Comparison of CO_2 and VOC

Indoor air composition differs from the atmospheric and is affected by everything from people or animals, to the material of the floor mat. Carbon dioxide is one of the most common indicators of indoor air quality as it is strongly related to human activity, where human breath contains approximately 4% CO_2 (Rengholt, 1991). VOC on the other hand, is currently not the most popular indicator of air quality, but there are studies promoting TVOC as a more exhaustive parameter as it includes uncomfortable odours and a wider range of compounds that might affect the health of occupants (Mølhave, et al., 1997) (Sun, et al., 2017). Of course, as TVOC allows for inclusion of multiple contaminants, this makes for a more complicated parameter to assess. Moreover, it is currently difficult to compare studies of TVOC as no standards of what VOCs to include are available, and transparency is thus an important key factor when conducting research related to this.

A consequence of including many compounds into an indicator, as opposed to CO_2, is a more unstable behaviour. Measuring TVOC to assess indoor air quality can thus prove problematic as VOCs can be affected by any new furniture, occupants, office equipment or even plants. In a study published in 2006 (Wood, et al., 2006), it was found that total VOC levels can be reduced significantly simply by keeping potted plants in the office. In addition to this, occupancy derived VOC concentration levels can vary greatly with for example age or on what a person has recently eaten (Sun, et al., 2017), as well as depend on perfume or personal hygiene. Sun, et al. also found that levels above 100 ppb might be more stable and reliable when comparing VOCs to CO_2, as low levels were less affected by the introduction of plants (Wood, et al., 2006).

Linking human activity to VOC may thus not be as obvious as linking it to CO_2, but this does not mean that VOC is not at all representative. An article from 2013 (Su, et al., 2013), analysed environmental, individual, and social determinants of VOC, based on the data from the *Relationship of Indoor Outdoor and Personal Air* (RIOPA) study. The study did find resemblance between overall indoor concentration of VOC and personal VOC concentration. Indoor VOC emissions in classrooms were found to be 57% due to occupants and 35% due to air supply, in a study from 2016 (Tang, et al., 2016), where the remaining 8% were linked to non-occupant sources. According to that study, the typical engineering student emits at an average 6.3 mg/h of TVOC. Human breath has showed to contribute with a significant amount of VOC in indoor environments (Fenske & Paulson, 1999), and there are other studies agreeing that the human impact on VOC should not be neglected (Mølhave, et al., 1997) (Sun, et al., 2017). A German study from 1989 (Seifert, et al., 1989) found that TVOC levels in homes can drop with as much as 50% in periods when all occupants are absent (for example on vacation). The link between human occupancy and VOC levels is thus most likely quite strong.

A study concerning the IAQ of different schools in Michigan emphasised the importance of influence from different activities or use of rooms and halls, as they presented large variance between normal classrooms and e.g. swimming halls or science rooms and the classrooms directly adjacent to those (Goodwin & Batterman, 2006). Although there seem to be some link between CO_2 and VOC, it is clear that the relationship is not linear. There is however ongoing research regarding the matter, and manufacturers of sensors claim to develop reliable algorithms for estimating CO_2 based on TVOC (AMS, 2017).

While using VOC as a parameter of air quality, measuring VOC has shown to provide a good indication on ventilation quality as well, both regarding flow-rate and air distribution, by using multi-point measuring (Mølhave, et al., 1997) (Berglund, et al., 1997). Whether it is best to meter CO_2 or VOC for assessing indoor air quality ultimately comes down to the type of application and weighing the benefits against the disadvantages.

2.3 What is Good Indoor Environment Quality?

Thermal comfort and indoor air quality is subjective and is thus difficult to rate on a simple scale. There are some guidelines available, both on international and national levels. The World Health Organization (WHO) is an example of an international organisation, while the Public Health Agency of Sweden (Swe: *Folkhälsomyndigheten*) or the Swedish Building Code (BBR) are some examples of national authorities that stipulate those kinds of guidelines.

The Swedish Building Code (BBR) states that the ventilation system should be designed so that any substances that are health hazardous, humidity, disturbing odours, pollutants from people or material, or general emissions from the activity of the building, should be removed (Boverket, 2017). It states a minimum air flow rate of 0.35 l/s per m^2 floor area, with an additional air flow rate per person depending on the type of building. In buildings other than dwellings, completely shutting off the ventilation is allowed given there is no occupancy. The system should be turned on prior to occupants arriving so that air quality can be ensured.

It is primarily the environment in the *occupied zone* which should fulfil requirements for indoor environment quality. The bathroom however, which technically belong to the occupied zone, is typically not routinely checked as people only spend short period of times there (Folkhälsomyndigheten, 2016).

2.3.1 Typical Indoor TVOC Concentration and Air Pollutant Thresholds

A threshold for carbon dioxide in indoor air is 1000 ppm, but no upper threshold has been set for combined VOCs in Sweden. In an article from 1998, Boverket states that the level of total VOC (TVOC) is not representative for how people generally perceive the indoor air quality (Samuelsson, 1998). Instead, it suggests focusing on limiting singular VOCs that has clear effects on health or comfort, but without defining which VOCs to limit. An ISO-standard concerning indoor air quality, named ISO 16000, approaches the matter of TVOC in many of the parts. Typical thresholds for singular VOCs are listed, but no threshold regarding TVOC. Even though TVOCs are mentioned many times in ISO Standard 16000, the defintion is vague and allows for multiple combinations of VOCs to be classified as TVOC.

A study made in a French hospital measured the levels of more than 40 different VOCs (Bessonneau, et al., 2013). The conclusion of the report was that the mixture samplings of VOCs were complex and that it was thus difficult to estimate the exact effects the levels can have on living beings in the hospital. In the study, the reception hall was chosen as a reference location, but the overall VOC levels did not vary significantly between the reception hall and other sites, or between morning and afternoon.

The average value of TVOC in Swedish dwellings is roughly 200-300 $\mu g/m^3$ (A Persson; Karolinska Institutet, 2014). A non-Swedish study from 1994 suggested a wider range of 70-1130 $\mu g/m^3$ (Brown, et al., 1994), and a study in Michigan schools found a typical average indoor concentration of 48 $\mu g/m^3$ with a typical maximum of 384 $\mu g/m^3$. Breath has been found to contain widely varying concentrations of between 70-950 $\mu g/m^3$ (Fenske & Paulson, 1999), and can vary even more if including other occupancy-derived VOCs. In summary, it is difficult to conclude typical concentrations as many factors influence the final values.

WHO stated in their *Air Quality Guidelines for Europe* (WHO Regional Office for Europe, 2000) that formaldehyde should not exceed 100 $\mu g/m^3$ for more than 30 minutes (levels can be detected at concentrations above 0.03 $\mu g/m^3$). In Sweden, the threshold for formaldehyde is 200 $\mu g/m^3$ (Rengholt, 1991). The ISO Standard 16000-5:2007 gives example of thresholds for some other VOCs as well.

Some previously suggested indication levels of TVOC for evaluating indoor air quality are *comfort* (<0.2 mg/m3), *multifactorial exposure* (0.2-3 mg/m^3), *discomfort* (3-25 mg/m^3), and *toxic* (>25 mg/m^3). Another suggested method of air quality indication is to keep a single threshold which should not be exceeded, for example 300 $\mu g/m^3$ (sources cited by (Mølhave, et al., 1997)). There are yet other suggestions to simply keep VOC levels as low as reasonably achievable (*ALARA*), as health effects are not well explored (Berglund, et al., 1997).

2.3.2 Temperature Guidelines

The Public Health Agency of Sweden provides recommended temperature ranges to ensure good health of the occupants. The operative indoor temperature (for groups of people that aren't considered sensitive) should generally be in the range of 20-23°C, while a temperature range of 18°C to 24°C is considered adequate. For short period of times, temperatures as high as 26°C are considered acceptable without being regarded as a health hazard (Folkhälsomyndiheten, 2014:17). The air temperature, as opposed to the operative temperature, should be in the range of 20-24°C long term, measured with a common thermometer (Folkhälsomyndigheten, 2018).

Variation in mean operative temperature between 0.1 and 1.1 m above the floor should be less than 3°C to avoid discomfort, and the radiative temperature difference between window and the opposing wall, as well as between ceiling and floor, are regulated as well (10°C and 5°C, respectively) (Folkhälsomyndiheten, 2014:17).

It is stated that when measuring and logging the temperature for a long period of time to evaluate air quality, the sensor must be placed in the occupied zone, in a place where it not reached by solar rays (Folkhälsomyndigheten, 2018). Temperature specifically is recommended to measure at 0.6 and 1.1 m above the floor, and when needed also at 0.1 and 1.1 to ensure a minor temperature difference.

Even though the regulations are less strict regarding bathrooms, it could be beneficial to ensure that the temperature is not below recommended levels, partly to avoid mould or excessive humidity, but also because people generally wear less clothes within the bathroom (Folkhälsomyndigheten, 2016).

2.3.3 Relative Humidity

A normal indoor relative humidity of a Swedish multifamily building is approximately 30%, according to a report from Boverket (Eng: *the Swedish National Board of Housing, Building and Planning*) (Boverket, 2009). The same report shows statistics suggesting a normal range of 20 – 45%. It is normal that the relative humidity surpasses 70% however, especially in late summer when the outside air is hot and humid.

Studies suggest different levels of relative humidity for "optimal health", but generally tend to keep somewhere within the range of 40-60% (Derby, et al., 2016) (Arundel, et al., 1986), although WHO recommended in 1988 indoor RH levels to be between 30 and 50% (World Health Organization, 1988). This indicates that the general indoor relative humidity of a normal Swedish household is low (<40%). The effects of low humidity on volatile organic compounds has been reported as *non-uniform* (Derby, et al., 2016). Formaldehyde (a common VOC) and relative humidity has however been linked as the levels of formaldehyde increase significantly with higher relative humidity (Arundel, et al., 1986).

As the Swedish climate offers long, and comparingly cold, winters however, a low relative humidity might be beneficial as this would decrease the risk of condensation on windows or exterior walls. When condensation occurs within a building there is a possibility of occupant discomfort or mould. Keeping a temperature above the dew point in the bathroom, as mentioned in section 2.3.2, is of extra importance to avoid the negative effects of condensation.

The dew point, which is the temperature at which condensation occurs, for different levels of humidity, is shown in Figure 1. That is, if the air is kept at 40% relative humidity and the indoor temperature is 22°C, a window temperature of just below 8°C is enough for condensation to occur, while a relative humidity of 30% would require a window temperature of less than 3.5°C. The dew point temperature of the graph in Figure 1, is based upon psychrometric charts (Havtun, 2014).

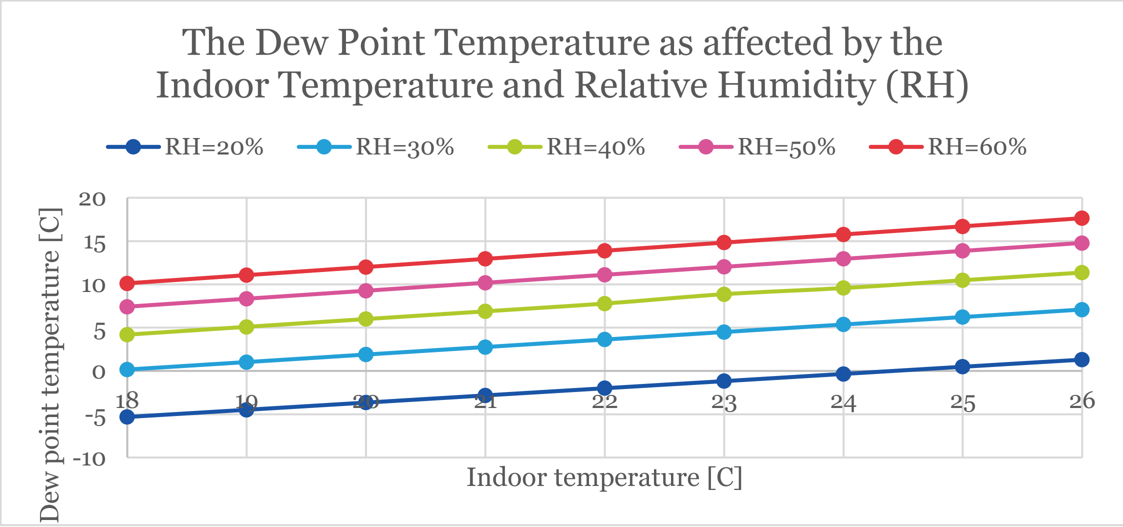

Figure 1. How the dew point temperature depends on indoor temperature and relative humidity

In Stockholm, the recommended indoor relative humidity for dwellings is 25-50%, with an additional recommendation to keep it below 45% to avoid dust mites (Stockholms stad, 2018). There are currently no threshold values on a national level regarding indoor relative humidity issued by Swedish authorities. The Swedish Work Environment Authority (Swe: *Arbetsmiljöverket*) states on their website that the impact of relative humidity on perceived air quality is both small and difficult to evaluate, as it varies with outdoor air during the year or even the day (Arbetsmiljöverket, 2015).

Regarding distribution of humidity, one report concluded that the distribution of relative humidity within a room is small using the k-ε model of numerical turbulence (further explained in a later section), but that walls that absorb water vapour could have an impact on the distribution of humidity in a ventilated room (Iwamae, 2007).

2.3.4 Indoor Environment Quality Indices found in Literature

Due to the experience of air quality being individual to each occupant, it is difficult to settle on one assessment index that work well for all applications. The European ISO-standard is based on the PMV (Predicted Mean Vote) index and the PD (Predicted Percentage Dissatisfied) index. The first allows people to define the thermal comfort at a scale from -3 (very cold) to +3 (hot). The latter is a quantitative prediction of how many people can be expected to be unsatisfied with the indoor environment. Not all people can be satisfied at once, and the highest score is thus a PD of 5% (Rengholt, 1991).

The PMV was used as base in a study by (Zhu & Li, 2017), who suggested a model that takes into account CO_2, formaldehyde (a common type of VOC) and respirable particles. Zhu and Li provide suggestions for thresholds in [ppm] and *PMV* index values in relationship to the effect on human comfort. The combined PMV, in the study by Zhu and Li calculated as

$$PMV_{IAQ} = \max(PMV_1, PMV_2, PMV_3), \quad \text{(e21)}$$

should have a low value to ensure proper comfort to occupants. The scale is presented as comfort (0), little discomfort (1), discomfort (2), and extreme discomfort (3). For CO_2, it was reported that a PMV of (1) correspond to 700 ppm, (2) correspond to 1000 ppm, while 480 ppm or less can be regarded as good occupant comfort. A Brittish study (Ncube & Riffat, 2012) instead suggested evaluating indoor air quality based on CO_2 using percentage dissatisfied, according to

$$PD_{IAQ} = 395 \cdot e^{-15.15 \cdot C_{CO2}^{-0.25}} \quad \text{(e22)}$$

in which the concentration refers to the difference between indoor and outdoor, which should in this case not surpass 650 ppm to keep below the recommended 1000 ppm, according to English conditions.

Moschandreas and Sofuoglu compared how a symptom index correlated to the Indoor Environmental Index for office occupants in 100 buildings in the United States. They advanced an existing index for air pollution and included indoor discomfort to create a combined Indoor Environmental Index (IEI) (Moschandreas & Sofuoglu, 2012). It is clearly stated in their report that the model is only applicable for office buildings, and that there is not enough research yet to use the model for other types of buildings.

The Indoor Discomfort Index (IDI) that Moschandreas and Sofuoglu developed includes temperature and relative humidity. It is a simple relation explained by eq. (e23) in which T is temperature and RH is relative humidity. The indices give further description of each variable, where opt means optimum comfort level, obs means the observed value (and thus the actual input), and ucl and lcl refer to the upper and lower comfort levels.

$$IDI = \frac{1}{2} \cdot \left(10 \cdot \frac{\mathrm{T_{opt}} - T_{obs}}{T_{ucl} - T_{lcl}} + 10 \cdot \frac{RH_{opt} - RH_{obs}}{RH_{ucl} - RH_{lcl}} \right) \quad \text{(e23)}$$

The report suggests that temperature comfort range is set to 19-25°C, with 22°C as optimum, and that the relative humidity comfort range is set to 35-55% with an optimum of 45%. The ranges and optimum values are not compliant with Swedish statistics or recommendations (see sections 2.3.2 and 2.3.3.).

The Air Pollution Index (API) is similar to the IDI but takes into account multiple sources of air pollution, including for example fungi, CO_2, TVOC, and, bacteria. The IAPI is written as

$$IAPI = \frac{1}{I} \cdot \sum_{i=1}^{I} \frac{1}{J} \sum_{j=1}^{J} \frac{1}{K} \sum_{k=1}^{K} 10 \left(1 - \frac{C_{i,j,k}^{max} - C_{i,j,k}^{obs}}{C_{i,j,k}^{\max} - C_{i,j,k}^{min}} \left(\frac{C_{i,j,k}^{dmc} - C_{i,j,k}^{obs}}{C_{i,j,k}^{dmc}} \right) \right). \quad \text{(e24)}$$

I, J, and K denotes the group level to allow for grouping of for example gases, type of gas, and specific gaseous compound. Instead of comfort levels, the index uses demarcation values. As no demarcation values are defined for TVOC, another approach using a separate unit value depending on the mass concentration is used for the TVOC input (Moschandreas & Sofuoglu, 2012). A sensitivity analysis of the total IEI, done by the same study, showed that temperature has the largest impact on the index while relative humidity has the lowest impact.

2.4 Sensor Placement According to Standards and Previous Studies

There have been many studies before this concerning research of IAQ sensor placement. Mahyuddin and Awbi suggested optimal placement of CO_2 sensors in a room through experimental research in an environmental test chamber (Mahyuddin & Awbi, 2010). They looked at four situations, all of which were evaluated at three different heights (0.2, 1.2, and 1.8 m) for which the highest concentration of CO_2 occurred at 1.8 m rather than breathing height (1.2 m). An interesting finding is the correlation between high temperatures and high CO_2 levels, while they found that more than one sensor may be necessary at low air flow rates to provide a representative picture of the IAQ.

Another report used data analysis to analyse the CO_2 distribution within a classroom (Mahyuddin, et al., 2014). The sensors were placed at 0.2, 1.2, and 1.8 m above the floor at five different locations, for three different classrooms. A total of 12 sampling points for each classroom were statistically analysed using the ANOVA technique to determine the relationship between CO_2 concentrations and spatial position, occupancy patterns, ventilation strategies, and other environmental parameters (such as temperature, relative humidity, and air velocity). In a room with well mixed air, the placing of sensors should be unimportant. Mahyuddin, et al. however, found a statistically significant difference between the studied locations in all but one classroom, and that the vertical position is not of significant importance as variations were small (although all locations were within the occupied zone). The statistical analyse was done at a 5% level of significance.

Mahyuddin, et al. also concluded that the presence of stagnant air may cause large variations of CO_2 concentration. The study thus found that sensor position is of importance, but that open doors or windows give a more well mixed scenario in which the difference between locations is less significant (Mahyuddin, et al., 2014).

The ISO Standard 16000-5:2007 was developed to help in the process of measuring VOCs. It provides guidelines for both short- and long-term measurement, although it does not completely comply to continuous “permanent” measurement. What can be derived from the standards is the importance of metering indoor air quality as perceived by occupants. The placement guidelines provided in ISO 16000-1:2006, includes placing the sensor at least 1 meter from walls and between 1.5 and 2.0 meters to account for the breathing height of occupants. Another recommendation is to place the sensor where it is protected from human intervention, which is in reality difficult if placed within the recommended volume.

The cost of the sensor is another common parameter. One study looked at the optimal placement, from a cost and coverage perspective, in a closed parking complex using a combination of CFD modelling (for predicting CO distribution) and a genetic algorithm in Matlab (Mousavi, et al., 2018). The combination allowed for a more thorough prediction and optimisation of the sensor number and placement, although the study of Mousavi, et al. only took into consideration positions at breathing height (1.5 m).

Bulińska, et al. approached optimal sensor placement through experimentally validated CFD, by looking at areas in a typical bedroom which provide a high possibility of CO_2 concentration close to the average of that room (Bulińska, et al., 2014). Suitable locations showed to be in the middle of the room or closer to the door (which was the outlet in their simulations). One condition for suitable sensor position suggested in the report, is that the monitored CO_2 levels should not exceed those of the source(s). Close to the radiator or window were considered non-suitable, as well as too close to a sleeping person/CO_2 source (expanded for the entire room height) or within 40 cm from a wall. Any height in the middle of the room provided representative results, which is much like concluded in the report by (Mahyuddin, et al., 2014).

Bulińska, et al. stress upon doing the research for multiple scenarios as temperature and ventilation conditions may vary throughout the year, thus changing the air flow patterns (Bulińska, et al., 2014). The report also concluded that varying window geometry and radiator temperature may have a large impact on the general distribution of CO_2. It is however stated that an estimation of optimal placement can likely be done, and that monitoring CO_2 concentration in the centre of the room will yield representative values. The impact on heating method was also analysed by (Zhang, et al., 2017), who primarily looked at the behaviour of cooking VOC depending on method of heating. Their finding was that vertical distribution was of less importance with uniform floor heating than with traditional radiator heating, although they only considered heights within the occupied zone.

There have been many studies related to optimal sensor placement with respect to quickly detecting dangerous pollutants and infectious diseases (Fontanini, et al., 2016) (Mazumdar & Chen, 2007) (Zhang, et al., 2013). To rapidly detect relevant compounds, the sensors must be placed so that maximum coverage is provided. Depending on the application, other air quality factors might not be of importance as any level of for example infectious disease is unwanted. In this case, a good location might be that to which air travels the fastest and most consequently (most likely the ceiling, which is suggested as appropriate placing of sensors in airplanes by (Mazumdar & Chen, 2007)).

An algorithm is suggested in the study by Fontanini, et al., which evaluated sensor placement with respect to number of sensors and response time. The algorithm is based on the finite dimensional Perron-Frobenius concept, and could, according to the authors, potentially be used both for sensor placement for sufficient response time in case of emergency as well as placement for representative coverage of indoor air quality (Fontanini, et al., 2016), although most likely not simultaneously. Ideally, and according to the constraints of the suggested algorithm, sensors for IAQ should sense the occupied zone only, whilst not actually being placed within the occupied zone to avoid accidental damage to the sensors. Thus, the outlet is stated as an appropriate position.

Factors of another nature than temperature or IAQ could be of great importance when installing sensors in a public environment. In a study of IAQ in Michigan schools (Goodwin & Batterman, 2006), the ideal spatial position of a sensor was stated as a minimum 0.6 m away from floor or ceilings, 0.5 m away from areas in which the air risks being too stagnant (e.g. bookshelves), sufficiently far away from windows, doors, or recognised pollutant sources, while simultaneously inaccessible for children. The stated restrictions leave little space for discussion when placing sensors, although it could be a safe way of sampling IAQ with no further information regarding air flow in the specific class rooms.

3 Methodology

The method presented in this chapter is a suggestion for how candidate areas for placing TVOC-based IAQ sensors may be evaluated in terms of compliance towards the mean IAQ of the occupied zone. Throughout the development process of the method, an apartment and an office were used as reference which allowed for validation of the models with an actual IAQ sensor. Only a few scenarios and reference rooms were approached in this study, partly due to the focus being on developing a general model to be used as sensor placement assessment tool, and partly due to the iterative nature of optimisation through CFD (which would otherwise require more time than available). These references and scenarios are presented as case studies later in this report. Through clearly defining common parameters and the placement assessment process, this method could be further developed and adapted to suit other building, furniture settings, VOC sources and ventilation types.

3.1 Overview of Method for Evaluating Sensor Position

This section describes the method used for the case studies starting at page 21 in this report. An apartment and an office were used for reference which allowed for validation of the models with an actual IAQ sensor. The office and apartment were recreated in 3D using the *Solid Edge* software and then imported into the *Ansys Fluent* computational fluid dynamic (CFD) software, primarily to evaluate TVOC distribution. CFD is a valid and time efficient way of estimating indoor air flow compared to experimental research, according to many studies (for example (Fontanini, et al., 2016)). More information regarding the software are provided at page 12. Simplifications regarding both geometry and physics were done in favour for solution stability and speed.

The process of determining optimal spatial position of sensors for widely varying room types is very iterative. While CO_2 has been studied many times before, no previous studies of sensor placement concentrated solely on TVOC was found during the literature review. TVOC is expected to behave differently to CO_2, not only because of the volatile nature but also due to the lower concentration which sometimes result in readings of 0 ppb, whereas CO_2 typically stays at a minimum of around 400 ppm. Spikes in concentration are common and has by a companion study parallel to this, see Appendix A and B, been linked to movement of air as concentration often goes up before it rapidly declines when opening windows or doors. Previous studies have observed better mixing of air in rooms with open windows or doors (Mahyuddin, et al., 2014), and that enclosed spaces with low air mass flow contain areas with older air and therefore also higher concentrations of air borne particles (Mahyuddin & Awbi, 2010). The importance of the spatial position of an IAQ sensor thus appears to be greater in an enclosed space with less movement than in a better mixed room (as the position should not matter provided an ideally mixed room). Consequently, this study mainly focuses on “worst-case” scenarios in which occupants are assumed to be keeping the same position for an extended period of time; sleeping, doing office work, studying, and cooking.

Instead of evaluating discrete points, which is common for many similar studies, this study provides areas within a specified tolerance. The areas are primarily those on which it is reasonable to attach a sensor, such as walls, lamp surfaces or the ceiling. A few horizontal planes were used in the analysis as well to see whether a theoretically more suitable position could be further from the walls. This area method has been used similarly before by (Bulińska, et al., 2014).

To complement the visual inspection of areas, the entire averages of cross planes were calculated as well. The idea is to provide general height distribution as previous studies have concluded that the vertical position is of less importance than the horizontal (Bulińska, et al., 2014) (Mahyuddin, et al., 2014). By comparing the average particle concentration at different heights throughout the entire model, this study provides an indication of whether height difference can be neglected entirely or if some heights should be avoided for sensor placement due to an overall unrepresentative TVOC concentration compared to the mean of the occupied zone.

The general methodology used for evaluating potential placements of VOC sensors is outlined below in point 1-14, with the additional steps (for example literature review and tolerance limits) included in the methodology of this thesis added to the overview shown in Figure 2. To compare the potential sensor positions to how well they correspond to the average values of the occupied zone, see step 10, an index was developed which primarily focuses on the percental difference in TVOC compared to the volume average of the entire occupied zone.

1. Acquire general information of room dimensions, air flows and surface temperatures in a chosen reference room
2. Choose a sample of occupancy-based scenarios to evaluate (e.g. sleeping or working)
3. Select horizontal cross-sections and/or walls to evaluate closer[2]
4. Choose one scenario and model the reference using a 3D-cad software - include a defined volume to represent the occupied zone (see definition in section 3.4.1)
5. Import the model into a CFD software and solve for particle[3] concentration[4]
6. Run iterations until desired convergence is reached
7. Evaluate the volume average of particles in the occupied zone

[2] This study uses 0.6, 1.4, and 2.0 m above the floor (all within the occupied zone) and lamp height
[3] Representing VOC
[4] A CFD overview is presented in section 3.5.1

8. Evaluate the average particle concentration for cross sections at different height above the floor
9. Evaluate the average particle concentration at walls
10. Compare values attained in step 8-9 to the occupied zone average attained in step 7 and decide upon tolerance level
11. Repeat step 3-10 until all scenarios have been evaluated
12. Compare results and look for patterns
13. Discuss results and relate to findings by experience or previous studies and existing limitations due to local regulations or practical placement
14. Draw conclusions

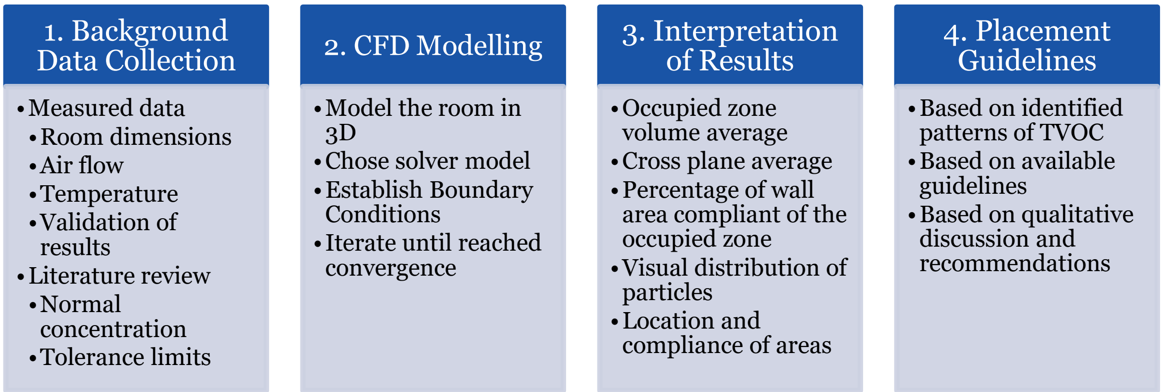

Figure 2. Overview of the methodology used for the main-study of this thesis

3.2 Software

The modelling of airflow was done numerically using a student version of the CFD software *Ansys Fluent*. It is a common CFD modelling tool which is comprehensive and allows for complex simulations based on a wide range of numerical models. The difference between the student version and the commercial version is the limitation in cells (512 000).

The 3D models were created externally using the Siemens *Solid Edge ST10*, which is a 3D-cad software.

3.3 Sensor Specifics

The sensor used by the large-scale project is a CCS811, which can detect VOCs based on seven types of chemical character according to documents from the manufacturer's website (AMS, 2017); alcohols, aldehydes, ketones, organic acids, amines, and alphatic and aromatic hydrocarbons. The manufacturer does not further specify the types of VOC detected. Alas, the sensor is assumed to measure ideal TVOC, which will be a source of unknown error.

Apart from TVOC, the sensor can also detect hydrogens and measure humidity levels and temperature. An illustration of the sensor input and outputs are shown in Figure 3. One of the sensor outputs is e-CO_2, or equivalent CO_2, which is calculated through an algorithm, thus making the sensor a *virtual* sensor for CO_2. The algorithm for TVOC to e-CO2 conversion and the accuracy of the sensor are not reported in available factsheets or on the manufacturer's website, nor could it be obtained directly from the manufacturer or provider due to confidentiality reasons.

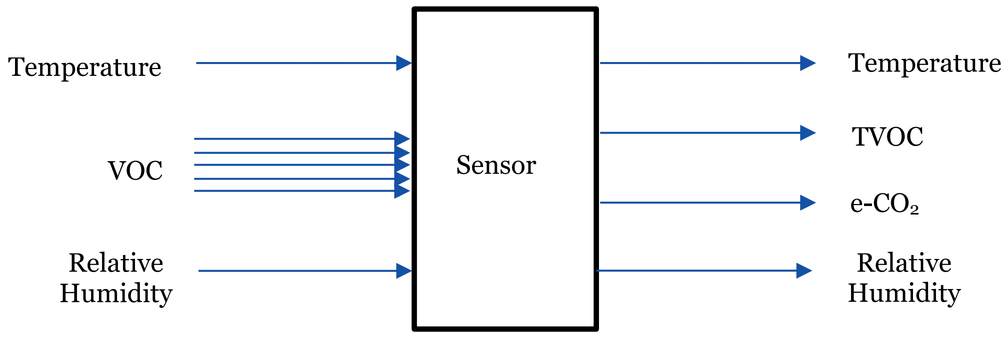

Figure 3. The inputs and outputs of the CCS811 sensor used by the large-scale project at the time of this study

According to the manufacturer, the sensor monitors IAQ through VOC using a metal oxide gas sensor, a micro controller unit, an Analog-to-Digital converter, and an I^2C interface. One benefit with the sensor of choice is the low energy consumption, which widens the options of candidate location to investigate. Actual application suggestions include smartphones and wearables as it is small in size. The lifetime is predicted to be more than five years (AMS, 2017). The sensitive surface of the sensor should not be in contact with liquids.

3.4 General Modelling Definitions

In this section, modelling parameters common for different building types or room settings are defined. The main VOC sources are assumed to be the occupants, which is partly due to the fact that the sensor seems to primarily react to those sources (when the room is empty the sensor tend to show close to zero ppb TVOC, see Appendix A and B) and partly due to the importance of linking CO_2 to VOC when adapting to existing Swedish IAQ standards.

3.4.1 The Occupied Zone

The definition for the occupied zone was taken as the one defined in the Swedish building code (BBR) established by Boverket (National Board of Housing Building and Planning):

> *"The occupied zone in the room is enclosed by two horizontal levels, one 0.1 m above floor level and the other 2.0 m above floor level, and a vertical level either 0.6 m from the exterior wall or other external limit, or 1.0 m by windows and doors." (Boverket, 2017)*

For both models, the occupied zone was modelled as a zone within the surrounding zone, already defined in the 3D-model. Please note that different agencies might use different definitions of the occupied zone. The Public Health Agency of Sweden for example, defines the occupied zone as 1 m from the entire exterior wall and 0.6 m from all internal walls (Folkhälsomyndigheten, 2016). Boverket is however the decision-making body behind OVK, hence the definition of Boverket is assumed to better reflect building regulations and air quality for this application.

3.4.2 Occupant Temperature and Geometry

The people modelled in this study are simplified as rectangular cuboids measuring (1.42 x 0.32 x 0.32) m which corresponds to a surface area of 1.92 m^2 (an average man has a skin area of roughly 1.9 m^2 (Sacco, et al., 2010)). Their entire surface area is assumed to keep a constant temperature of 34°C, which is the warmest in the normal range according to the Public Health Agency of Sweden (Socialstyrelsen, 2005).

3.4.3 VOC Sources

This study primarily focuses on occupancy-caused VOC rather than VOC emitted by for example floor mats and wall paint. The reason to this is that the purpose of installing new IAQ sensors is to continuously evaluate the air quality according to Swedish standards, which today is largely based upon CO_2 (heavily related to occupancy). As the sensor calculates e-CO_2, the thresholds for CO_2 could potentially be used for assessing air quality rather than TVOC (which currently has no recommended levels). A potential difference between the distribution of TVOC from occupants and for example floor mats is the temperature, which could cause variations in air flow paths. Further investigation of the relationship between VOC increase and friction between occupants and VOC emitting material is outside the scope of this study, which motivates the simplification as this study is reliant on previous findings.

The entire surface of the occupant(s) is assumed to be a source of occupancy affected TVOC. The TVOC rate of an average person is assumed to be 6.3 mg/h (Tang, et al., 2016), or approximately 1.75e-09 kg/s. The initial velocity is assumed to be 0 m/s. Some other surfaces, which may not always remain steady are modelled to check for distribution of multiple sources. These include the oven and the fresh air inlet of the apartment but are further described in the case study at page 33. TVOC is modelled as injections of CO_2-“particles” in this study. More information regarding how the sources are modelled in Ansys Fluent can be read in section 3.5.3.3.

3.5 CFD Modelling

To ensure a working CFD model, each model was developed iteratively, adding more complexity with each run. All models were assured to provide converged and realistic results regarding temperature, pressure, and velocity, before simulating TVOC sources. In this chapter, solver assumptions for modelling indoor air flow are further specified.

3.5.1 Overview of CFD Method

The general method used for the CFD modelling is outlined below in steps 1-8.

1. Import 3D-cad file into a CFD software
2. Create a mesh suitable for the model, and select and name boundaries of importance
3. Specify solver type, governing equations, and gravity (direction and magnitude)
4. Allocate boundary conditions for each boundary
5. Define solver method (scheme, gradient, and method for each parameter)
6. Define solution controls and under-relaxation factors
7. Solve for the equations until desired convergence is reached (for faster convergence, DPM was activated first after desired convergence was reached for the other variables)
8. Acquire results for distribution of temperature, pressure, and TVOC either graphically or by using built-in functions of the software

3.5.2 Importing and Meshing of Models

The 3D model was created externally using *Solid Edge* and then imported into Ansys Fluent *Design Modeller*. Meshing was then automatically performed by the Ansys Design Modeller software. Meshing options were set to *curvature* and the elements were tetrahedral (although a more structured approach could prove beneficial if the solution is oscillating). Refinement of the mesh was necessary around all inlets and outlets, especially at the very narrow slit of the inlet in the office (see section 4.1.1) as the slit height difference compared to other dimensions in the room is in the order of 10^3. The student version of Ansys has a limit of 512 000 elements, which thus limited the possible improvement of the mesh.

3.5.3 Solver Type, Governing Equations and Solver Models

The solver was set to pressure-based. All simulations in this study were steady state as primarily situations that are assumed to occur for extended periods were analysed, such as sleeping or working. The velocity formulation was set to absolute and the gravity was set towards the floor at 9.82 m/s² as the project is set in Sweden.

The governing equations of the pressure-based CFD solver are based on the continuity and momentum transportation equations, but also take into consideration the chosen solver models specified in Table 2.

Table 2. Overview of solver models common for all CFD models of the study

Model	Setting
Viscous Model	Standard k-ε model with standard wall functions
Energy Equation	Activated
Discrete Phase Model	Activated, interaction with continuous phase

The major governing equations of Ansys Fluent are the integrals representing conservation of mass and momentum, which are solved using a finite-volume process according to the user manual. Ansys solves for both equation simultaneously if using the coupled scheme. The continuity and momentum equations can be written as

$$\oint \rho\bar{v} \cdot d\bar{A} = 0 \tag{e31}$$

and

$$\oint \rho\bar{v}\,\bar{v} \cdot d\bar{A} = -\oint p\boldsymbol{I} \cdot d\bar{A} + \oint \bar{\bar{\tau}} \cdot d\bar{A} + \int_V \bar{F}\, dV, \tag{e32}$$

where ρ is the density, $\bar{v}$ is the velocity vector, $\bar{A}$ is the surface area vector, **I** is the identity matrix, $\bar{\bar{\tau}}$ is the stress tensor, and $\bar{F}$ is the force vector (ANSYS, inc., 2009). The density and time related terms are cancelling out in this model due to the steady state and incompressible solver type.

3.5.3.1 Viscous Model

The viscous flow is discretised based on the turbulence model k-ϵ with standard wall functions, which is a semi-empirical model that, according to the handbook, can provide *robustness, economy, and reasonable accuracy for a wide range of turbulent flows* (ANSYS, inc., 2009). It solves for turbulent viscosity, μ_t, as

$$\mu_t = \rho C_\mu \cdot \frac{k^2}{\epsilon} \tag{e33}$$

where C_μ is a constant and turbulent kinetic energy, k, and dissipation rate, ϵ, are solved through transport equations. These transport equations consider multiple aspects, including Prandtl numbers and turbulence due to both velocity gradients and buoyancy.

Many articles report using the standard k-ε model for taking into account turbulent flow, which appears to provide adequate results when predicting the behaviour of air flow compared to similar models (Posner, et al., 2003) (Zhai, et al., 2007) (Stamou & Katsiris, 2006). The RNG k-ε is sometimes preferred (Zhai, et al., 2007), but the models are similar and have both proven to be quite stable during calculation (Cehlin, 2006). Even when comparing other types of turbulence models, no model appears to be generally superior to another (Teodosiu, et al., 2014). One drawback is that although the k-ε model uses a factor for Buoyancy, it does not account for natural convection very well (Risberg, 2015) (Zhang, et al., 2013) which is why air is complemented with the Boussinesq approximation[5] in the material section.

3.5.3.2 Energy Equation

Temperature has a significant impact on air movement and has been shown to also correlate to concentration of CO_2 in indoor environments (Mahyuddin & Awbi, 2010). Hence, the energy equation was activated. The Boussinesq model, which was assumed for air density as material parameter to better include the effects of buoyancy and natural convection, is also dependent on the energy equation. The energy conservation equation solved by Ansys Fluent includes terms solving for conductive heat transfer, heat caused by chemical reactions, as well as energy transfer due to species diffusion and viscous dissipation, according to the user manual (ANSYS, inc., 2009).

3.5.3.3 Discrete Phase Model (VOC Source Modelling)

In this study, the modelling of VOC sources in Ansys Fluent was simplified as particle injections of CO_2. While the Ansys material library also offers many VOC's (n-hexane or n-heptane vapour, benzene vapour, acetone, and n-octane vapour to name a few), each VOC possess different qualities which when combined can result in many different versions of TVOC depending on the amount of each compound. The reason for modelling CO_2 rather than a single type of VOC was partly due to the sensor providing e-CO_2 as output, and that the values of CO_2 were well defined. An available input of TVOC would not be without uncertainty either, due to the hundreds of compounds. Given the small quantities of particle injection and the comparingly large volume analysed, the particles trajectories are expected to correlate with air flow anyway. The simplification is assumed to give sufficient accuracy given the method of research.

In Ansys Fluent, the *Discrete Phase Modelling* (DPM) was activated. It uses a Lagrangian frame of reference and is valid assuming the volume fraction is low (<10-12%) which is the case of VOC as it generally occurs in the concentration range of 0-1000 ppb. The mass and heat transfer, as well as the trajectories are then calculated to simulate the behaviour of the new source. The discrete phase uses a Lagrangian model (ANSYS, inc., 2009).

The sources were defined as the entire occupant surface, and inlet or oven depending on the scenario, with injection direction defined as normal to the surface. The velocity was set as zero, except for at the inlet where the velocity was set equal to inlet air flow velocity. The injected particles were assumed to be inert. Drag law was set to *spherical*. All tracking parameters were set to default.

The model was run until stable before enabling the *interact with continuous phase* mode, to allow for faster convergence. DPM sources were then updated with every iteration until the model reached a steady state once more. The walls were assumed to have a *reflective* effect on the particles, while any particles hitting an outlet were assumed to *escape*.

[5] The Boussinesq approximation is valid for small temperature change, which is the case for the indoor model at 23°C and a constant air density of 1.18 kg/m³. The thermal expansion coefficient of air was set to $3.4 \cdot 10^{-3}\ \mathrm{K}^{-1}$.

3.5.4 Solver Method

The solver scheme was set to coupled, and the gradient to least-square cell-based. The solver methods for each of the other parameters were 2nd order upwind for momentum and energy, and 1st order upwind for turbulent kinetic energy and turbulent dissipation rate. Convergence was determined by considering the change in residuals. When the residuals no longer declined or oscillated, the model was assumed to have converged. Typical residuals of the case studies were in the range of e-03 or e-04 for velocities, continuity, and turbulence factors, while energy typically ended at a residual of around e-06 or e-07.

3.5.5 Estimating Mean TVOC Concentration

The resulting mean concentration in the occupied zone was calculated using the ANSYS CFD-post tool for volume averages on the predefined occupied zone volume. To convert mass concentration of CO2 (representing TVOC) to parts per billion (ppb), the density of air was used according to equation (e34).

$$particle\ mass\ fraction\ [ppb] = \frac{particle\ mass\ concentration\ \left[\frac{kg}{m^3}\right]}{\rho_{air}\ \left[\frac{kg}{m^3}\right]} \cdot 10^9 \qquad (e34)$$

Equation (e34) was used in the same manner for surfaces of cross-sectional planes.

3.6 Validating CFD Models

The simulations were run at steady state until desired residual convergence, by default set in ANSYS Fluent to 10e-4 for all equations except energy which has a residual convergence limit of 10e-6. Before compiling and analysing results however, validation of the CFD models was needed. Temperature, velocity, and pressure distribution were checked visually at both horizontal and vertical cross sections.

As ventilation requirements of BBR only comply to the occupied zone, the TVOC mean volume concentration of the occupied zone was thus assumed to be representative of the IAQ of the entire model. It is outside the scope of this study to look at whether the magnitude of TVOC plays an important role regarding the room distribution. Instead, experimental results (from the reports included in Appendix A and B) and literature review was used to provide values for how indoor TVOC typically varies. The injected particles were then ensured to stay within the compiled normal variation.

The experimental data for normal variation was obtained using the sensor to measure IAQ during multiple days in the reference office and apartment. The sensor was placed inside the occupied zone for both references. A sample of randomly chosen 24-hour periods were further analysed by comparing average, median, max, and min values in a table (see Table 3) as well by using a box-plot diagram (see Figure 4). Typically, the level of TVOC appear to remain low, although occasional spikes are common. The high value of 1089 in the office can most likely be neglected as an outlier judging from the box-plot diagram but could be regarded as realistic with an increased occupancy (17.02.2018). The median is consistently lower than the average.

During occupancy, the average TVOC level is around 90-100 ppb. Assuming the CFD model only considers human presence related TVOC, the model results could either show levels within the average increase with occupancy (office: around 14 to 71 ppb) or relate to the total measured ppb. The latter is deemed valid as the box-plot diagram clearly shows that low levels (close to zero) are common, ultimately indicating that the sensor mainly measures occupancy-sourced TVOC.

Table 3. Measured TVOC average, median, max, and min values during 24-hour periods in the office (14-15.02 and 07-08.03) and apartment (17-19.02)

	14.02	15.02	17.02	18.02	19.02	07.03	08.03	Average
Average	57	24	157	81	37	35	69	66
Median	50	8	54	51	30	20	66	40
Max	346	206	956	311	150	197	1089	465
Min	0	0	0	8	0	0	3	2

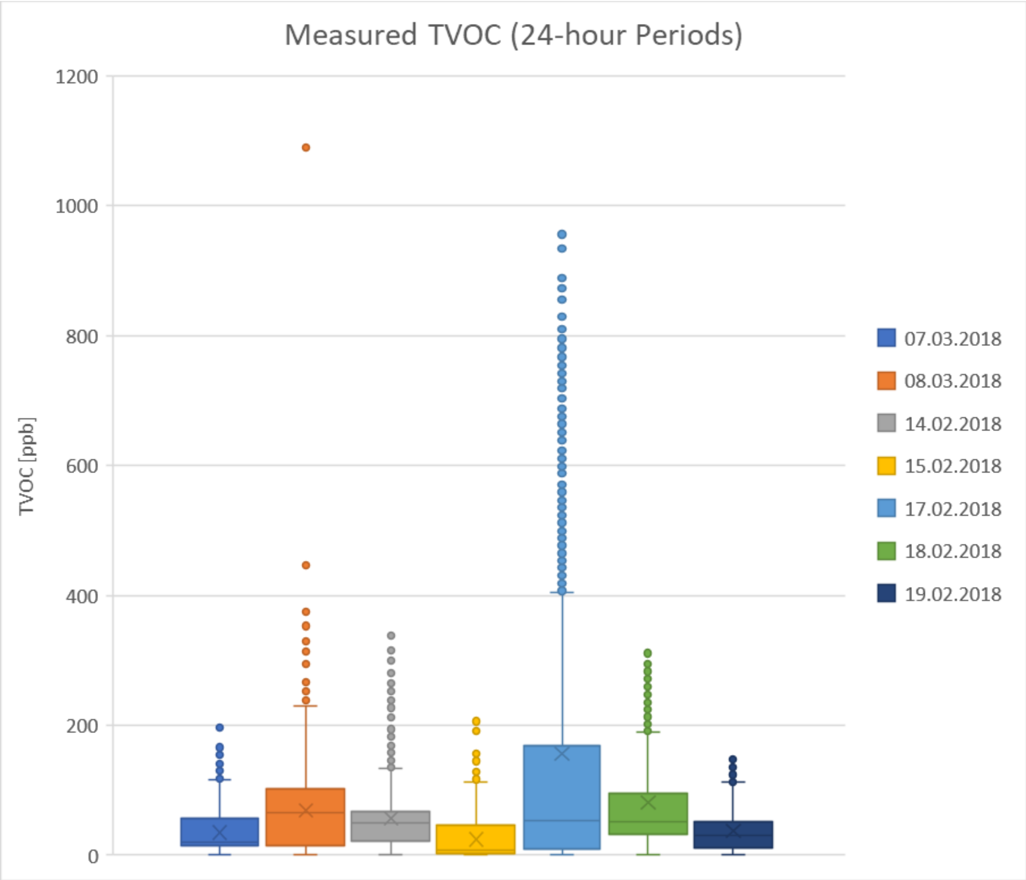

Figure 4. Measured TVOC during 24-hour periods in the model references using the CCS811 sensor (office: 07-08.03 and 14-15.02, apartment: 17-19.02)

3.7 Evaluating Sensor Positions

Ideally, the air inside the occupied zone should agree with indoor thresholds regarding all variables. Hence, putting the sensor anywhere within the occupied zone should provide representative values for the entire room. The spatial position of the sensor however, will most likely have an impact on the logged data depending on local variations of air movement, temperature, humidity, and TVOC. To evaluate how well the position of the sensor represents the mean TVOC concentration of the occupied zone, a percentage-based variation index was introduced named the *Occupied Zone Compliance Index* (OZCI). The risk of under- or overestimating occupied zone IAQ is considered elevated at surfaces where irregular concentration is occurring, or where larger areas seem to keep lower or higher concentration than is included in the tolerance level of choice.

The average OZCI was used to evaluate entire cross sections to eliminate any heights that had unacceptably large deviations of temperature or TVOC compared to the average of the occupied zone, where a similar analysis method was used by (Zhang, et al., 2017) for determining VOC concentration differences between different heights when cooking. A closer evaluation of each cross section was then done using a similar approach to that used by (Bulińska, et al., 2014) who used it for identifying acceptable areas for installing CO_2 sensors in a bedroom. It was suggested in their report to look at three different tolerance levels for placement on horizontal cross planes, where one of the tolerance levels considered the compliance to the average CO_2 concentration of the room, much like this study takes into account the average TVOC concentration within the occupied zone. The parameter changes of this study are position of occupants, heat loads, and VOC injection variations. The tolerance levels are further presented below in section 3.7.4.

The average cross section concentration was calculated at every 0.1 m to provide an overview of the overall steady-state concentration distribution of TVOC. Then the walls were further investigated with respect to $OZCI_{TVOC}$ as the walls provide realistic surfaces for mounting sensors. A selection of horizontal cross-sectional planes was investigated in a similar manner, at 0.6, 1.4, and 2.0 m above the floor (all within the occupied zone, 1.4 here representing breathing height).

3.7.1 Compliance with Respect to TVOC

Using the simulated volume average of TVOC in the occupied zone, $\bar{c}_o$, and a discrete point value or the surface average of an object, c_p, the deviation from the mean concentration in the occupied zone was calculated as per equation (e35). Basically, the OZCI gives the percentage of the variation of VOC as compared to the average of the occupied zone where 0 corresponds to 0% change compared to the occupied zone, and a negative or a positive value means that the concentration is lower or higher than the average of the occupied zone.

$$OZCI = \frac{c_p - \bar{c}_o}{\bar{c}_o} \tag{e35}$$

3.7.2 Expanded Compliance with Respect to Temperature and Relative Humidity

The objective of putting up IAQ sensor for continuous measuring is, according to the large scale-project, to develop a more comprehensive method of ensuring good ventilation than the OVK system of today. Rather than controlling that the air flow rate of a system works according to design every three to six years, this instead opens the possibility to adapt the control of air quality to fit the actual use of the building or room. While relative humidity and temperature plays a role in both thermal comfort and IAQ, it is not within the scope of the current OVK as the guidelines for relative humidity are vague and temperature is not usually controlled primarily by ventilation.

Therefore, multi-variable compliance of the occupied zone is approached qualitatively, for temperature and relative humidity. The base for discussion is built upon existing guidelines, recommendations and previous studies.

The variation in indoor temperature have an impact on sensor position, both regarding suitability of placement surfaces and regarding trajectory paths of airflow. It is beyond the scope of this study to do case studies covering different seasons, but a qualitative analysis covering existing guidelines could provide a base for recommendations. Wall temperature is expected to vary during the year, even though indoor air temperature might stay approximately the same. Although Sweden is not subjected to any particularly extreme weather, winters are long and exterior walls and windows/doors tend to have lower surface temperatures than interior ones. Well-insulated buildings might however differ significantly for poorly insulated buildings. The Public Health Agency of Sweden states that logging of temperature for evaluating air quality during a longer period of time must be done within the occupied zone in a location that is not affected by solar radiation (Folkhälsomyndigheten, 2018).

3.7.3 Tolerance Level

Ansys Fluent offers a tool, iso-clip, which only shows surfaces that fulfil criteria set up by the user. In the paper by (Bulińska, et al., 2014), *tolerance level 1* was stated as ± 10% of CO_2. The nature of VOC however is more unstable and occurs in concentrations roughly 1000 times smaller than CO_2. The two chosen tolerance levels for estimating sensor positions in this study was thus set to ± 50% (T_1) and ± 100% (T_2) of the particle volume average of the occupied zone (these correspond to OZCI of ± 0.5 and ±1). Through analysing the results of the case studies, suggestions for when to use which tolerance level are discussed.

3.8 Limitations

There are some limitations to different aspects of this study which may affect the results. One example is human errors, which are difficult, not to say impossible, to eliminate completely. Great care has been taken during this study to avoid such errors.

The simplifications done to increase computation speed or decrease the number of mesh elements could potentially be sources of error. These simplifications include geometry (diffuser slit rather than inlet circles, lack of small pieces of furniture, smooth walls, human cuboids, etc…), temperatures, and injections of TVOC. The latter was simplified in the sense that the TVOC injections were imitated by particles of CO_2 at constant density, and the injections did therefore not consider the varying qualities of TVOC constituting of hundreds of different compounds. This could arguably be cancelled out by the fact that the sensor output only provides values of TVOC in [ppb] as specification of the actual concentration, which is equally vague and thus a source of sensor error instead. Another simplification is that inlets and outlets are regarded as the only locations for air to enter or exit.

The uncertainty of the sensors themselves may have affected the numbers used for validating the initial office model. As the algorithm for calculating e-CO_2 from TVOC and the name of the compounds registered by the sensor was unavailable during the study due to confidentiality reasons, the error was neither known, nor could it be calculated. The compatibility of the CFD model and the sensor might have been better had the kinds of compounds been known.

The Ansys Fluent version used in this study was a special student edition, which included mesh limitations such as a maximum of 512 000 elements. This limitation affected the detail of a grid convergence study, as well as a thorough flow path study due to the geometry of the references including both walls measuring in metres, and inlets measuring a few millimetres. Another aspect of limitation is the user experience of the Ansys Fluent software. It is possible that more skilled operator could get more or less deviating results, which in this study was compensated to a certain degree by doing multiple simulations instead of only a few as well as sensitivity studies in which only single parameters were altered.

4 Case Study: Office

In this chapter, the suggested tool for evaluation of sensor placement (presented in the methodology chapter) is applied to an office. Office layout and boundary conditions are provided throughout section 4.1, and obtained results are included at the end of this chapter in section 4.2.

4.1 Modelling the Office

The office used as reference is small and occupied by one person. The fresh air intake is 10 l/s. In this section, methodology and CFD results for the office are presented.

4.1.1 Layout and Dimensions

The general layout of the office is displayed in Figure 5, the occupied zone being shadowed. Both the inlet diffuser (1) and the outlet (2) are located around 2.7 m above the floor. A cooling beam is located immediately above the diffuser but is neglected in the CFD model as it was inactive at the time of measurement. Only one of the walls is external and is to a large part covered by windows (3). The radiator is located below the windows on the same wall (4). Two standard ceiling lamps are present, in the picture denoted as (5), both of which are 2.3 m above the floor. The occupant is expected to be sitting and is shown as the rectangular cuboid (6). The door (7) is leading into another room. The wall closest to the viewer on the left is to a large extent covered by bookshelves while the opposite wall has bookshelves above the desk. Anything located on the desk is neglected, except for the computer screen.

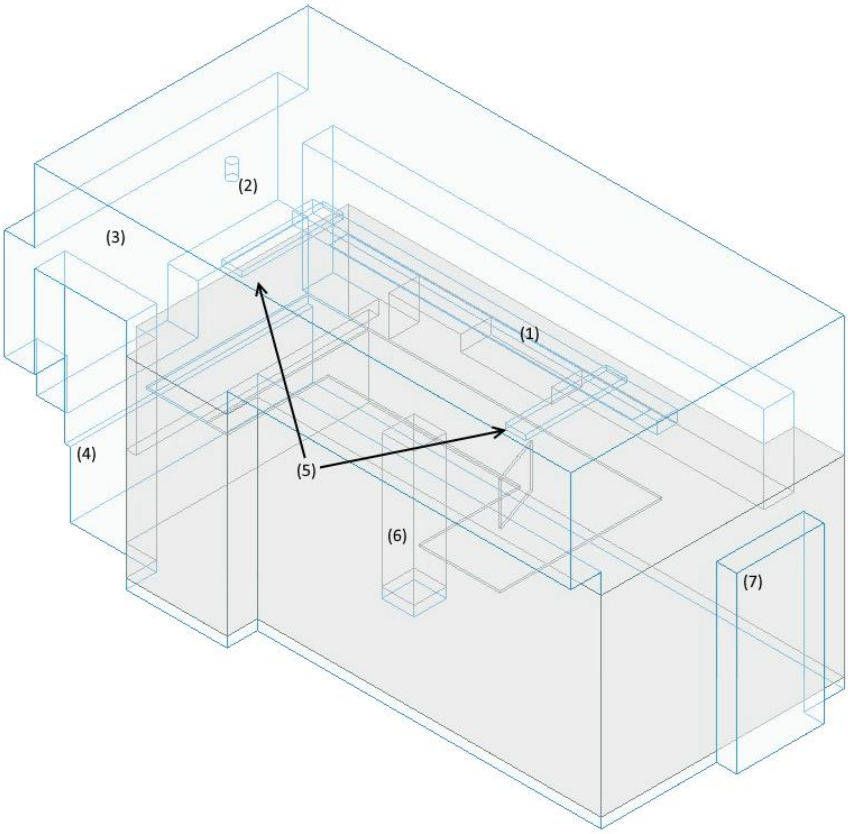

Figure 5. General layout of the office used as reference

Some information regarding measurements, assumptions and simplifications are given in point I-IV below.

I. The volume of the room, furniture and occupant volumes removed, totals to 42.6 m^3.
II. The furniture includes three desks pushed together in a U-shape, three chairs and some bookshelves. The chairs are neglected in the 3D-model.
III. Inlet air is provided by a diffuser with multiple circular outlets distributing the air through a slit measuring 3500 x 50 mm. The fresh air intake is 10 l/s. To satisfy the air flow, the slits are modelled as 3000 x 4 mm.
IV. The outlet is a circular slit measuring 100 mm in diameter. It is located in the ceiling close to the window as seen in Figure 5 (2).

A closer view, with lengths given, is given in Figure 6 and Figure 7.

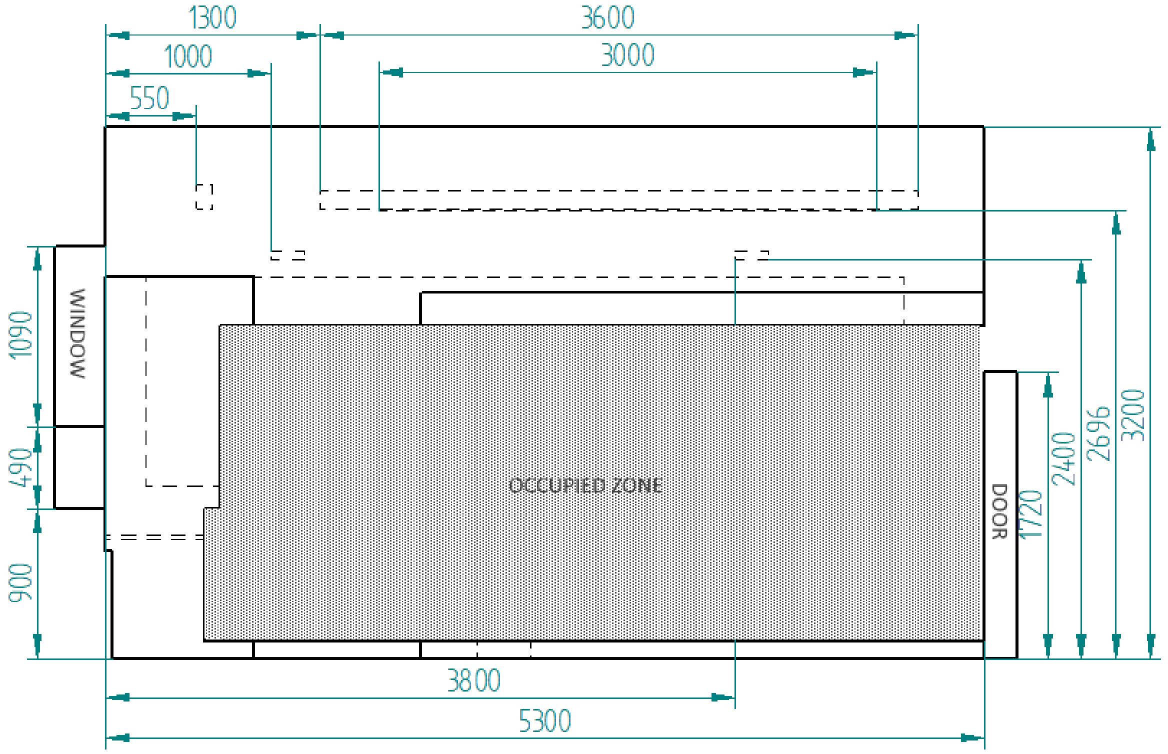

Figure 6. Lengths and distances [mm] as seen from the side of the office

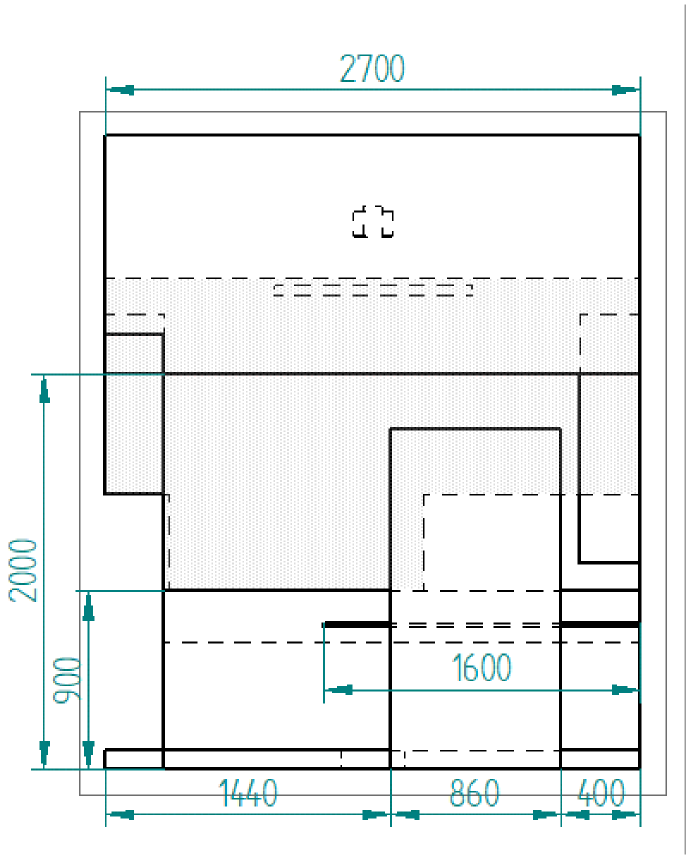

Figure 7. The office as seen from the door with lengths given in [mm], window is shadowed

4.1.2 Temperature, Heat Sources, and Boundary Conditions

Surface temperatures and general heat sources in the room were identified using an IR camera, see Figure 8. Realistic approximations regarding surface average were then made, using a uniform temperature of the windows, radiator, and ceiling lamps in the CFD model. Other surfaces, except for the person, were assumed to be adiabatic.

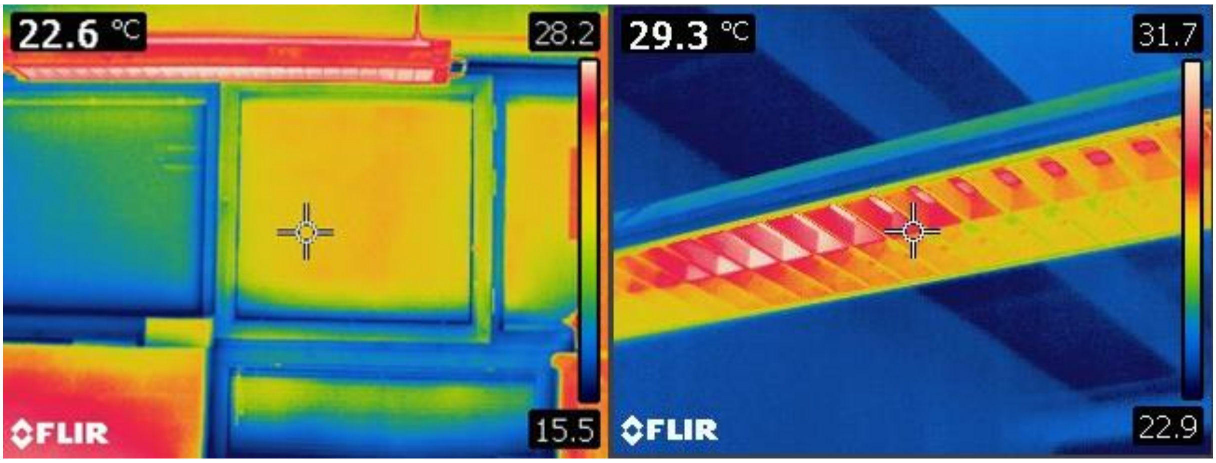

Figure 8. Part of the window wall (left) and one of the ceiling lamp fixtures (right) as viewed with an IR camera

Some general assumptions are listed below in point i to vii.

i. Heat sources are the person (including breath), the computer, the computer screen, the desk lamp, and the lamps in the ceiling. The computer screen did not show signs of significantly elevated heat when controlling with the IR camera, and the desk lamp was neglected for simplification.
ii. Heat generation rates are based on the calculated volume for each body, modelled as a void in the numerical model, and given in [W/m^3].
iii. The occupant is assumed to be doing light office work corresponding to 1.2 Met or 70 W/m^2 (Havtun & Bohdanowicz, 2016). The entire surface of the occupant (rectangular cuboid, 1.42 x 0.32 x 0.32 m) is assumed to emit heat.
iv. The radiator is assumed to work with 1000 W.
v. The lamps in the ceiling lamp fixtures are assumed to be two 30 W T8 tubes each.
vi. Temperatures of the window, radiator, ceiling lamps, and person are taken as surface averages.
vii. Walls, desks, book shelves, and cooling beam are adiabatic.

Boundary conditions based on temperature and heat sources are given in Table 4.

Table 4. Type, temperature, and heat source boundary conditions for the office model

Boundary	Boundary Type	Temperature [K] (°C)	Volume [m3]	Heat Generation Rate [W/m3]
Inlet	Velocity inlet	296.65 (23.5)	-	-
Outlet	Pressure outlet	296.95 (23.8)	-	-
Windows	Wall	291.9 (18.75)	-	-
Walls, Ceiling, and Floors	Wall	Adiabatic	-	-
Radiator	Wall	310.35 (37.2)	0.075	13 000
Ceiling Lamp Fixtures	Wall	306.4 (33.25)	0.010	6 000
Occupant	Wall	307.15 (34)	0.13	280

4.2 CFD Results and Discussion (Office)

As ventilation requirements of BBR only comply to the occupied zone, the mean value of concentration was assumed to be the ideal representation of actual indoor air quality, regarding TVOC. The simulations were run at steady state until desired residual convergence assuming only occupancy-caused TVOC sources, and the resulting mean TVOC mass concentration in the occupied zone was then 46 μg/m3, or 41 ppb. This value is within the experimentally measured range of 14 to 71 ppb for how much TVOC concentration typically increases with occupancy for the multi-day sensor reading loggings.

4.2.1 Average Particle Distribution Depending on Height

An overview of overall distribution of TVOC depending on height above the floor is presented in Figure 9. Elevated levels can be seen at 0.3 m, 2.7 m (inlet), and in the ceiling, where OZCI indicates variations from the occupied zone mean TVOC concentration of significantly more than 100%. The dramatic increase at inlet height could be explained by the inlet air creating an “air wall” which brings TVOC horizontally rather than vertically for that particular cross-section before distributing the particles along with the overall movement of air. This phenomenon is supported by the cross-section showed in Figure 13. The small increases of average OZCI at other cross-sectional planes appear to be caused by random collections of concentrated TVOC, with no apparent change in overall distribution compared to other cross-sectional planes. The desk height is around 0.7 m.

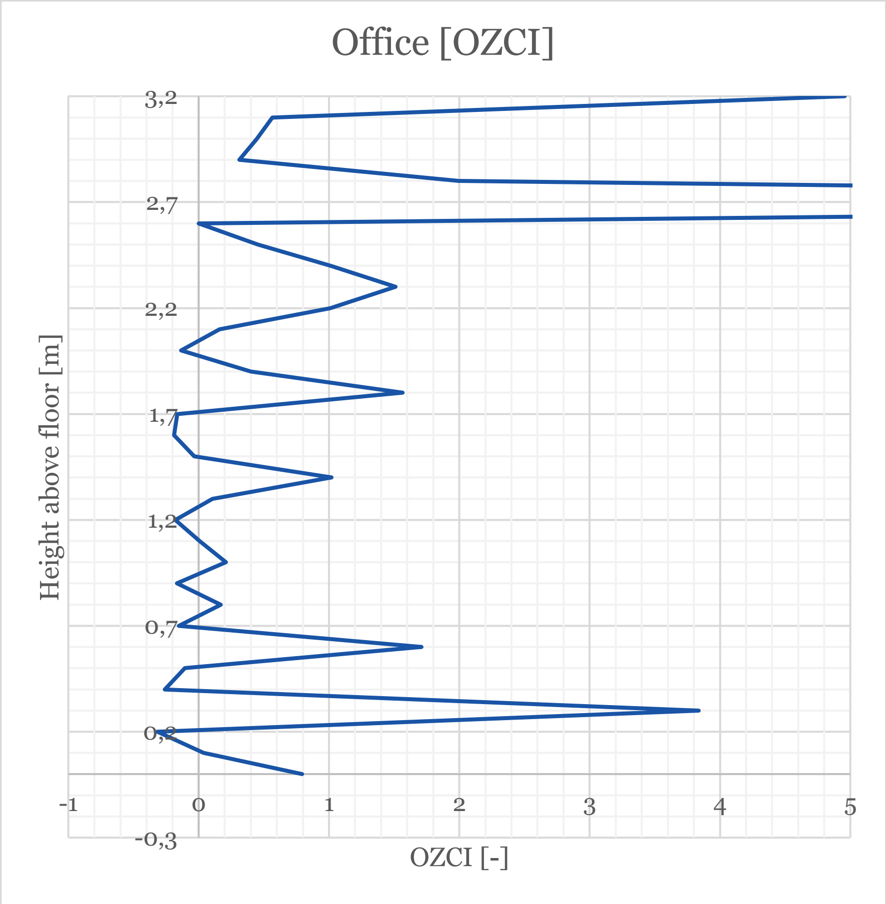

Figure 9. Average OZCI for entire horizontal cross-sectional planes in the office

4.2.2 Wall Surface Compliance to the Occupied Zone

Figure 10 provides an overview of the amount of wall surface area that is corresponding well to the mean TVOC concentration in the occupied zone. Approximately 21% of the wall area in the occupied zone is within +-50% variation from the occupied zone mean. Elevated levels of TVOC (more than 100% of the average occupied zone value) are present in approximately 11% of the occupied zone wall area, which leaves around 68% belonging having values in the range of ±100% and ±50% variation from the occupied zone mean value. The unoccupied zone provides in total more surface area compliant to the occupied zone mean value, but also larger areas with elevated particle concentration.

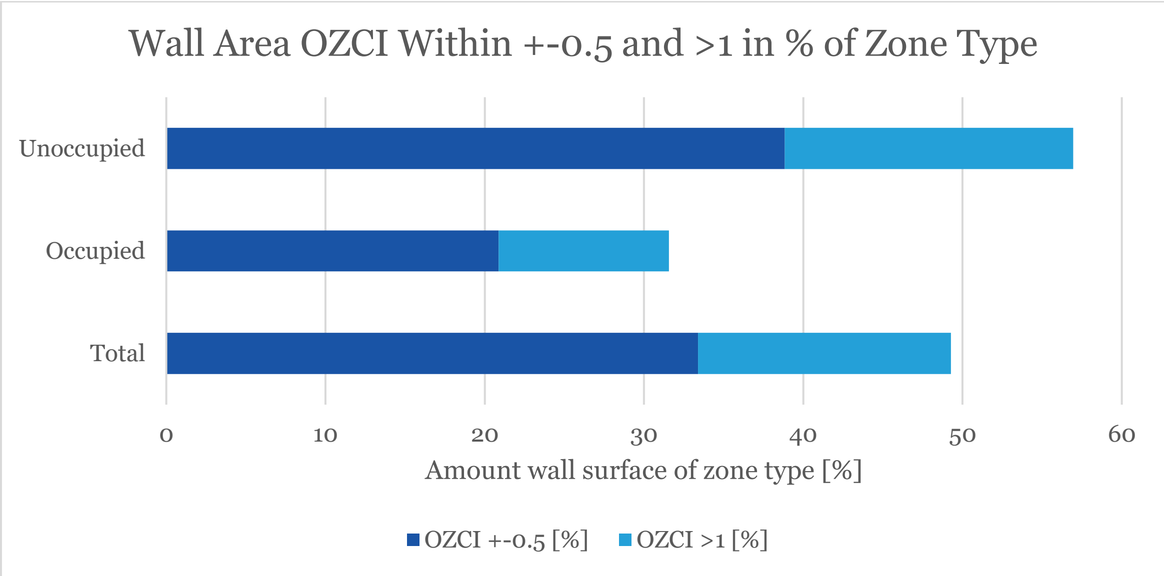

Figure 10. Wall surface area for OZCI within the T1 tolerance level and with more than 100% variation from the occupied zone mean TVOC concentration depending on zone type

4.2.3 Horizontal Cross Sections

Looking at Figure 11, it is evident that the chosen sample heights (0.6, 1.4, and 2.0 m above the floor) do not suggest any outstanding points of measuring. Black areas differ from the occupational zone mean concentration with more than 100%. The two greener areas represent levels within the tolerance level of 50% deviation (T1), while blue and orange parts represent areas within 50-100% lower and higher (T2) respectively. One placement indication is that TVOC concentration seem to be less stable closer to the door than to the outlet as the concentration appear overall lower than average with selective spots with significant increased TVOC concentration.

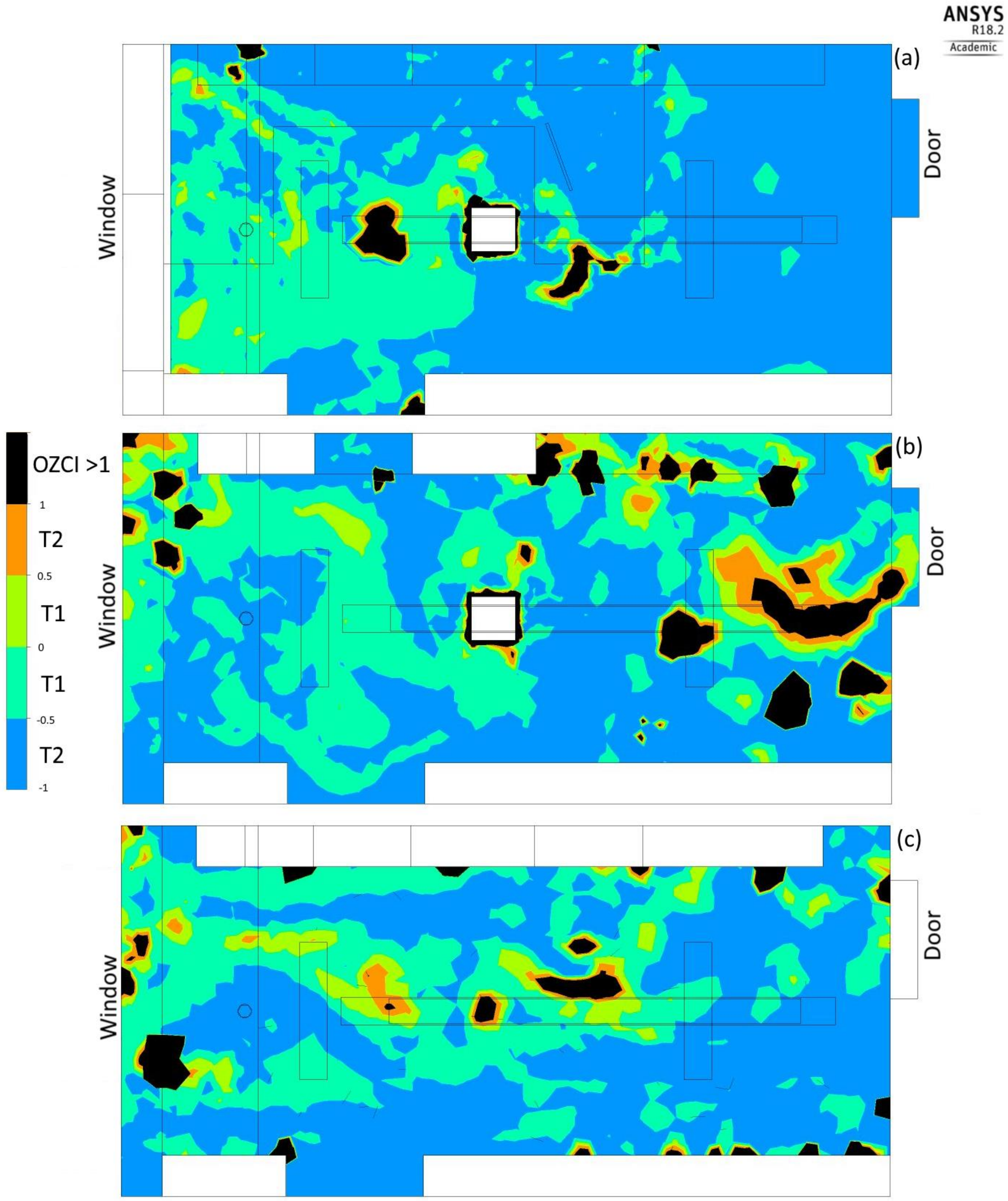

Figure 11. Horizontal cross-sectional planes at 0.6 (a), 1.4 (b), and 2 (c) m above the floor for the office model

Above the occupied zone, the mixing is a bit different (see Figure 12). At lamp height, levels appear acceptably stable closer to the outlet, including the lamp upper surface. The lamp is set to a higher temperature than the surroundings, as per measured in the reference office. One should bear in mind, however, that the temperature is taken as an average distributed uniformly across the entire surface rather than colder on the sides and hotter on the inside. Even so, the lamp closer to the outlet (which is located above the occupied zone but below the outlet and inlet) appear to represent TVOC concentrations close to that of the average of the occupied zone. The black areas in direct connection to the lamp could be an indication that it is possible that TVOC will collect closer to the hotter surface. The upper-left corner in cross-section (a) is more stagnant as it is just above the shelves and as the heat from the radiator travels upwards. As for the ceiling in cross-section (b) of Figure 12, it shows unstable levels of TVOC with many areas showing significantly elevated TVOC concentration (at least more than 100% higher than the occupied zone-mean). No obvious patterns can be reported from only one caption, but there is an indication of higher TVOC spots favouring either the walls or the middle of the ceiling.

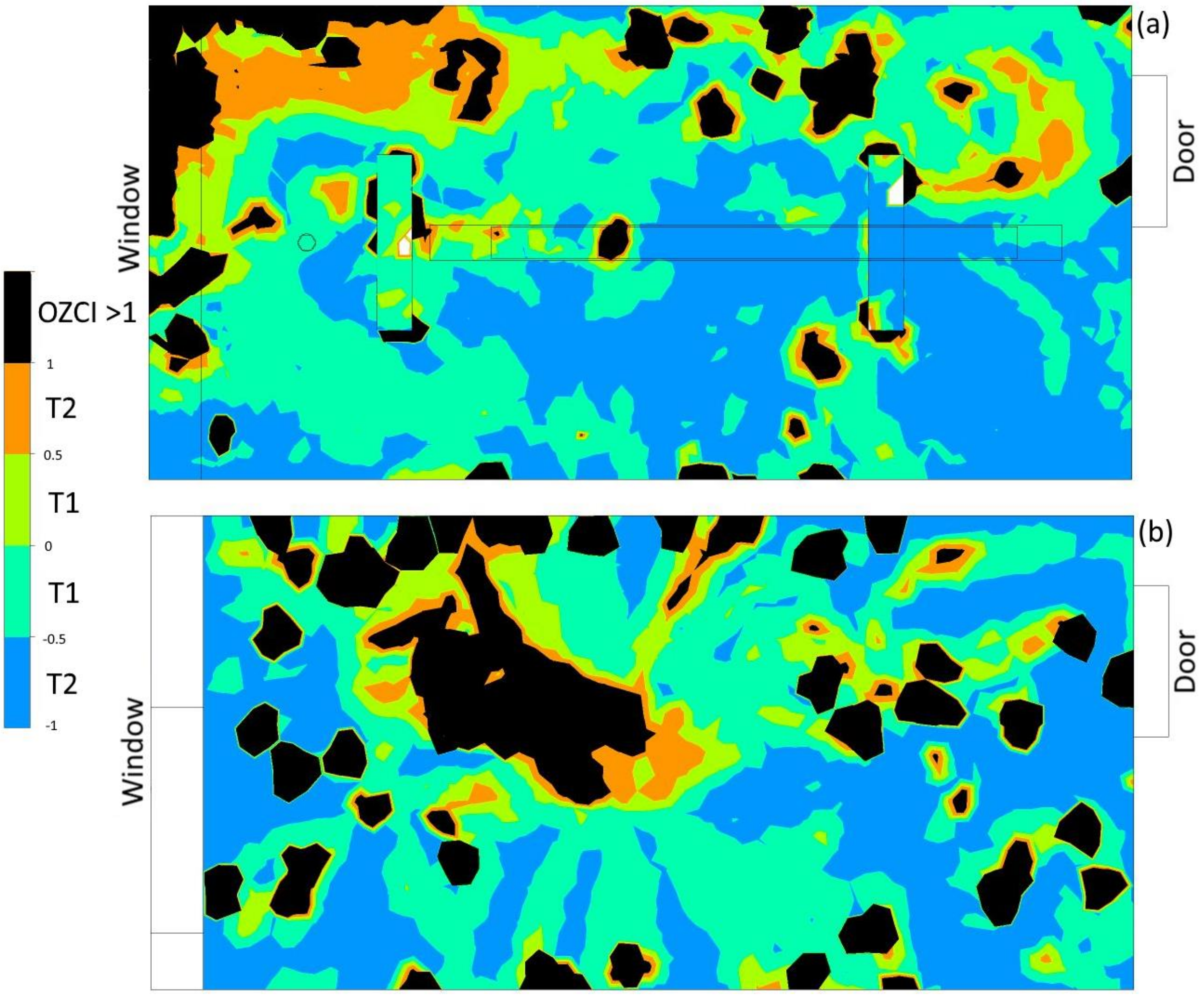

Figure 12. Horizontal cross-sectional planes at lamp height (a) and ceiling (b)

4.2.4 Vertical Cross Sections

A snapshot of the results for the vertical cross-sectional plane clearly shows TVOC primarily rising towards the ceiling (black symbolising areas where TVOC concentration is more than 100% higher than average levels of the occupied zone). Most likely, this is closely connected to heat driven air flows. The clear path of elevated TVOC is disturbed at the inlet height which forces the particles to find new paths. What is remarkably clear from Figure 13 is that the area to the left of the occupant (closer to the outlet) is more evenly distributed and overall green (values closer to the average of the occupied zone), while the area to the right contains either very low concentration of TVOC (blue) or particular areas with very high levels (black). In a steady state scenario, it thus seems that the air is better mixed on the outlet and window side. This could indicate that sensors should be placed between the inlet and the exhaust rather than on the far-side of the inlet.

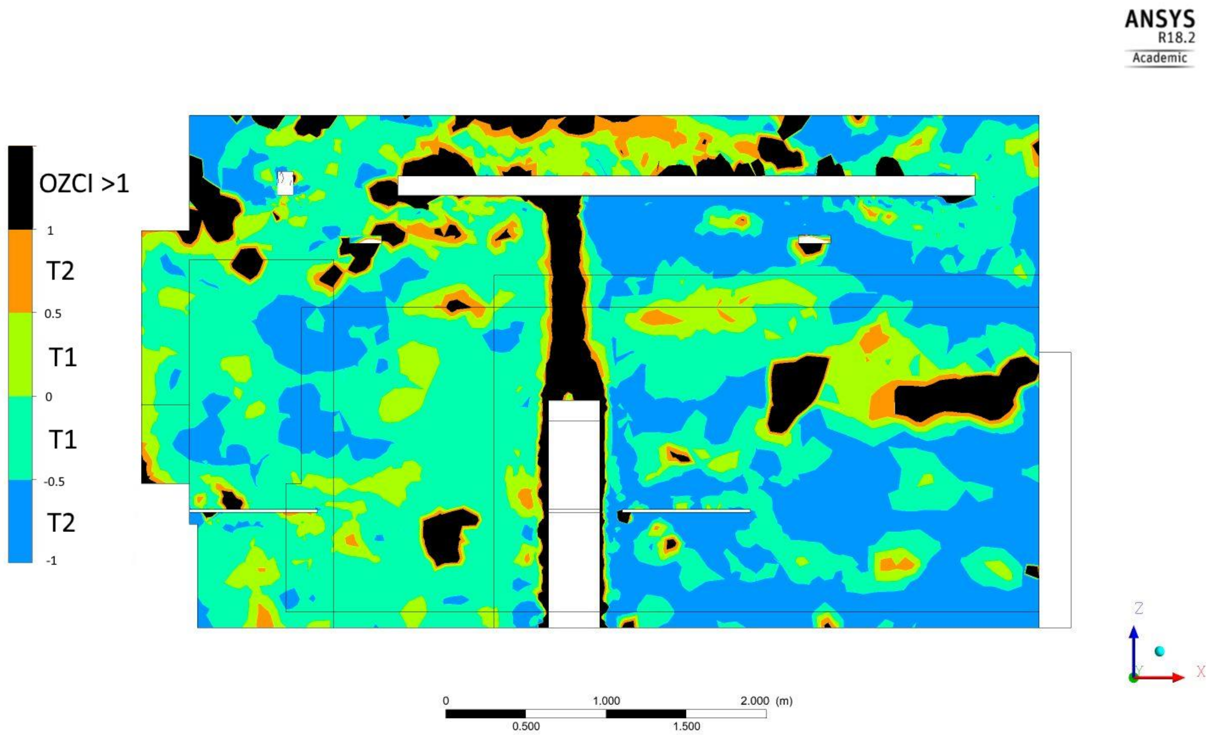

Figure 13. Vertical cross-sectional plane in the middle of the office

5 Case Study: Apartment

In this chapter, the suggested tool for evaluating sensor placement (presented in the methodology chapter) is applied to an apartment, see Figure 14. The apartment used as reference is a one-room student apartment inhabited by two people. The apartment room is equipped with a kitchen, a large window, and a bed. There is a bathroom connected to the apartment. A site visit was done the 28th of March 2018 to estimate dimensions, flow rates, and temperatures. The layout and boundary conditions are further explained in section 5.1. Results are provided towards the end of this chapter.

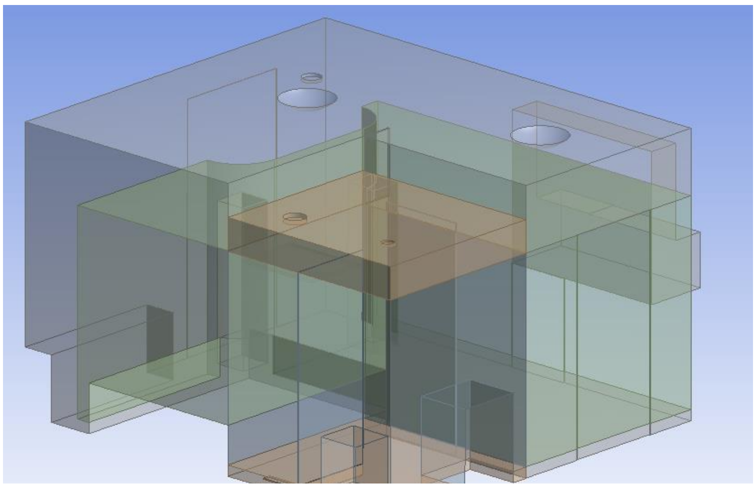

Figure 14. The entire reference apartment including bathroom (red) and occupied zones

5.1 Modelling the Apartment

An apartment may contain more complex or unpredictable behaviour patterns than an office (which can be assumed to be a place for office work only). To estimate how the VOC moves within the apartment, a sample of occupancy activities were chosen; sleeping, studying, and cooking. The main difference between the scenarios is the spatial position and heat generation rate of the occupants. The oven door is assumed to have an elevated temperature during cooking, while an increase of TVOC from the oven is attempted as a separate model parameter variation. The bathroom of the apartment was modelled separately to give an indication of how TVOC distribution affects the optimal placement of sensors in an apartment bathroom. Bathroom simulations concern a single standing person, assuming no or negligible VOC of incoming air from the apartment through the door/door slit. The studied parameters of the apartment are thus

1. Occupant location and activity
   i. Sleeping
   ii. Studying
   iii. Cooking and Studying
2. Multiple VOC sources
   i. Alteration of *Studying*
   ii. Alteration of *Cooking and Studying*
3. Bathroom
   i. Open door
   ii. Closed door

5.1.1 Apartment Layout and Dimensions

In Figure 15, the general layout of the reference apartment can be seen without the bathroom (see Figure 14 for an overview of the entire apartment). The apartment has one fresh air inlet (1) in the ceiling, at a central part of the main room. It is a cylindrical slit with a measured flow rate of 16.0 l/s. There are two ventilation outlets, one in the kitchen (2) and one in the bathroom (3) ceiling. Beneath the door to the bathroom, there is a slit (3) for the air to travel between the rooms. The kitchen outlet measured 9.0 l/s when on while the bathroom outlet measured 12.7 l/s. There is a large window door (4), a door to the shared corridor (5), and a large bed (6). The walls are covered with shelves and closets. A small table is located in front of the window, most of which is outside the occupied zone as defined in section 3.4.1.. Two lamp fixtures are located in the ceiling. Simplifications of geometry include neglection of shelves at the kitchen wall, no chairs, and simplified door frames.

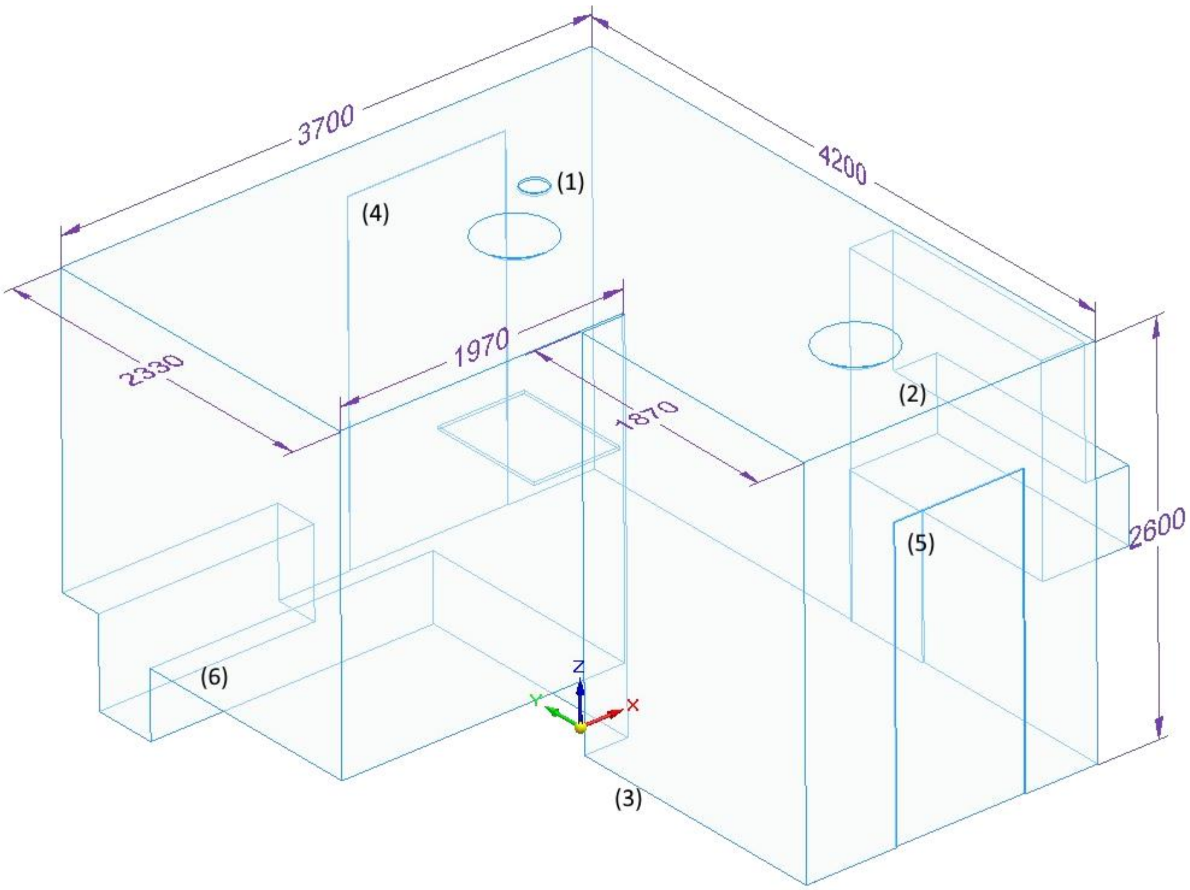

Figure 15. The reference apartment not including the bathroom, dimensions in [mm]

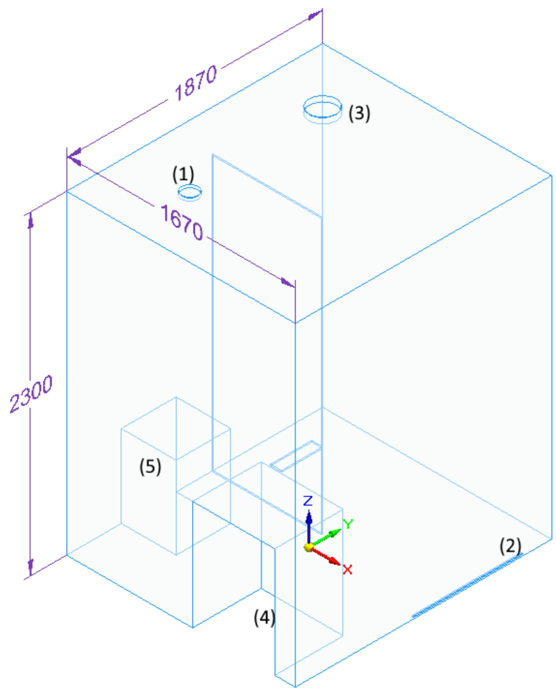

Figure 16. The reference apartment bathroom, dimensions in [mm]

The bathroom of the reference apartment is showed in Figure 16. There is a cylindrical outlet (1) in the ceiling, while incoming air comes from the apartment beneath the door (2). The shower is in one of the corners (3) with a rectangular water outlet in the floor below. The bathroom is also equipped with a sink (4) and a regular toilet (5).

5.1.2 Apartment Heat Sources

At the time of measurement, no large temperature deviations were found in neither the apartment nor the bathroom, including the ceiling lamp fixtures. The weather was sunny, and as it was early spring the resulting temperature variations on the exterior wall were small enough to neglect, allowing for modelling the walls as adiabatic.

The heat generated by the occupants depend on the type of activity. The metabolic generation rate and their corresponding heat generation rate is given in table Table 5.

Table 5. Occupants as heat sources depending on activity

	Sleeping	Studying	Cooking* (+studying)	Bathroom (in shower)
Number of people	2	2	1 (+1 studying person)	1
Metabolic rate per person	0.7 Met	1.1 Met	2.0 Met	2.5 Met
Heat generation per person	40 W/m^2	65 W/m^2	115 W/m^2	145 W/m^2
Heat generation rate per person**	590 W/m^3	960 W/m^3	1700 W/m^3	2139 W/m^3

**The oven is contributing as radiant heat source in this scenario with an emissivity of 0.1*

** Based on 1.92 m^2 skin area and a body volume of 0.13 m^3

5.1.3 Apartment Boundary Conditions

Temperature, flow rate and boundary types for the apartment are given below in Table 6, and for the separate bathroom in Table 7. The occupancy flow rate is the total for two people in the apartment (two times 1.75e-9 kg/s as defined in the common parameters section) and one person in the bathroom. The bathroom model door was both modelled as closed (mass flow inlet) and open (pressure inlet).

Table 6. Temperature (T), flow rates (FR) and boundary types (BT) in the apartment model

Boundary	Sleeping	Studying	Cooking & Studying
Inlet	BT: mass flow inlet T: 293 K (20°C) FR: 0.019 kg/s	BT: mass flow inlet T: 293 K (20°C) FR: 0.019 kg/s	BT: mass flow inlet T: 293 K (20°C) FR: 0.019 kg/s
Outlet (kitchen fan)	BT: mass flow outlet FR: 0.003 kg/s	BT: mass flow outlet FR: 0.003 kg/s	BT: mass flow outlet FR: 0.011 kg/s
Outlet (bathroom door)	BT: mass flow outlet FR: 0.015 kg/s	BT: mass flow outlet* FR: 0.015 kg/s	BT: pressure outlet T: 300 K (27°C)
Walls/Ceiling/Floor	BT: wall T: adiabatic	BT: wall T: adiabatic	BT: wall T: adiabatic
Oven	BT: wall T: adiabatic FR: -	BT: wall T: adiabatic FR: -	BT: wall T: 323 K (50°C) FR: 0**
Occupants	BT: wall T: 307 K (34°C) FR: 3.50e-9 kg/s (VOC)	BT: wall T: 307 K (34°C) FR: 3.50e-9 kg/s (VOC)	BT: wall T: 307 K (34°C) FR: 3.50e-9 kg/s (VOC)

** Set as pressure outlet in the open-door model*

*** Set to 1e-9 kg/s (VOC) from the upper part of the oven in the cooking-sourced VOC model*

Table 7. Boundary conditions for the bathroom model

Boundary	Boundary Type	Temperature [K] (°C)	Flow Rate [kg/s]
Slit below door	Massflow Inlet	296 (23)	0.015
Ceiling Outlet	Massflow Outlet	-	0.015
Walls, ceiling, floor	Wall	Adiabatic	-
Occupant	Wall	310 (37) Heat generation rate[6]: 2139W/m^3	1.75e-9 (VOC)

5.1.4 Additional VOC Sources

Two cases of additional VOC sources were added to (1) look at the effects on distribution when the general TVOC concentration is higher and to (2) look at the effects of distribution when multiple sources are occurring.

The additional VOC sources were the inlet (added to the studying scenario) and the oven (added to the cooking scenario). Both the oven and the inlet were set to contribute with 1e-9 kg/s of VOC. No initial velocity was assumed for the oven slit and the VOC from the inlet was assumed to enter with the same speed as incoming air (1 m/s).

5.2 CFD Results and Discussion (Apartment)

In this chapter, the CFD results for the apartment model is presented. The *cooking & studying* case is at most times denoted simply as *cooking*. Also provided in this chapter, are the CFD results for the separate bathroom model.

5.2.1 Particle Concentration Within and Outside the Occupied Zone

Comparing the volume average of particles in the occupied and unoccupied zones, there seems to be a tendency of higher particle concentration outside of the occupied zone. Looking at Figure 17, the occupied zone shows consistently lower levels of particles for all scenarios. If not including the bathroom, the sleeping scenario shows the largest difference between zones which might be to the uniformly distributed heat from the bed as it is also the only scenario which has all particle sources within the occupied zone.

The results suggest that higher levels of TVOC could be reported by the sensor if installing it outside of the occupied zone. One positive effect of consistently underestimating the IAQ of the occupied zone is that the air surrounding the occupants would always be better and any improvements could be done earlier which would reduce the risk of health effects. The negative effects of underestimating actual IAQ include a higher energy demand or unnecessary costs for the building owner if an already adequate ventilation system must be improved.

[6] Assumed to correspond to *Washing dishes, Standing*, 2.5 Met or 145 W/m^2 in Table 3-3 (Havtun & Bohdanowicz, 2016)

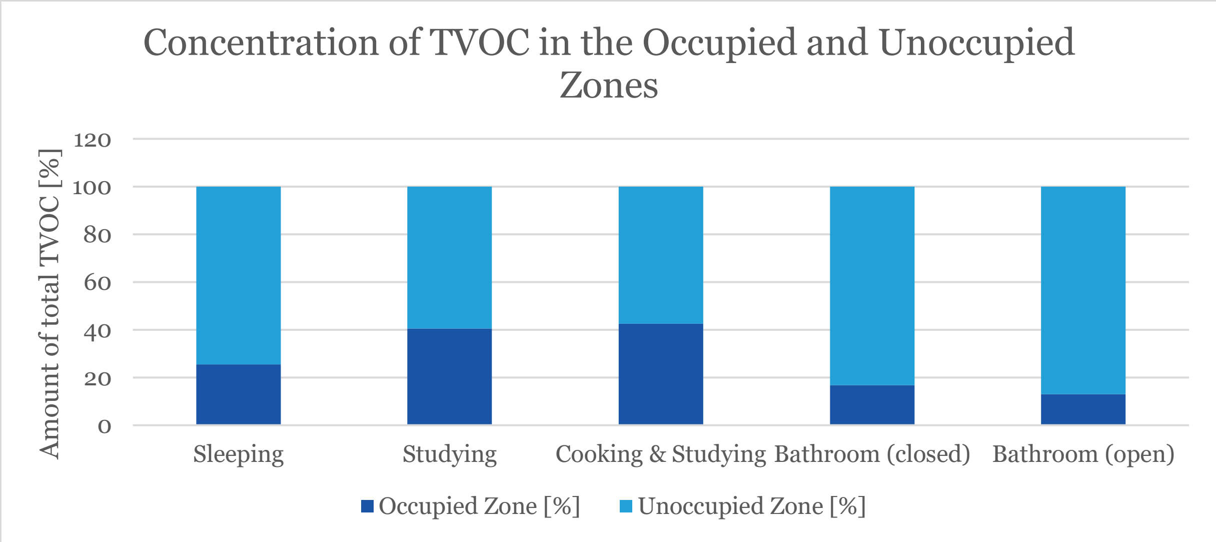

Figure 17. Distribution of TVOC particles in the occupied and unoccupied zones

An overview of general particle height distribution in the apartment can be seen in Figure 18, which shows the three base scenarios with only occupancy-caused TVOC. The TVOC is assumed to be emitted uniformly from the occupants. Elevated levels are shown at the ceiling for all scenarios, and at the floor (except for the sleeping scenario, in which none of the occupants touches the floor). It is thus evident that the ceiling is generally unrepresentative of the occupied zone concerning TVOC, which is further supported by the findings presented in Figure 17. The peak at above 0.5 m for the sleeping scenario is most likely due to the bed. The average OZCI of each horizontal plane for the cooking scenario is within or close to within the primary tolerance level, T1 (50% variation towards occupied zone mean TVOC) for all heights except close to the floor or ceiling. This could be due to the additional heat source (the oven), which has shown to provide better mixing of air in a similar previous study (Bulińska, et al., 2014). It can however not be ruled out that the lack of TVOC peaks is due to other reasons, such as occupant position or higher air flow of the kitchen outlet which is located further up than the door slit.

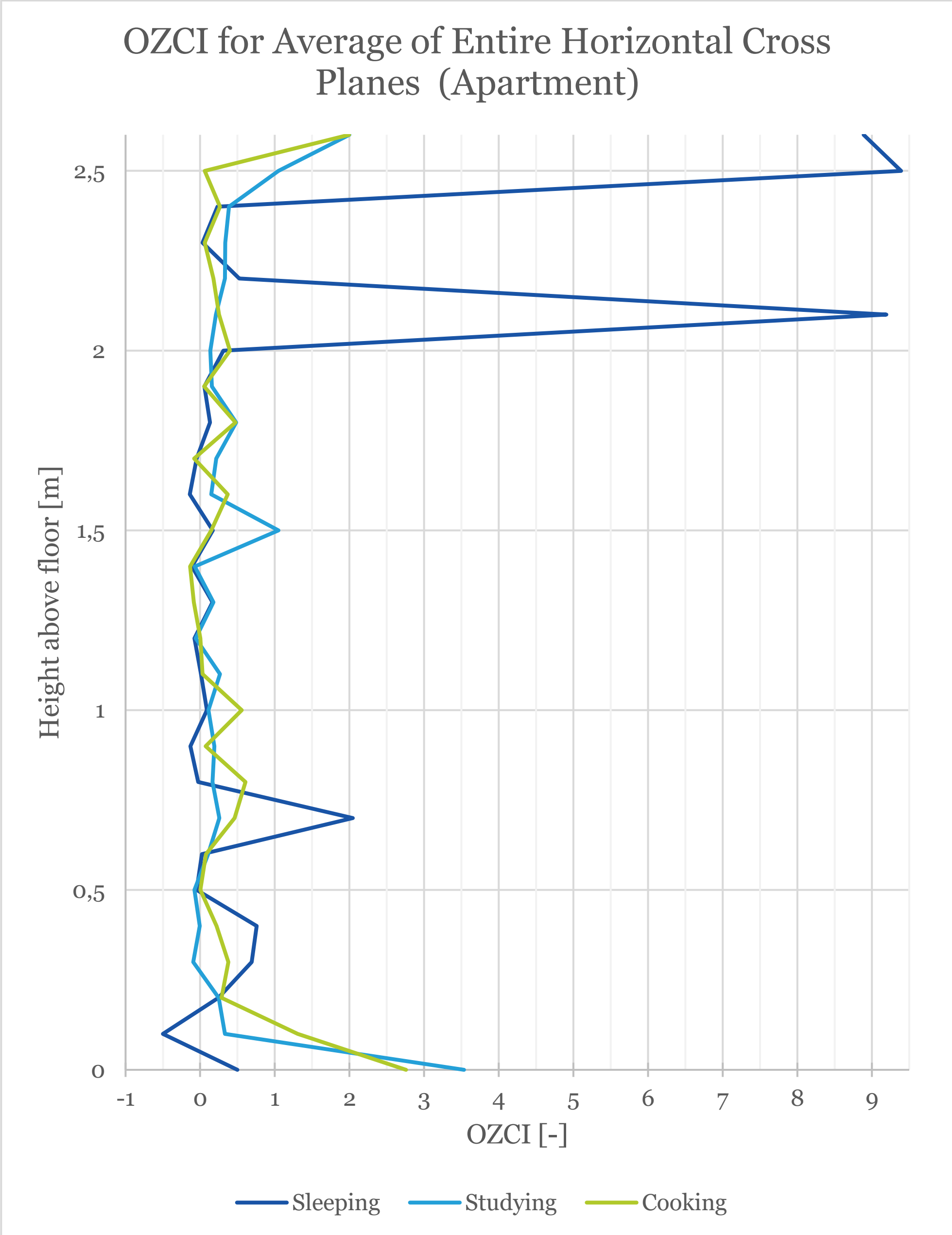

Figure 18. OZCI for the average TVOC mass concentration of horizontal cross planes at different height above the floor in the apartment for the three scenarios

5.2.2 Wall Surface Compliance to the Occupied Zone

Walls provide convenient surfaces for mounting sensors, and the concentration distribution on walls is therefore analysed further. Just as discussed in section 5.2.1, the risks of misinterpreting actual IAQ of the occupied zone should be minimised. The risk of under- or overestimating occupied zone IAQ is considered elevated at surfaces where irregular concentration is occurring, or where larger areas seem to keep lower or higher concentration than is included in the tolerance level of choice.

The total amount of wall surface, including floor and ceiling, that fulfils the tolerance level T1 and T2 regarding OZCI are displayed in Figure 19 for all base scenarios, where only the occupants were considered sources of VOC. As T2 naturally includes areas with 0 ppb, it may be wise to primarily consider the T1 tolerance level unless concentrations are low. In the open-door bathroom case, the overall particle concentration, 17 ppb, is much lower than in the other cases, averaging 72 ppb, due to many of the particles escape through the open door. In this case, it is likely wise to instead consider the T1 tolerance level.

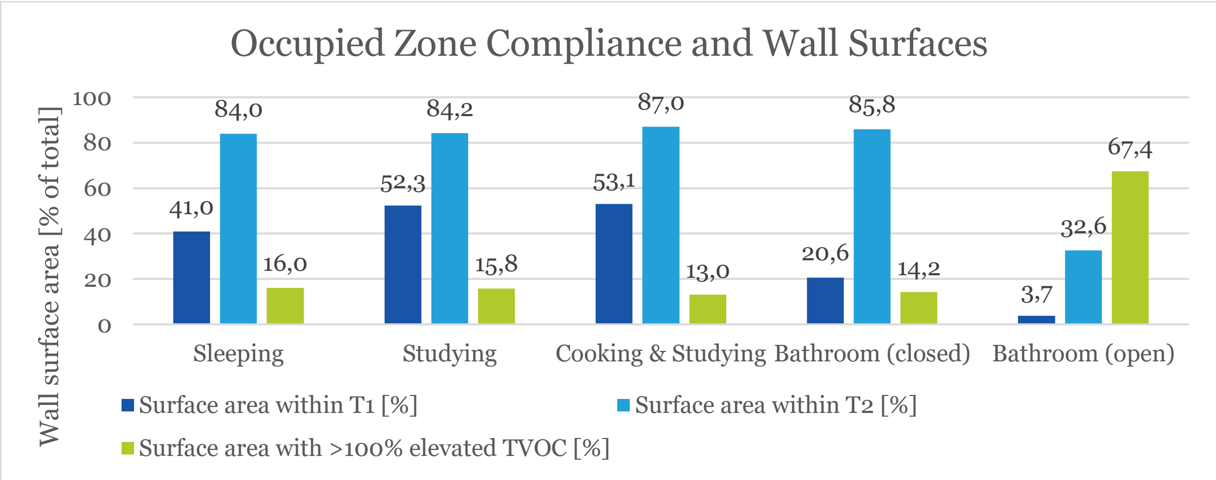

Figure 19. Amount of total wall surface (including ceiling and floor) that fulfils tolerance level T1 and T2 for compliance to the occupied zone mean concentration

A more comprehensive graph is shown in Figure 20, in which the T1-compliant areas for the occupied and unoccupied zone is shown in percentage. Also shown in the graph is the amount of surface area with particle concentration of more than 100% of the occupied zone average. Again, the risk of installing the sensor in a zone with unrepresentatively high concentrations is higher outside of the occupied zone. The graph also hints that the walls of the occupied zone may be well-suited for installation of sensors as at least 45% of the apartment walls within the occupied zone comply with the average concentration in the scenario. The possibility of finding an acceptable wall placement of the occupied zone also seems high.

The bathroom again differs from the apartment. This might be due to the geometry or VOC source position but is most likely due to the outlet airflow being dimensioned for the entire apartment rather than only the bathroom. The clearly elevated particle concentration of the ceiling, where >40% appears to show concentrations of more than 100%, advices against installing a sensor in the unoccupied part of the bathroom even though it also shows more surface area within the T1 tolerance level than the occupied zone.

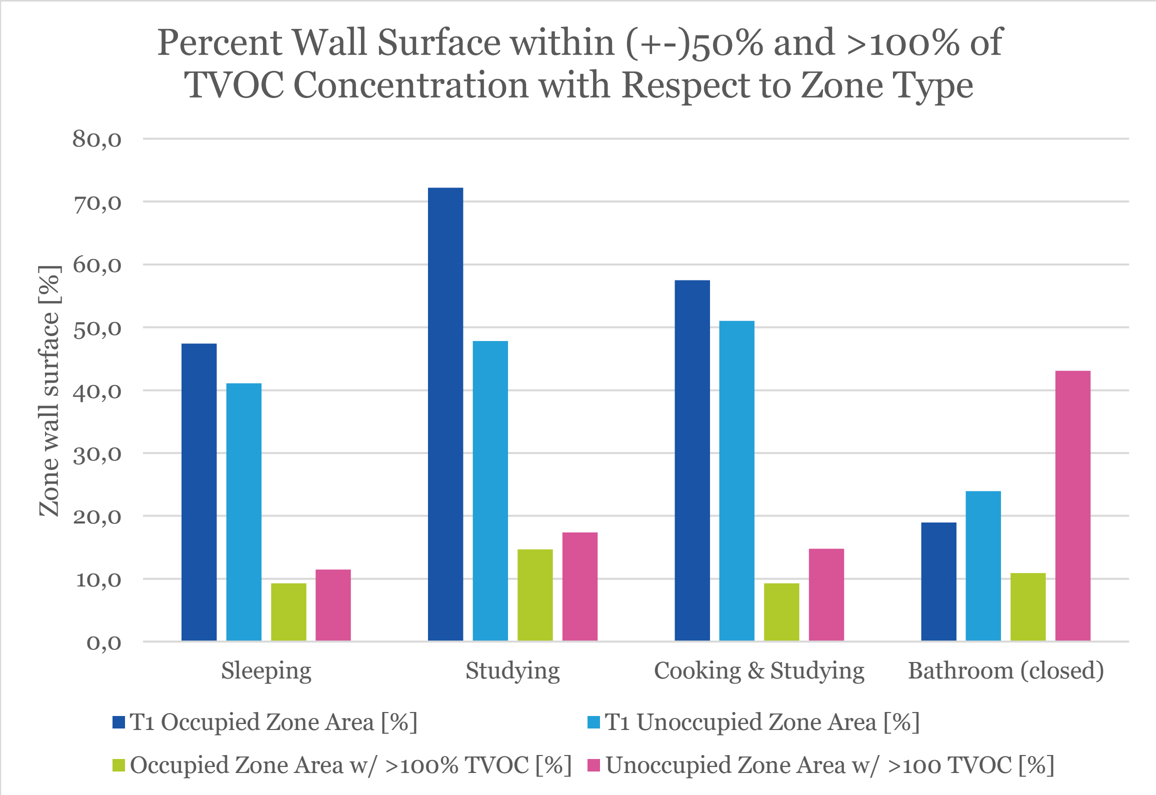

Figure 20. Amount of wall surface with respect to zone type that fulfills OZCI T1 tolerance level or exceeds the TVOC mean occupied zone concentration with at least 100%

While Figure 20 showed the percentage of occupied zone compliant areas, Figure 21 instead offers a visual overview of how the areas are distributed. The location of occupants and heat sources seem to have an impact on particle distribution of the apartment as the location of areas with elevated concentration is different for each scenario. Generally, the particle concentration at walls appear rather unstable. It seems that a corner placement might cause unpredictable TVOC readings, which is especially true closer to the ceiling and further from the outlets.

Comparing the scenarios, a wall placement would be more likely to provide a closer representation of the mean IAQ of the occupied zone if placed in the middle of a wall, preferably as far away from obstacles or corners as possible. Looking at the lamp fixtures, it seems that the one closest to the bed (horizontally placed between the inlet and outlet) may act as a suitable sensor area from a TVOC perspective. The findings give a hint as to what surfaces might be suitable for sensor installation rather than concludes any optimal placement, as qualities such as simplicity and easy adaptation are prioritised over finding the optimal solution. However, it is likely that these steady-state simulations offer a worst-case scenario solution and that air is better mixed (providing larger “green areas”) in a room with movement and variation of VOC sources.

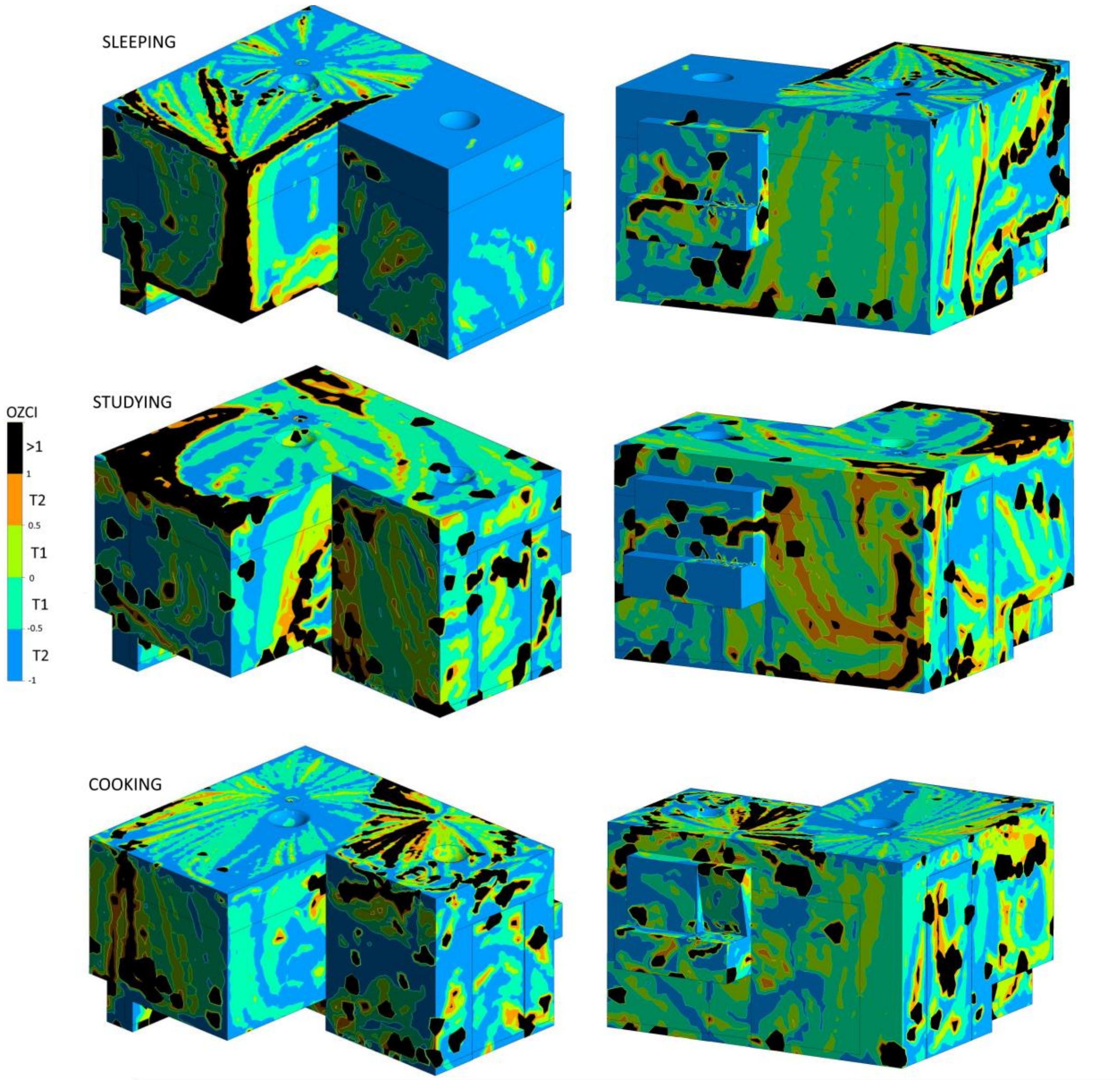

Figure 21. Wall surfaces and compliance of average TVOC in the occupied zone in the apartment

5.2.3 Horizontal Cross Sections

In Figure 22, horizontal cross-sectional planes at three sample heights are shown for each base scenario (only occupant-sourced VOC). Comparing the scenarios for each height, the distribution appears overall similar throughout the apartment no matter the placement of occupants. In this case, the apartment room appear rather well mixed – especially at 0.6 and 1.4 m above the floor where the green areas (within the T1 tolerance level of ± 50% variation from the average of the occupied zone) are continuous and cover most of the space. At 2 m above the floor, there are visibly more black areas showing more uneven distribution of TVOC. Comparing with the continuity of green areas in Figure 21, it seems that it would be theoretically better to install the sensor in the middle of the room than at the walls.

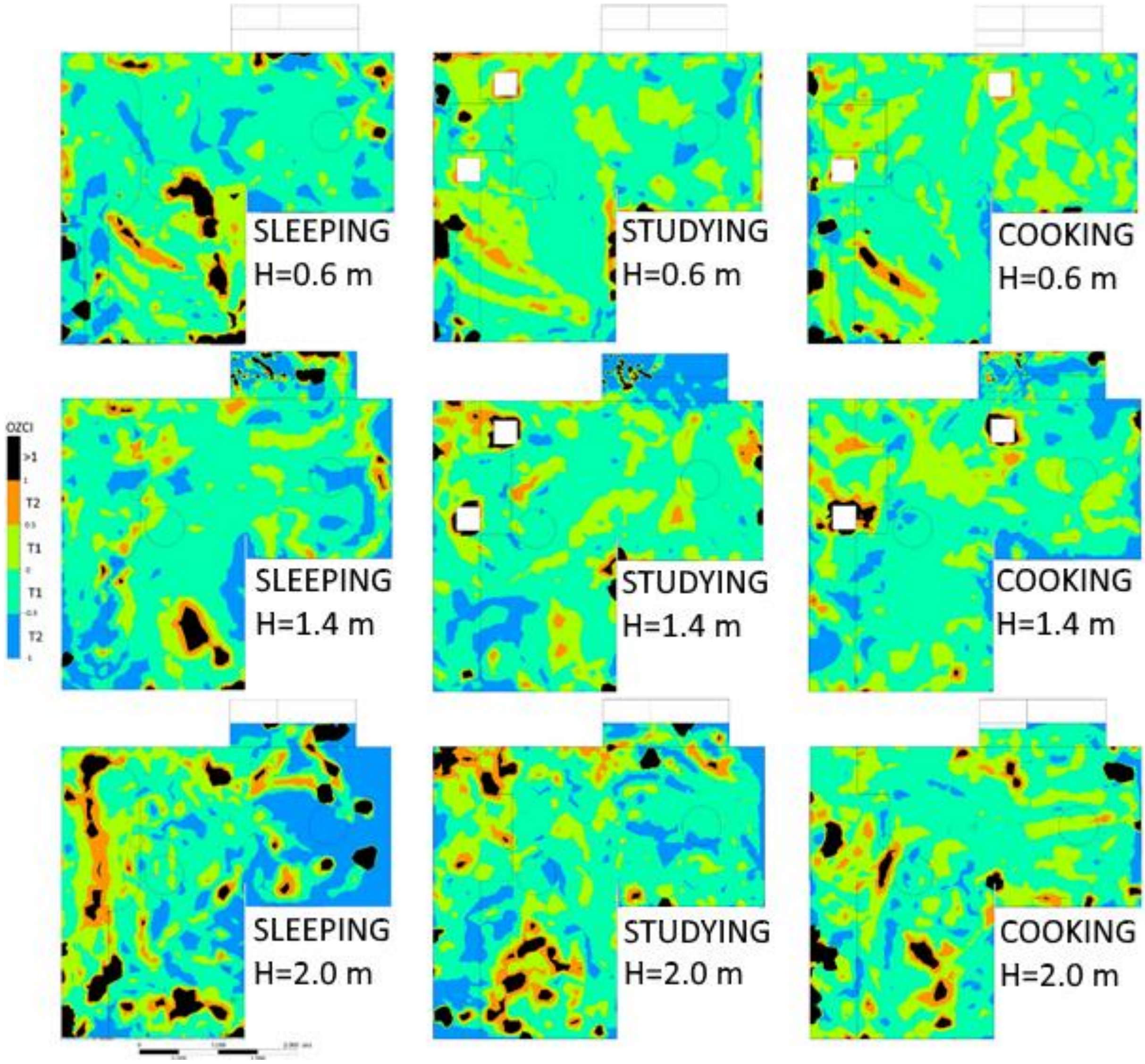

Figure 22. Horizontal cross-sectional planes for the three base scenarios in the apartment at 0.6 (1st row), 1.4 (2nd row), and 2.0 m (3d row) above the floor

5.2.4 Impact of Immediate Contact with Walls

There is a visible difference between the TVOC distribution at ceiling height and 10 cm further down, which is shown for the three base scenarios (without extra VOC sources) in Figure 23. For sleeping (a), most TVOC is collected in the area further from the outlets which is also were the sources are. No outlets are located in the ceiling, so badly mixed air seem to create collections in the corners between the ceiling and walls above the bed. The distribution in the study scenario acts similarly, apart from more particles spreading across the kitchenette which is probably due to the different location of occupants. Overall, the mixing in the three corners located in the bed side of the apartment, away from outlets, seem worse than the overall mixing in the rest of the apartment. A comparison between the ceiling cross-sections shown in Figure 23 and the average distribution from the graph in Figure 18, further strengthens the indication of an existing significant difference between the ceiling and 10 cm below. Despite the overall higher concentration of TVOC, the middle of the ceiling, away from walls or warmer VOC sources, could be a good sensor location.

Three things are different in the cooking scenario compared to the other two; the occupants are further away from each other, the oven creates an added heat source, and the kitchen fan has a higher mass air flow making it the main outlet. These differences could explain the more scattered black areas shown for *cooking & studying* (c).

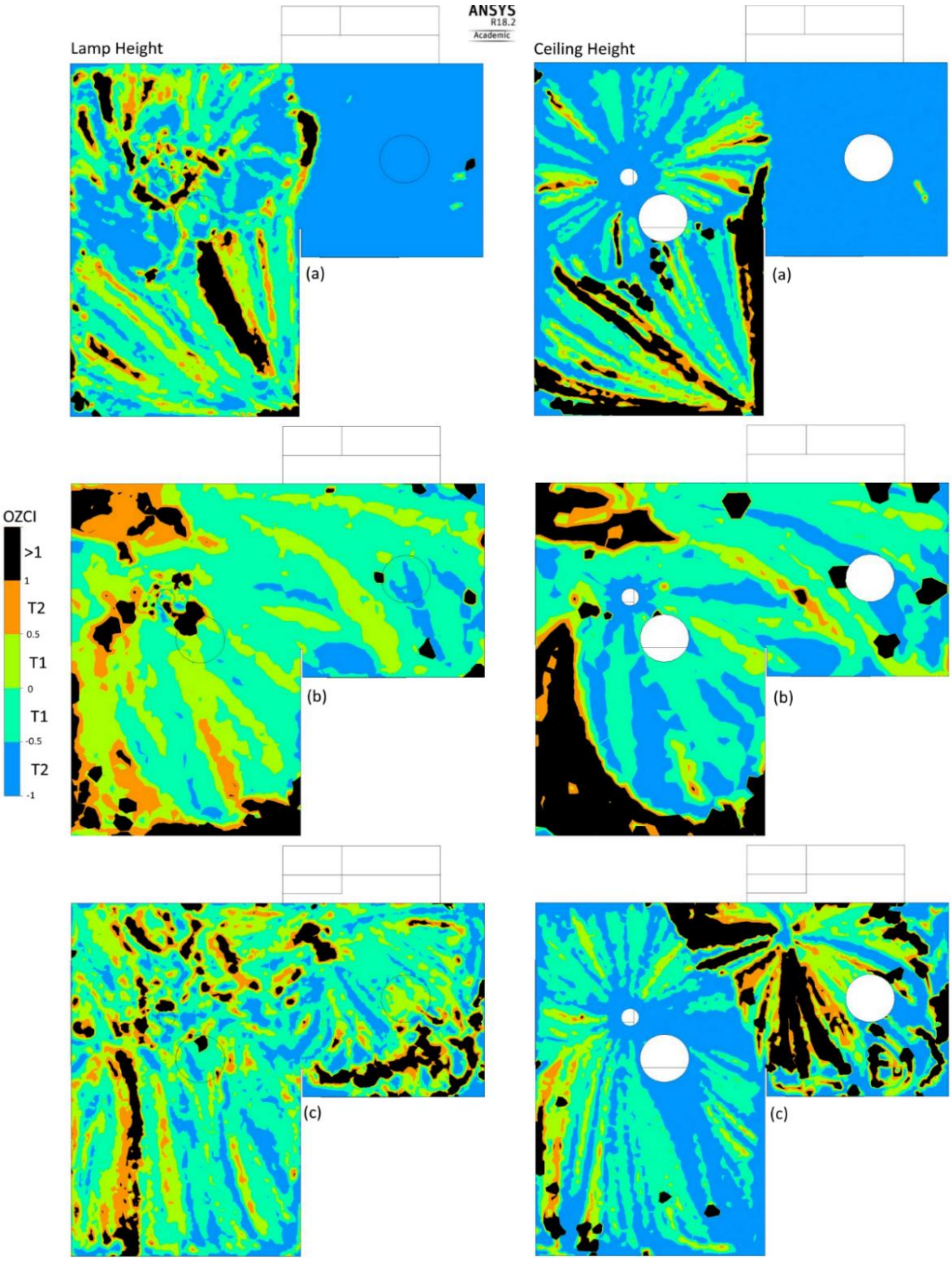

Figure 23. Horizontal cross-sectional planes at lamp height (left) and ceiling (right) for the sleeping (a), studying (b), and cooking (c) scenarios

A sample of vertical cross-sectional planes supports that there may be more uneven distributions and areas of elevated TVOC at wall surfaces than in the middle of the room, which is displayed in Figure 24 where the left pictures show a cross-section 80 cm from the wall (cutting through the bed) while the right pictures shows the bed-wall cross section with the open kitchenette area on the left half. The green areas (good representation of the average in the occupied zone) are larger and more continuous away from walls while the concentration of TVOC is more unevenly distributed at the wall surface. This is partly shown in the left examples 80 cm from the wall (crossing the middle of the bed) and partly in the right examples in which the wall ends where the bed ends. In the latter, the change in continuity of green areas are obvious where the wall ends.

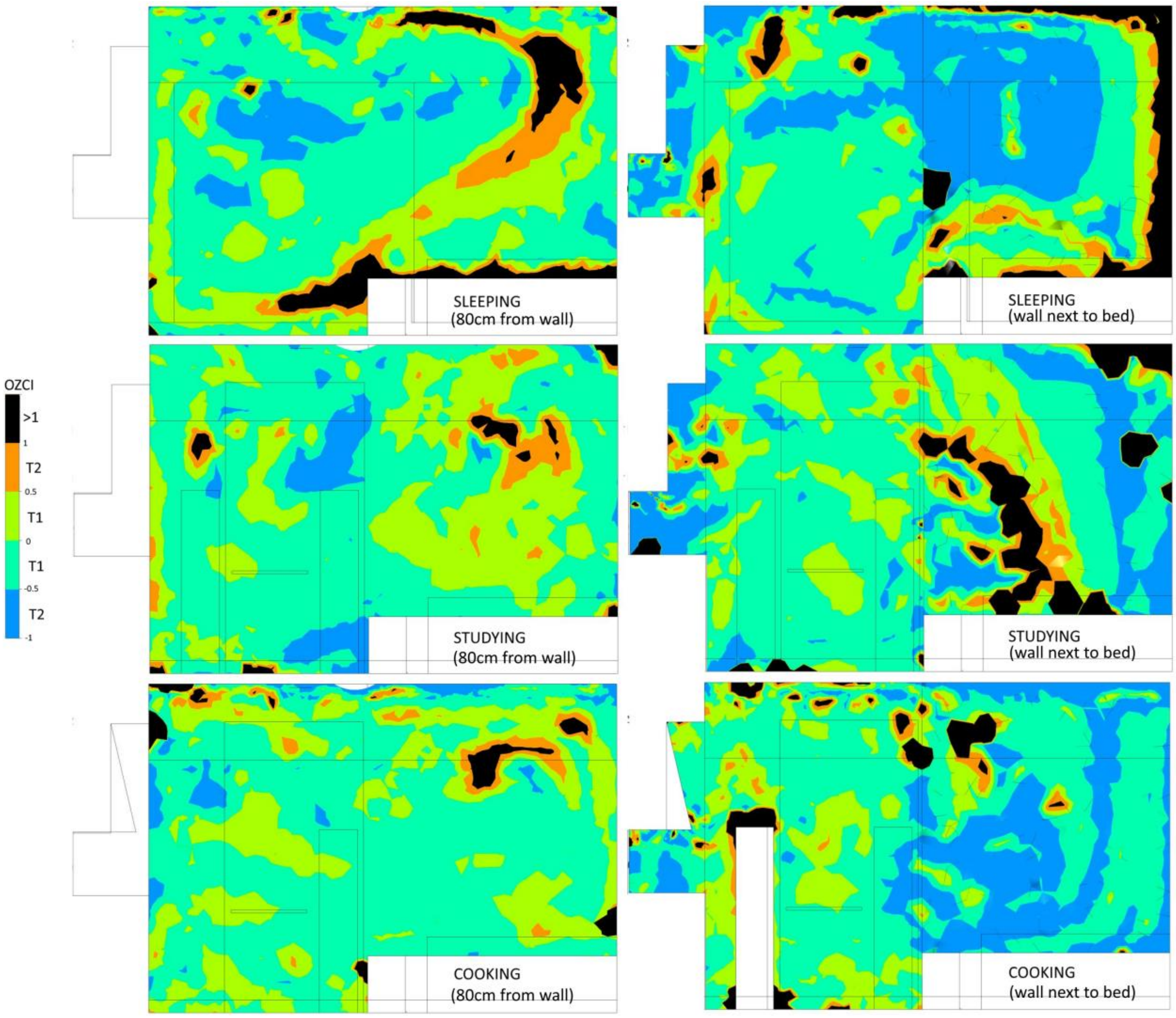

Figure 24. Vertical cross-sectional planes for the three base scenarios of the apartment showing middle of the bed (left) and at the wall next to the bed (right)

A closer look on how much impact the distance from the wall has on stability of sensor outputs is shown in Figure 25. The chosen wall is the one next to the bed as it has the least obstacles. The concentration is more evenly distributed further from the wall, and a short distance of only 5 cm out from the wall could have a positive impact on results regarding occupied zone compliance. The smallest difference in smoothness is for the sleeping scenario due to the particle source being immediately below the wall, although the greener areas get more continuous further from the walls for that scenario as well.

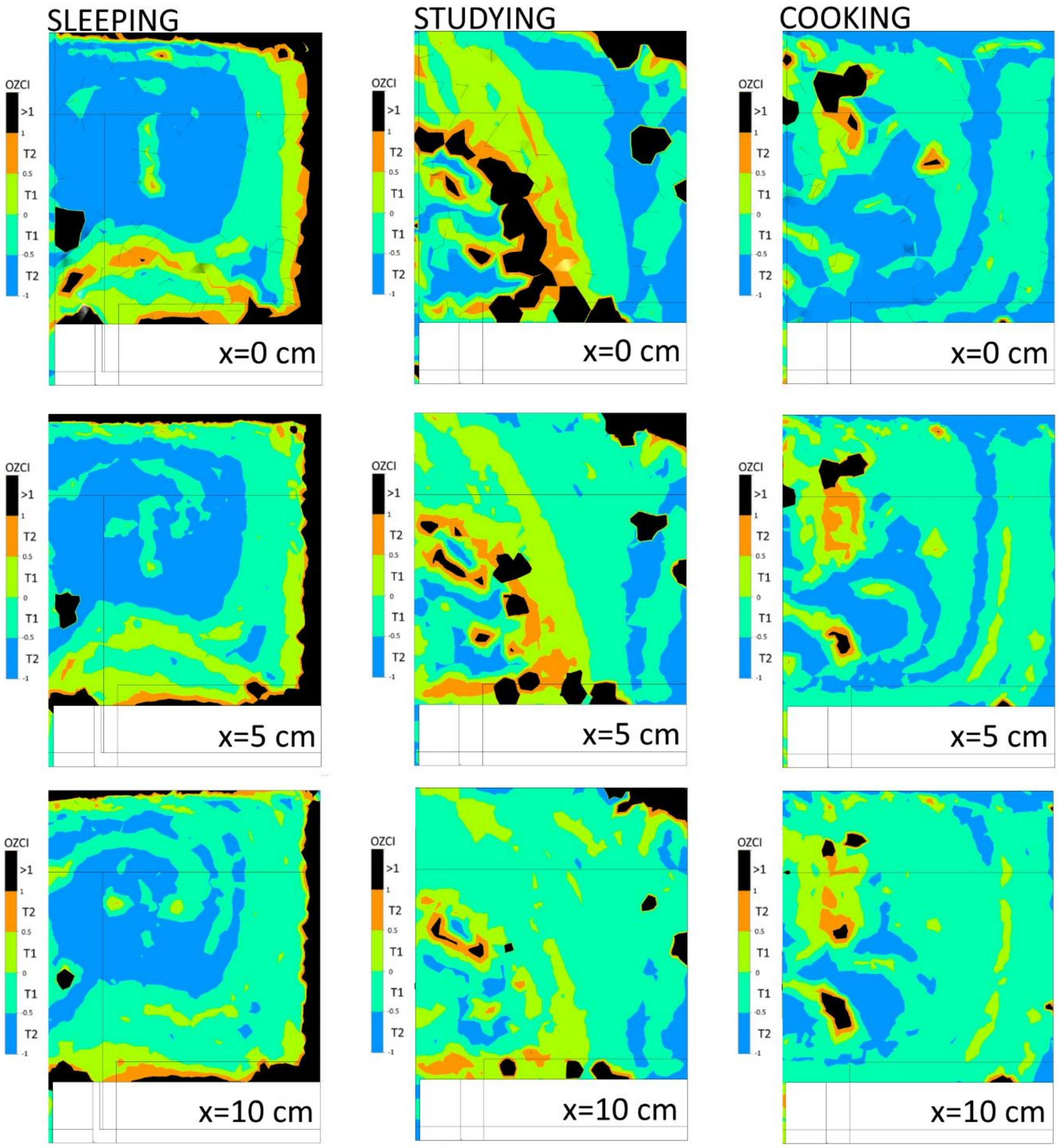

Figure 25. How particle concentration changes with distance from wall for the base scenarios, with x denoting the distance from the wall

5.2.5 Occupied Zone Compliance of Outlets

Except for the walls, it is of interest to check the variation of TVOC compared to that of the occupied zone for the outlets. Ideally, indoor air will mix with all room air and exit through the outlets without lingering in any area within the occupied zone. The OZCI was hence checked for the outlets of the base scenario, where the results further supported the idea of the outlet providing a representative point for measuring IAQ. All three scenarios reported an OZCI of below ± 0.6, which is within or close to the tolerance level T1, which suggests that the outlets are suitable placements from a TVOC perspective. An overview of OZCI for the outlets of the apartment is shown in Figure 26.

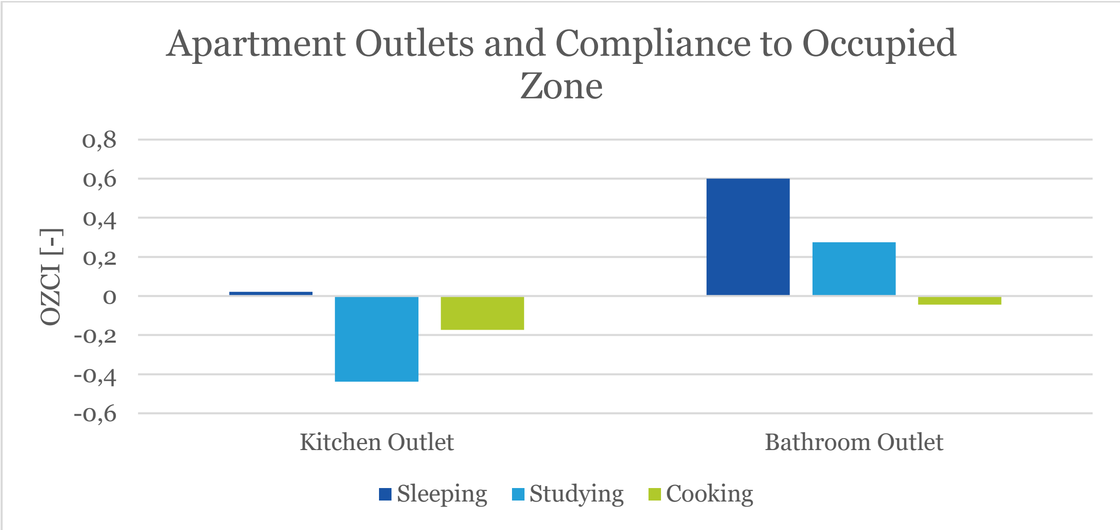

Figure 26. Outlet compliance to the occupied zone mean TVOC concentration for the base scenarios (no additional VOC sources)

5.2.6 Multiple VOC Sources

Occupants are most likely not the only sources of VOC in an apartment (or in any realistic setting). Aside from other indoor sources (for example paint), traffic or other outside pollutants could enter the room through the ventilation inlet. During the experimental parallel study, the logged data sometimes showed an increase in TVOC that could not be explain with occupancy or movement which indicates that the ventilation system could contribute with noticeable levels of VOC (see these studies attached in Appendix A and B). Therefore, the study case was complemented with injections of VOC at the inlet to compare the distribution difference (see Figure 27). Overall, the ceiling distribution is similar with respect to OZCI, naturally with less areas of very low or 0 ppb.

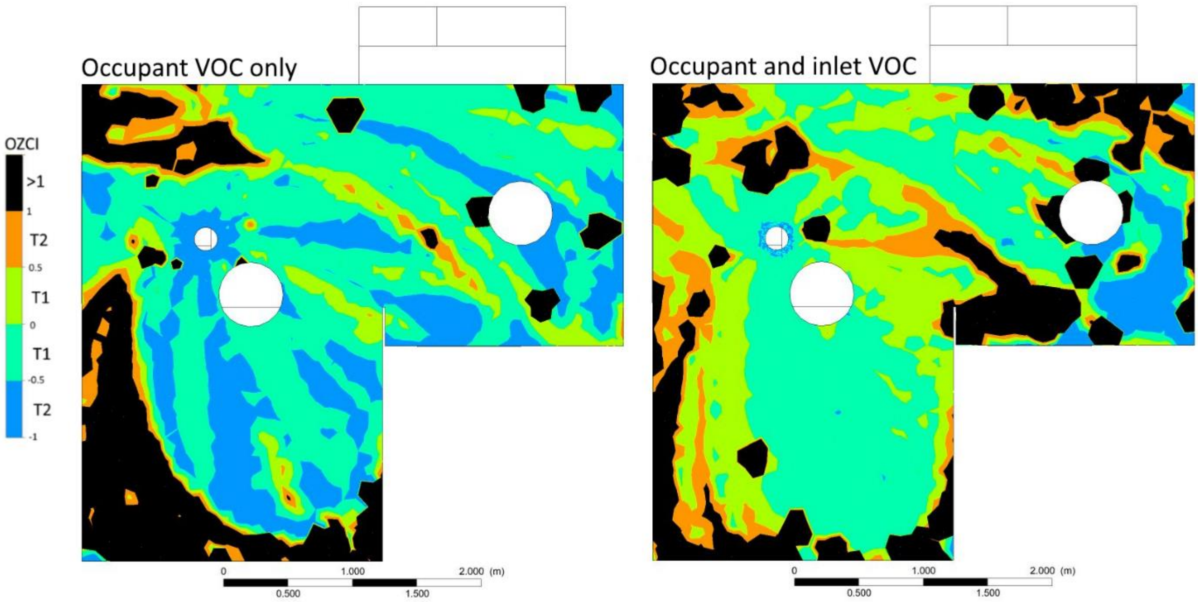

Figure 27. Ceiling for the studying case, in which the left shows the distribution with occupant-cause VOC only and the right shows the distribution with VOC also entering through the inlet

Spikes in TVOC was also shown in the apartment when cooking, see Appendix B. A steady state solution including an additional VOC injection at the oven was therefore conducted, representing a worst-case scenario as cooking is probably kept to short time periods. Overall, the OZCI vertical distribution appeared similar to the original cooking & studying scenario, see Figure 28, except for a spike at the end of the oven (~1 m), and lower concentration at the floor and higher at the ceiling. Regarding the extra input of VOC in the modified cooking simulation, the steady state is unlikely to be reached as the source is probably only emitting VOC for a limited time.

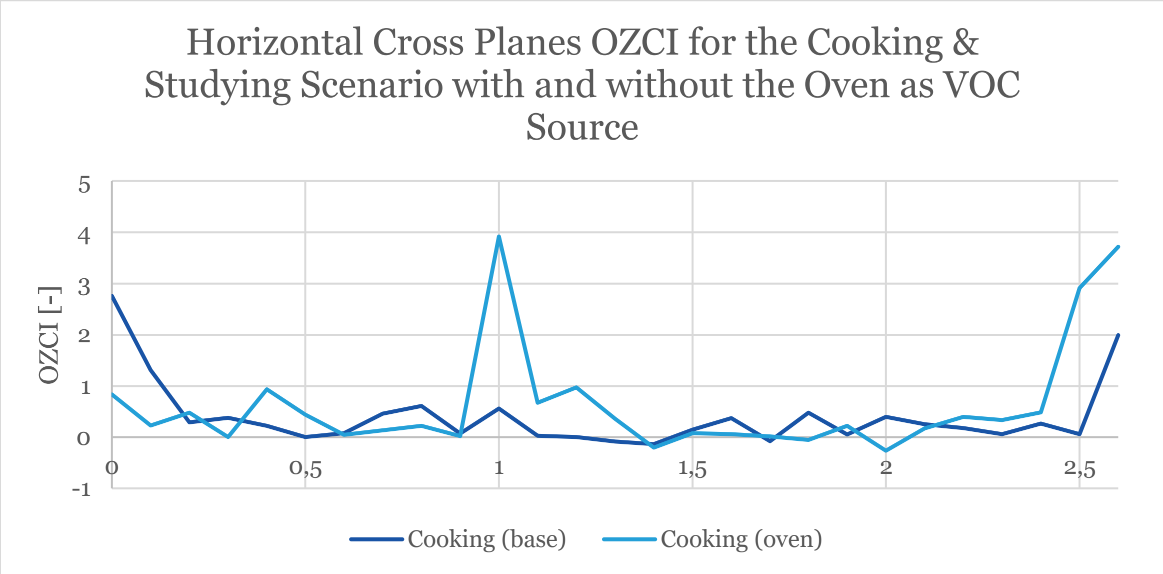

Figure 28. A comparison between the horizontal cross plane average OZCI for the cooking & studying case with and without an additional particle injection at the oven

5.2.7 Bathroom TVOC Distribution

The distribution of occupant-source TVOC in the bathroom is shown in Figure 29 for a scenario with a closed (left) and open door (right). As particles are allowed to escape through the door, but no VOC are assumed to enter, most particles collect near the ceiling in the open-door case (right). The overall particle concentration appears much lower with an open door than with a closed, in which most TVOC exits through the outlet in the ceiling. It is significantly more VOC in the ceiling for the closed door as well, although most particles prefer the corners of the ceilings and walls.

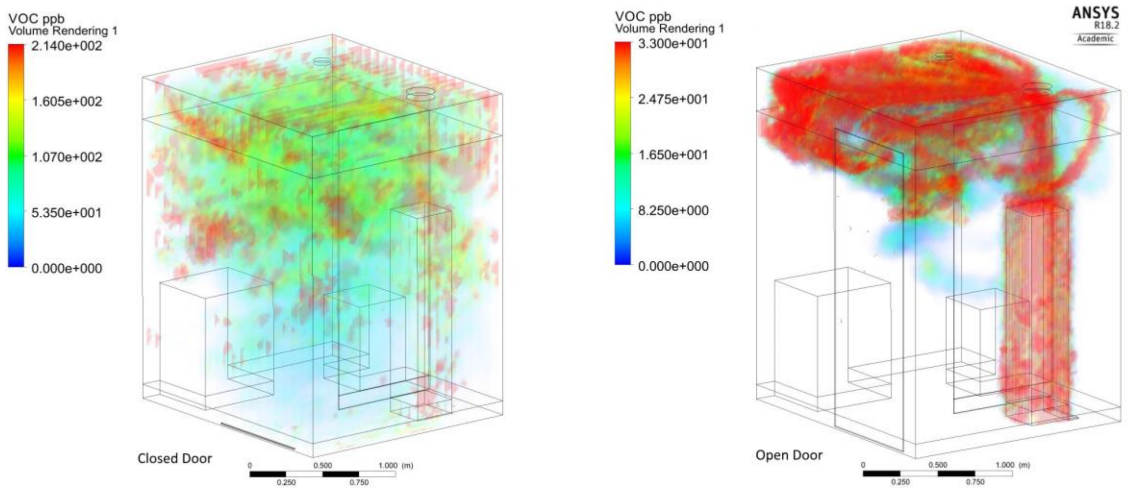

Figure 29. Bathroom particle distribution where transparent means 0 ppb TVOC and red is 100% more than the average of the occupied zone

The ceiling comparison showed in Figure 30 clearly shows an elevated particle distribution near the ceiling for both the closed and open door. The left pictures, showing the distribution 10 cm below the ceiling is significantly better distributed for the closed-door scenario. It is possible that the large concentration difference partly could be due to the much lower concentration in the open-door case. Putting a sensor in the bathroom seems to result in unpredictable readings, where further insecurities regarding the effect of common bathroom activities are outside the scope of this thesis.

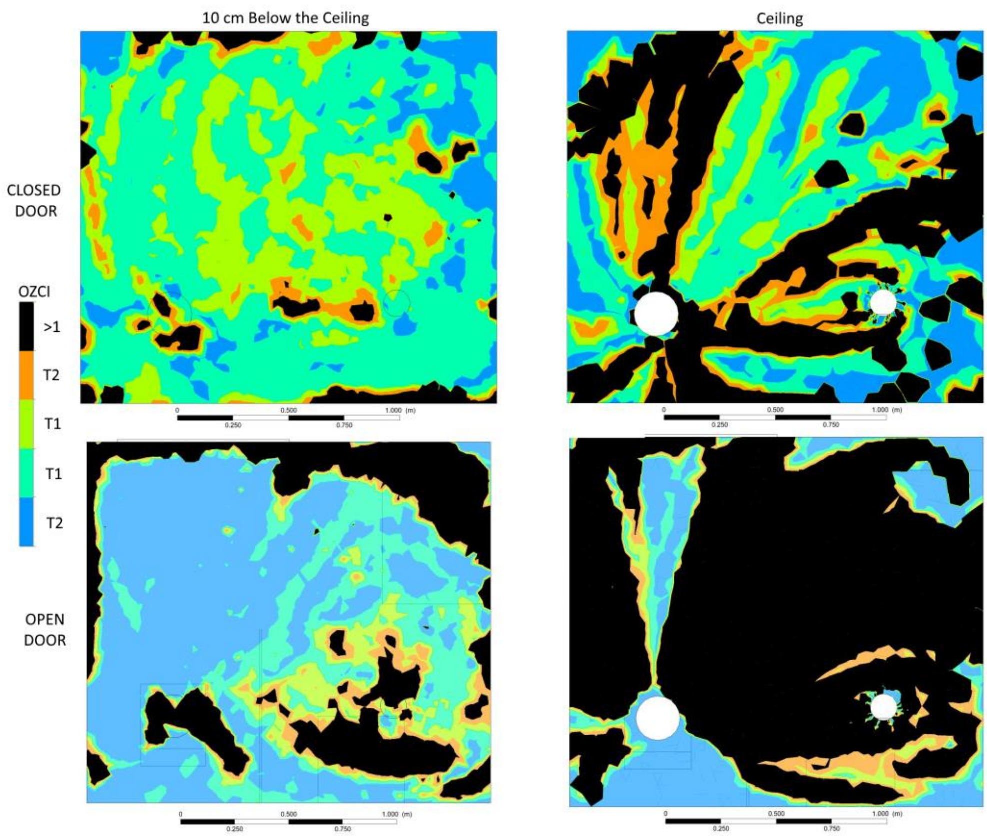

Figure 30. Comparison of ceiling and near-ceiling distribution for the bathroom with open and closed door

A final look on bathroom distribution is shown in Figure 31, where the preferred trajectory path of the particles is obvious. The left picture, showing the case with the closed door, has more scattered particle concentration than the picture from the open-door case. As all surfaces are adiabatic except for the occupant, it is likely that the main driver of air flow is heat, which explains the much higher concentration in the upper part of the room volume. Movement by the occupant would probably have a major impact on air flow and it is likely that particles are more evenly distributed in real life.

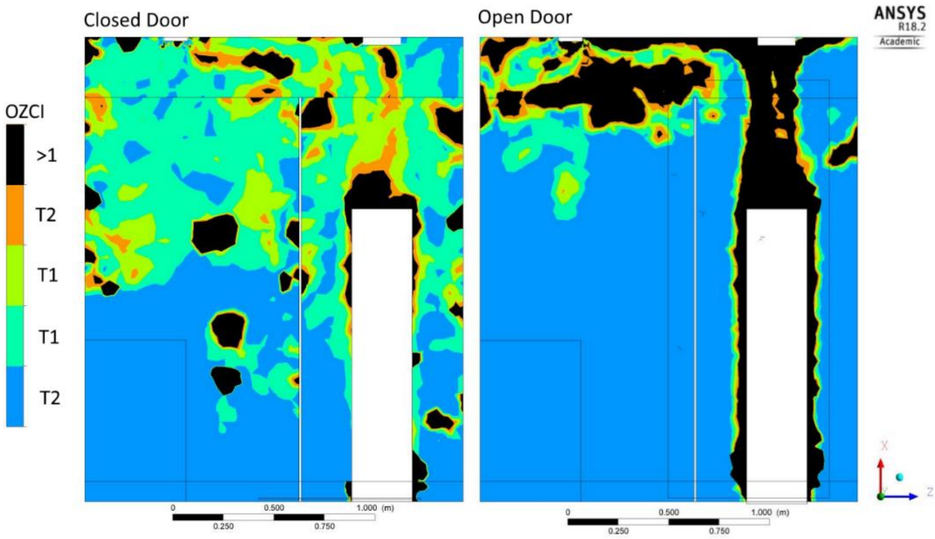

Figure 31. Vertical cross section showing OZCI in the bathroom through the person and outlet

5.2.8 Particle Size Sensitivity Analysis

The change in particle size for the simulations was considered a sensitivity analysis and was carried out for the apartment case with two studying occupants. The only parameter changed in the sensitivity analysis was the particle size, with the intent to find potential error sources and estimate the credibility of the results. Depending on the outcome, the analysis could result in recommendations concerning future studies as well. Checking the influence of particle size is further backed up by Zhang et al., who numerically studied the change in particle trajectories depending on size of particles derived from cooking in a simple kitchen model. They concluded that the size may affect the particle trajectories, and that small particles (0.1 μm) appear to behave more stochastically than larger particles (2.5 and 10 μm) (Zhang, et al., 2017).

In this thesis, TVOC was modelled as particles of CO2 in mass concentrations linked to TVOC. The DPM solver in Ansys allows the user to choose between a range of different options, including a particle size. The default setting is 1 μm. The basic studying scenario was used as base for how sensitive the simulations are to particle size in the DPM solver. The compared particle size was set to 0.1 μm and 10 μm (10 times smaller and 10 times larger, respectively). In reality, the size of TVOC molecules differ depending on the mix of different VOC available. The particles should however be small enough to presumably follow air flow.

In Figure 32, the results for different particle sizes of the injections in the studying scenario is showed. Stability of TVOC with variations of ≤ 1 can be seen between 0.5 and approximately 1.5 m above the floor. It appears that a size 10 times smaller than the original gives less stability closer to the floor while a size 10 times larger than the original result in more variation closer to the ceiling. The results indicate that future studies might increase credibility of results if the size of particles is considered, which can be done by enabling the Ansys function to randomize multiple sizes of particles derived from the source. However, accuracy should always be weighed against calculation time in CFD.

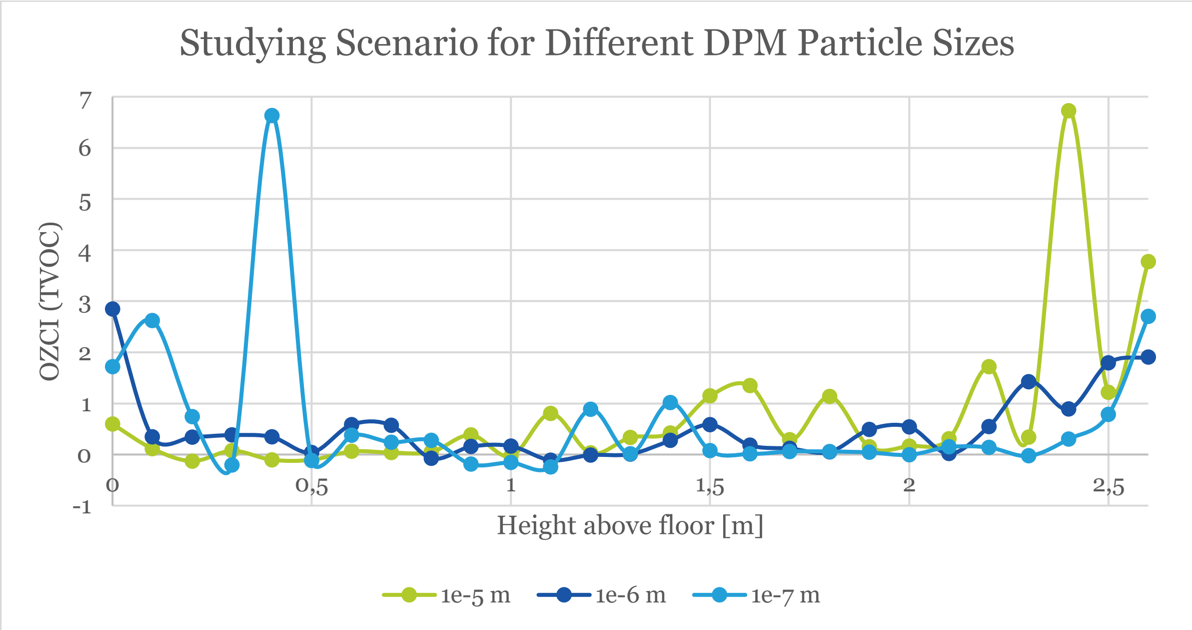

Figure 32. Studying scenario with different particle size for DPM injections

6 Interpreting Sensor Outputs to Estimate Air Quality

As mentioned in section 3.3 about the sensor specifics, the sensor outputs include TVOC, humidity and temperature. Compiling these into a single index could simplify the interpretation of current air quality in a building, which may contribute to promoting better indoor air quality and consequently also better health of occupants. One solution to an easily interpreted index-based system, is to categorise the index output into good, acceptable, and bad indoor air quality. A combination of Swedish thresholds and recommendations regarding indoor conditions, and previously developed indoor environment quality indices found in literature are used in this chapter.

The following method-proposal is intended as base for further discussion and is in no way conclusive. Simplicity and user-friendliness is considered important which limits the amount of detail. It is based on an existing suggestion developed by (Moschandreas & Sofuoglu, 2012), and is in their report stated to mainly apply to American offices. The method should be further developed to suit different building, application, and ventilation types. If occupants experience bad indoor climate even though the sensor readings appear fine, a more complete analysis of indoor air quality should be conducted since the proposed sensor-based index would neglect information regarding other pollutants, such as carbon monoxide, bacteria, or other particles. Other aspects neglected by the index is individual experience or technical errors.

One suggestion is to base the index upon the Indoor Environment Index (IEI) (Moschandreas & Sofuoglu, 2012), which is built upon two separate indices; one regarding pollution (IAPI) and one regarding thermal comfort (IDI) (see equations (e23) and (e24) respectively). Both part indices must be modified and adapted to suit the sensor outputs and Swedish conditions, and future studies should look at how the index could be altered to different building types. As earlier mentioned, there is incentive to give more weight to TVOC in an air quality index, as the objective is to complement (or replace completely) the current OVK procedure which focuses on air quality rather than thermal comfort.

In the method by (Moschandreas & Sofuoglu, 2012), the combined index, IEI, is the average of two part-indices; the *Indoor Discomfort Index* (IDI) and the *Indoor Air Pollution Index* (IAPI). The main difference between the original and the one proposed in this thesis, is that only TVOC is included as pollutant in equation (e24) and that thresholds and optimum values are adapted to Swedish recommendations, standards, and statistics.

The IDI part, based on equation (e23) requires adaptation of optimum, upper, and lower comfort levels regarding temperature and relative humidity. While Moschandreas and Sofuoglu states a temperature range of 19 to 25°C, Swedish standards recommend using 20 and 24°C as lower and upper comfort levels of air temperature (the operative temperature is considered adequate from 18°C).

Regarding the provided setpoints for relative humidity (Moschandreas & Sofuoglu, 2012), they do not comply with Swedish statistics (Boverket, 2009), nor with Swedish recommendations (Stockholms stad, 2018), as the air in the Northern countries is very dry during the cold months. Two different approaches for defining the upper, lower and optimum levels are therefore recognised; either they could be based on common (and overall accepted) levels in Swedish buildings, or they could be based on recommendations for optimal health. There are currently not enough evidence backing up optimal health levels to completely rely on the latter, which further encourages to instead use statistical data, although health research should be used for defining the optimum level, RH_{opt}. For now, the same optimum RH as defined by Moschandreas and Sofuoglu is suggested, which is 45%. A document from the Public Health Agency of Sweden's website (Socialstyrelsen, 2005) defines dry air as that with a relative humidity below 20%. The City of Stockholm (Stockholms Stad) recommends general dwelling indoor RH between 25 and 50%. How the range is chosen could further define the weight of RH, as a narrow range would result in a faster response of IAQ than a more extended range.

The IAPI index and TVOC requires demarcation values, which are undefined by larger authorities. As more data and research is available regarding CO_2, one solution to this would be to link CO_2 to TVOC and use either the translated demarcation values for TVOC or the equivalent CO_2 provided by the sensor. An important note is that this approach heavily relies on either good correlation between TVOC and CO_2, or on a well-defined conversion algorithm between TVOC and e-CO_2 incorporated into the sensor by the manufacturer.

From the collected sensor data in the reference rooms, see appendix A and B, an average relation between CO_2 and TVOC was concluded as

$$eCO_2 = 6.6671 \cdot TVOC + 401.84. \qquad \text{(e61)}$$

This relationship suggests that TVOC is on average roughly 90 ppb when e-CO_2 surpasses the recommended threshold of 1000 ppm, but the reliability is limited both by the unknown error, and the limited case studies and days measured. Moreover, common TVOC levels in Swedish dwellings are in the range of 200-300μg/m³ which corresponds to roughly 150 to 250 ppb (depending on air density) (A Persson; Karolinska Institutet, 2014). This means that, if the correlation in equation (e61) is correct, it is standard to keep CO_2-levels at more than the recommended 1000 ppm. The combination of correlation uncertainty, lack of experimental data, and the unknown error of the sensor advocates the use of e-CO_2 rather than TVOC.

The proposed index equation (e62), with modifications to the original equation by (Moschandreas & Sofuoglu, 2012), is shown in Table 8, along with examples of suitable optimum and threshold values. The observed value of e-CO_2 cannot be higher or lower than the maximum or minimum measured data. The index ranges between zero and 10, corresponding to excellent and bad IAQ respectively, and in the study by Moschandreas & Sofuoglu, the IEI of office buildings in the United States of America were normally distributed around a mean value 4.2. Their case study objects were divided into three sub groups, where an index of less than 3.6 was considered good and an index of more than 6 was considered bad. These limits should be used with caution as there are no Swedish studies backing up these categories. A similar study, relating the index to occupant symptoms, should be done for Swedish buildings where sensors are planned to be installed to conclude definite threshold regarding air quality.

Table 8. Suggested indexing solution to the CCS811 sensor outputs, based on the method by (Moschandreas & Sofuoglu, 2012)

$$\boldsymbol{IEI_{sensor} = \frac{1}{2}\left(\frac{1}{2}\cdot 10\left(\frac{(T_{opt}-T_{obs})}{T_{ucl}-T_{lcl}} + \frac{RH_{opt}-RH_{obs}}{RH_{ucl}-RH_{lcl}}\right) + 10\cdot\left(1-\frac{C_{max}-C_{obs}}{C_{max}-C_{min}}\left(\frac{C_{dmc}-C_{obs}}{C_{dmc}}\right)\right)\right)} \qquad \text{(e62)}$$

Temperature		**Relative Humidity**		**e-CO_2 (replacing TVOC)**	
$\boldsymbol{T_{opt}}$	$22°C$	RH_{opt}	45%	C_{dmc}	1000 ppm
$\boldsymbol{T_{ucl}}$	$24°C$	RH_{ucl}	50%	C_{max}	Measured
$\boldsymbol{T_{lcl}}$	$20°C$	RH_{lcl}	25%	C_{min}	Measured
$\boldsymbol{T_{obs}}$	Measured	RH_{obs}	Measured	C_{obs}	Measured

Thresholds for short periods of time are commonly reported every 15 minutes (Arbetsmiljöverket, 2017), and it is thus suggested that collected data comply with this. Longer averaged reporting periods could have the potential of lowering the impact of occasional TVOC spikes seen in the reference room sensor results provided in Appendix A and B. This could in turn lower the risk of reporting unrealistically elevated levels of e-CO_2.

7 Discussion

In this section, the method and combined case studies are discussed.

7.1 The Method

This study mainly uses CFD to evaluate particle concentration and indoor air flow, while initial validation of contaminant concentration in the references was done by analysing collected sensor data from a parallel study, to ensure that variation and general TVOC concentration were credible. When the large-scale project enters the phase of VOC-monitoring, the method used in this study could be adapted to quantitatively analyse new participant objects and the case-study findings could be used as base for qualitative discussion regarding sensor placement.

The proposed method is basically the same as the one presented in the Methodology-chapter (see section 3.1 Overview of Method for Evaluating Sensor Position), although a few tweaks to the original method may be necessary or beneficial before settling on a final proposal. One thing is the tolerance levels; for very low modelled concentrations, as evident in the open-door bathroom case study, the second tolerance level of $\pm$ 100% particle variation compared to the occupied zone mean should be used in order not to exclude representative areas due to too small reference frames. Alternatively, a minimum allowed TVOC variation should be set based on common fluctuation detected by the sensor as well as the error reported by the manufacturer. The normal fluctuation could either be developed over time through collection of more data, or through relating TVOC and expected fluctuation of CO_2. From the data provided in Appendix A and B, it appears that TVOC readings larger than 0 ppb are always fluctuating somewhat while CO_2 behaves generally more stable even at elevated levels. Meanwhile, the T_2 tolerance level is suggested for CFD simulations where the mean occupied zone value is below 45 ppb, based on the measured correlation from equation (e39) and 700 ppm CO_2, below which insufficient IAQ is stated to be at low risk (Samuelsson, 1998). This is to include areas of 0 ppb as representative for the occupied zone, but only when the average is low.

This thesis report includes additional steps to the method, such as validation according to literature review and measured data along with some statistical analysis. These are mainly used to evaluate the developed method and does not have to be conducted each time the proposed method is used, although an initial calibration of sensors could be beneficial in the beginning of the project to evaluate the compatibility with OVK and evaluate potential errors. An allowed error will most likely be necessary to incorporate when going large-scale, which could be developed based on specifications from the manufacturer and collected data.

The ISO Standard 16000-1:2006 provides standardised recommendations for placement of sensors for assessing air quality. While the standard puts a lot of emphasis on assessing the air quality as an occupant would experience it, it does not seem to address the issue of permanent sensor placement. The CFD model proposed in this thesis could here work as an evaluation of whether a sensor could be placed outside the recommended volume in the standard.

The method outlined in this report takes into account more possible sensor placements than experimental studies, as explained in for instance (Bulińska, et al., 2014) and (Mahyuddin, et al., 2014). This is primarily due to the use of CFD giving a more comprehensive picture of the entire simulated space while experimental studies are most likely limited to discrete measuring points. For CFD simulations however, it is beneficial to find support in experimental studies when validating results. Experimental studies also benefit from not having to assume boundary conditions, which could potentially change CFD results significantly.

While this study is more inclusive than those mentioned above, it is also simpler than for example that described in the report by (Fontanini, et al., 2016). This brings potential drawbacks such as lower accuracy but might at the same time allow for faster approximation and be better suited for the chosen sensor which is limited to only TVOC, e-CO_2, relative humidity, and temperature. Simplicity was also approached to make the method more accessible for multiple applications and types of users, and as the intention is to assess the general air quality of a room rather than optimising for fast-response or very detailed analysis, qualities such as quick and user-friendly qualified higher in the list of priorities.

The approach suggested by Fontanini et al. is heavily focused on finding the optimal number of sensors for fast response times, which may be an unnecessary variable to this study as rapid evacuation is not the aim of continuously monitoring the IAQ. Yet, it may be of interest for future studies to evaluate whether for example class rooms, auditoriums, or reception halls would benefit from using multiple sensors both from a coverage and cost perspective (with respect to the current cost of OVK), in which case the method provided by Fontanini et al. might be a good starting point for future research.

However, in the example IAQ study provided by Fontanini et al., it was concluded that when using constraints to only sense the air in the occupied zone and place the sensor outside the occupied zone (for practical reasons to avoid harm to the sensors) the optimal placement was consistently at the outlet. The comprehensive methodology consequently appeared redundant in the case of singular sensors, as the constraints set by the user dominated the possibility of further evaluating other spatial positions. From this point of view, this thesis offers more insight into the magnitude of importance of vertical and horizontal position when placing a sensor rather than finding a single optimum.

7.2 Sensor Location

There already exist guidelines and general recommendations regarding where to place sensors for logging air quality of temperature. Most agree that the sensor should be placed within the occupied zone (temperature sensors preferably not in direct sun light), but the definition of the occupied zone is varying between authorities. Following the definition stated by the Public Health Organisation of Sweden, the sensor should not be placed at a wall, as it would then be outside the occupied zone. According to BBR however, a wall placement should be fine if it is somewhere between 0.1 and 2 m above the floor and it is not an exterior wall.

Other factors to take into account that could vary from application to application is to avoid putting the sensor within reach of children, in particularly wet areas, or where occupants breath on the sensors, as this could lead to false readings or unrealistic outputs due to the algorithms (e.g. TVOC to e-CO_2 conversion). How the algorithm is affected by high local temperature or solar rays is outside the scope of this study and is difficult to estimate without the access to the actual algorithm from the manufacturer. Therefore, it is left for future studies.

The case studies in this report were run at steady state, assuming no movement or alteration of VOC. Incorporating movement would most likely improve the overall mixing of the room, which in turn would lower the risk of installing the sensor in an inadequate spatial location. The guidelines presented and discussed here are therefore considered conservative but might be unrepresentative for rooms with entirely different geometry, airflow, and activities.

7.2.1 Ceilings

From the CFD results of this study, it is clear that a sensor located in the ceiling could result in much higher TVOC readings than what is representative for the occupied zone. The visual inspection of cross-planes however showed that there are ceiling areas which could likely provide representative results regarding particle concentration. These areas are in the middle of the ceiling, far away from walls and not placed immediately above a heat source or where an occupant is expected to linger for longer periods. As the average particle concentration at the ceiling is much higher though, the risk of misinterpretation of IAQ is considered higher if the sensor is placed in the ceiling.

7.2.2 Walls

Wall placing recommendations based on the case studies are similar to the ceiling recommendations. The air in corners appear more stagnant which risks collecting more particles. Comparing walls to the free air the middle of the room, see for example Figure 24, clearly shows that the distribution close to walls is more uneven than in the middle of the room. Ideally, the sensor should thus be placed in the middle of the room but placing a sensor in thin air is not realistic. If it is possible to install the sensors so that the sensitive area is a few centimetres out from the wall, this might make a significant difference to occupied zone compliance.

7.2.3 Lamp Fixtures

The results regarding sensor placement in lamp fixtures are non-conclusive. While the concentration levels could be representative of the occupied zone only a short distance from the ceiling, there is still a possibility of elevated levels due to the heat changing the air flow pattern and the geometry creating obstacles for air flow. In the office case study, the hot lamp surface closest to the outlet appeared to well represent the occupied zone mean concentration while simultaneously showing collections of particles close to the sides. In the apartment case study, the lamp fixture had a smooth geometry which did not appear to significantly interrupt air flow. The uniform temperature boundary conditions and limitation of mesh elements restricted conclusions regarding lamp surfaces from a TVOC perspective. Lamps placed within, or close to, the occupied zone were not closer studied by the author of this report, although the vertical average concentration advocate for promising representativity concerning particle concentration.

Other concerns than TVOC are necessary to include in the lamp fixture analysis as well, where temperature might be the most significant concern. Many lamps in public buildings are turned on for longer periods and produce a considerable amount of heat (the tube in the reference office showed temperatures of at least 30°C). The impact on the CCS811 sensor outputs from elevated temperature is unknown due to the inaccessible algorithm and too little experimental background data. The initial advice is to avoid putting the sensor on surfaces with elevated temperature as correlation between higher CO_2 levels and high temperatures is supported by earlier studies (Mahyuddin & Awbi, 2010), and the reading of the sensor risk being non-representative for the actual values of the occupied zone. A future study should be conducted on lamps only, to check the impact on contaminant collection by different geometry and heat distribution.

7.2.4 Bathrooms

The bathroom provides a good base for discussion as there are many factors talking against assessing air quality there. In an insufficiently ventilated bathroom, there is a risk for condensation on the ceiling and wall surfaces, which should be considered when placing the sensor as it should not be in direct contact with liquid according to the manufacturer. Placing the sensor too close to a shower or water tap would naturally increase the risk of water-contact. It is also possible that suddenly elevated humidity levels could disturb the built-in algorithm for estimating e-CO_2 or otherwise affect collection of data. Yet another factor which could aggravate the process of assessing IAQ of a bathroom is the many sources of VOC which could create sudden spikes in the outputs (soaps, dry shampoo, cleaning products, etc). These pollutants should not be long-lasting but could create misleading averages of IAQ depending on the algorithm and how data is collected.

During the literature review, it seemed evident that the IAQ of bathrooms is not routinely checked and has less strict recommendations (excluding temperature) (Folkhälsomyndigheten, 2016) as people only tend to spend short periods of times in there. The current OVK-system considers airflow and that the ventilation outlet works according to design rather than evaluating overall IAQ when in the bathroom. The question is thus whether it is at all necessary to install a sensor in the bathroom. Further studies zooming in on bathroom conditions should be done before making conclusions regarding optimal placement. Meanwhile, it should be reconsidered whether it is sufficient to measure the IAQ outside the bathroom for continuous metering.

7.2.5 Initial Sensor Placement Guidelines

The guidelines compiled in this section are based on literature review (including previous studies and available guidelines) and the two case studies presented in this report. They primarily apply to room types similar to the ones of the case studies in this report (offices and apartments), and it is not guaranteed that the guidelines are suitable for objects which differ significantly in for example geometry or ventilation design. Only mechanical ventilation has been studied in this report, and the inlets were located in the ceiling for both studies. Variations due to for example floor material, furniture, or pets could cause the results to differ from the ones obtained from this study. New buildings tend to emit more TVOC than modern buildings older than three years (Shin, 2013) which should be considered as well when measuring TVOC to evaluate ventilation systems.

The proposed sensor placement guidelines are:

- Primarily consider mounting the sensor within, or close to, the occupied zone
- Avoid placing the sensor on surfaces with deviating temperature, such as exterior walls or hot lamp fixtures
- Avoid placing the sensor in corners
- Try placing the sensor as far away from obstacles as possible (for example corners or doors)
- Avoid placing the sensor directly above places where occupants are expected to linger for longer periods
- Avoid placing the sensor too close to a bed, especially corners or immediately above
- If possible, mount the sensor a few centimetres out from the surface so that it is not in immediate contact with it
- Avoid placing the sensor where it risks getting in direct contact with water or other liquid
- Avoid placing the sensor in direct sunlight
- Try placing the sensor out of reach for children

7.3 Future Work

It is of great importance that thorough follow-up is conducted related to the large-scale project. It is likely that recommendations regarding acceptable placement of sensors depend on different aspects such as ventilation type, building application, geometry, or inlet air flow rate. Therefore, the method of this report was developed so that it can easily be modified to further extend the case studies initiated here. The logged data acquired from sensors will likely contribute with great insight on how the spatial position of sensors may affect the registration of air quality, but also on how well buildings that meet OVK standards generally meet recommendations of continuously logged IAQ. The large-scale experiment can provide big data which can be used to provide accurate background TVOC levels, current IAQ of buildings, and better calibration of the instruments.

More research regarding the link between TVOC and CO_2 would further support using the TVOC sensors, as indoor air quality is today difficult to estimate based only on TVOC. Transparency of sensor algorithms will be of increasing importance in the negotiation process with authorities, while simultaneously allowing stronger validation of methods and instruments.

There are factors outside the scope of this study which should be approached as well. These include outdoor climate variation over the year, optimisation of tolerance level with respect to sensor error, cost, and energy, and looking at benefits from installing multiple sensors in a single space.

As lamp fixtures could not be entirely ruled out as potential surfaces for mounting sensors, although there is a cautious recommendation to avoid installing sensors there due to elevated temperature, a more comprehensive study should be done focusing on the impact on TVOC due to different heat distribution and lamp geometry. A future study should be conducted on bathrooms as well, in order to evaluate the impact on OVK compatibility and IAQ if sensors are chosen not to be put in bathrooms at all.

8 Conclusions

In this thesis, a simple model was developed for concluding how well different areas of a room correspond to the average TVOC concentration of the occupied zone, given that occupants are the main source of VOC. The model consists of a methodology outline and suggested inputs for CFD modelling, see page 10 and 51. By following the outlined methodology and using the inputs, the model can be modified to suit different rooms equipped with different heat sources, occupant number, and airflow and placement of mechanical ventilation. The intended use of the model is to decide upon good placement of IAQ-sensors for continuous metering. Added to the model are guidelines suggesting how to take into account temperature and relative humidity.

Through literature review and application of the suggested model on two case studies, one office and one apartment, some guidelines for placement of sensors were developed. The concluded recommendations mainly concern similar rooms, with similar ventilation and heat gains, but showed consistency between the studied objects. Listed below are the conclusions drawn from the case studies and literature review of this report.

1. Sensors may be placed outside of the occupied zone, from a VOC perspective
2. VOC sensors should not be placed in corners, as particles tend to collect due to the no-slip principle and more stagnant air
3. Particles collect in the ceiling, given the geometry and ventilation of the case studies, and the average concentration might be considerably higher there compared to other height averages
4. The best placement in theory is in the middle of the room, where none of the occupants touch or breath on the sensor, while VOC metering at walls may lead to spikes due to non-uniform behaviour in particle concentration
5. Measuring IAQ a few centimetres out from the wall or ceiling could result in values significantly closer to the average of the occupied zone
6. Bathrooms might not serve as appropriate places for estimating continuous IAQ, given the CCS811 sensor specifics

Also included in this report is a suggestion for how the sensor outputs, namely TVOC, temperature, and relative humidity, can be combined into a single index for easy interpretation of current IAQ. The suggested input modifications to the chosen index were proposed as to suit both the sensor outputs and Swedish standards and are presented in Table 8. A good correlation between TVOC and CO_2, or a well-working sensor algorithm for converting TVOC into e-CO_2, is presumed for the suggested input values.

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Appendix A: VOC and CO_2 Measurements in the Office

Author: Marie Cabau

VOC and CO_2 measurements

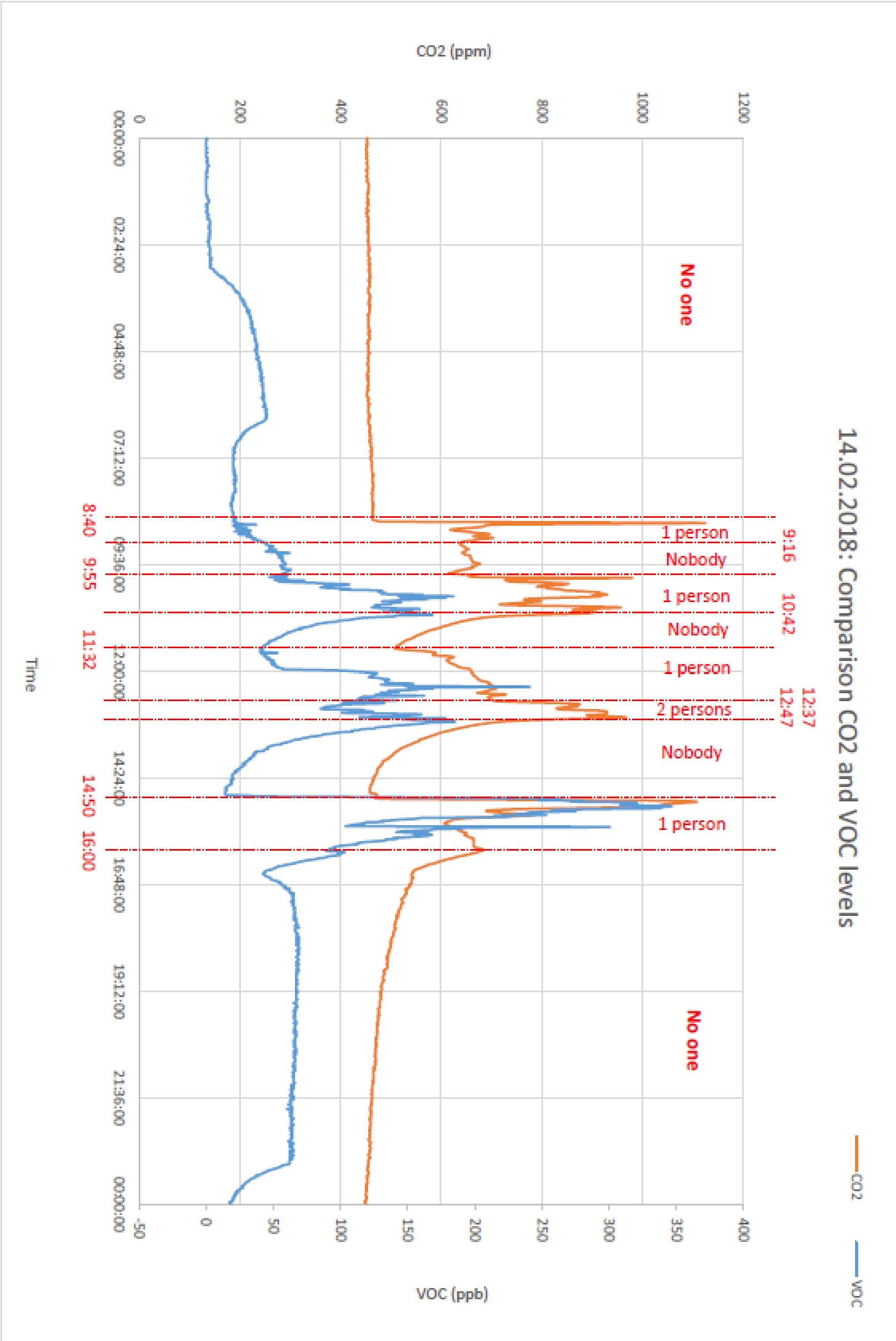
Office

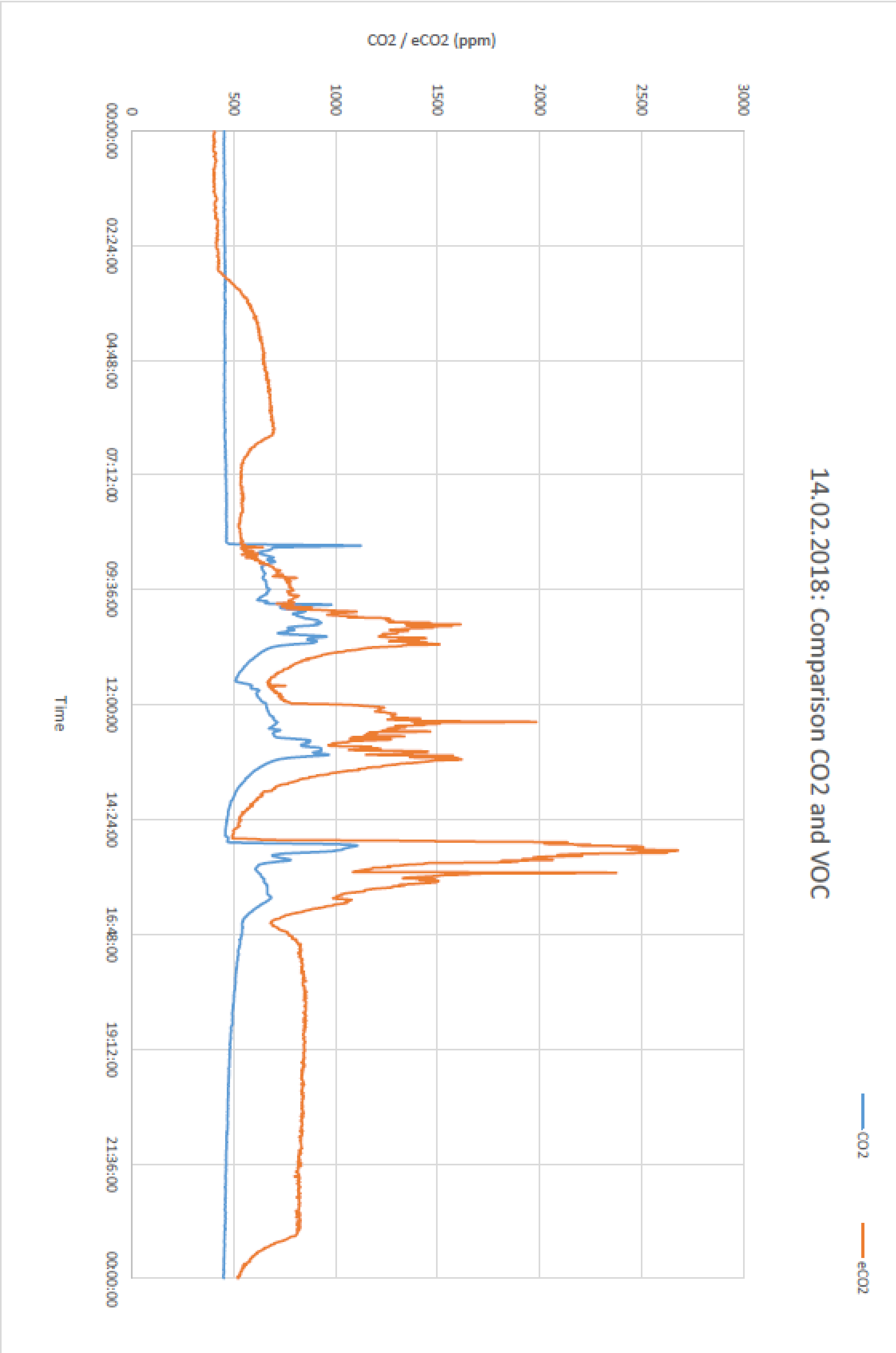
Description:
10 m² office, for only one person, windows almost always closed.

Place:
Brinellvägen 68, Stockholm

Sensors location:
On Joachim's desk, close to where he is sitting.

Ventilation:
ON from 7 am to 7 pm – 10 L/s


14.02.2018: Comparison CO2 and VOC levels
CO2 (ppm)
VOC (ppb)
Time
CO2
VOC
No one
1 person
Nobody
1 person
Nobody
1 person
2 persons
Nobody
1 person
No one
8:40
9:16
9:55
10:42
11:32
12:37
12:47
14:50
16:00
00:00:00
02:24:00
04:48:00
07:12:00
09:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
00:00:00
0
200
400
600
800
1000
1200
-50
0
50
100
150
200
250
300
350
400



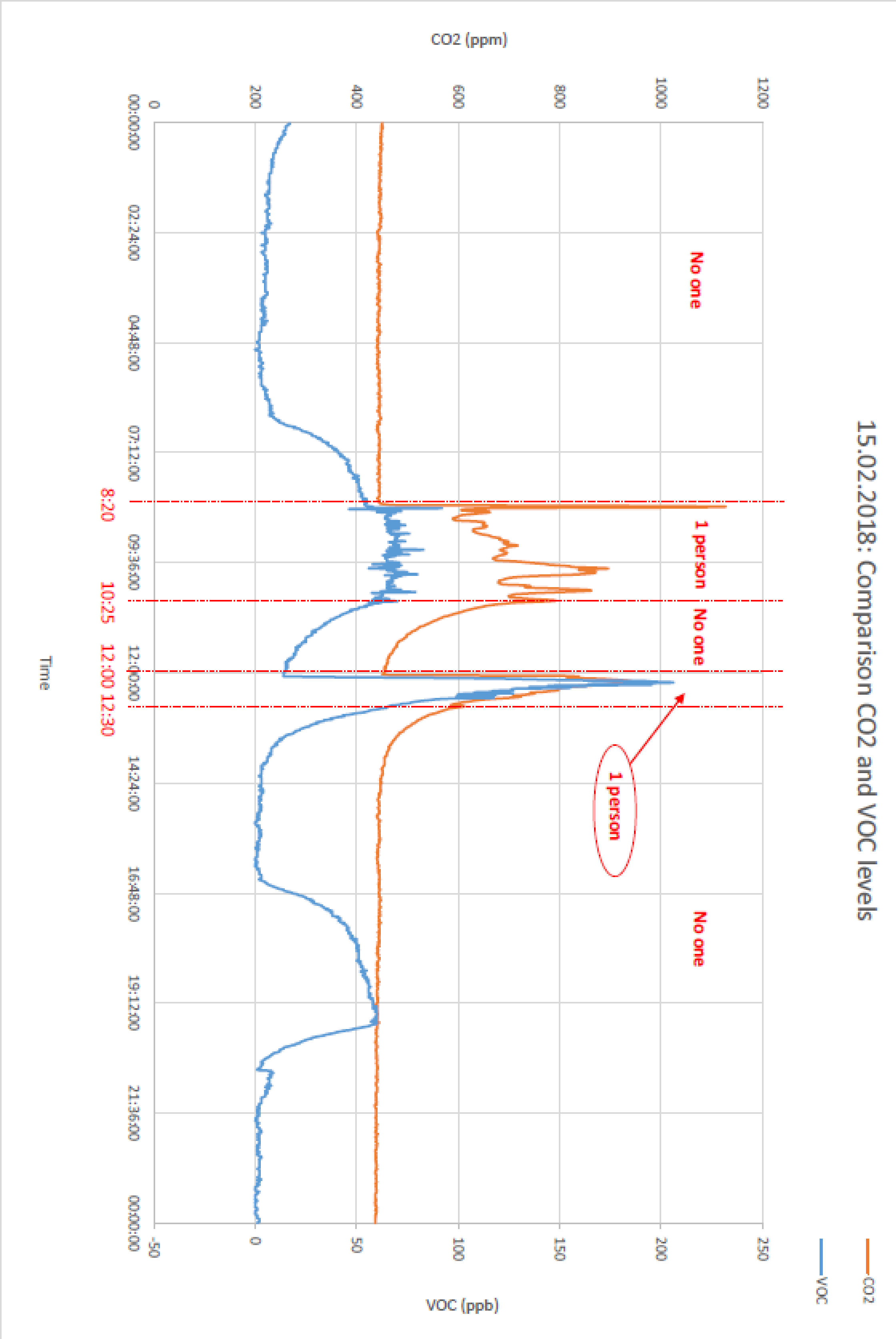
14.02.2018: Comparison CO2 and VOC
CO2 / eCO2 (ppm)
0
500
1000
1500
2000
2500
3000
Time
00:00:00
02:24:00
04:48:00
07:12:00
09:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
00:00:00
CO2
eCO2

Comments:

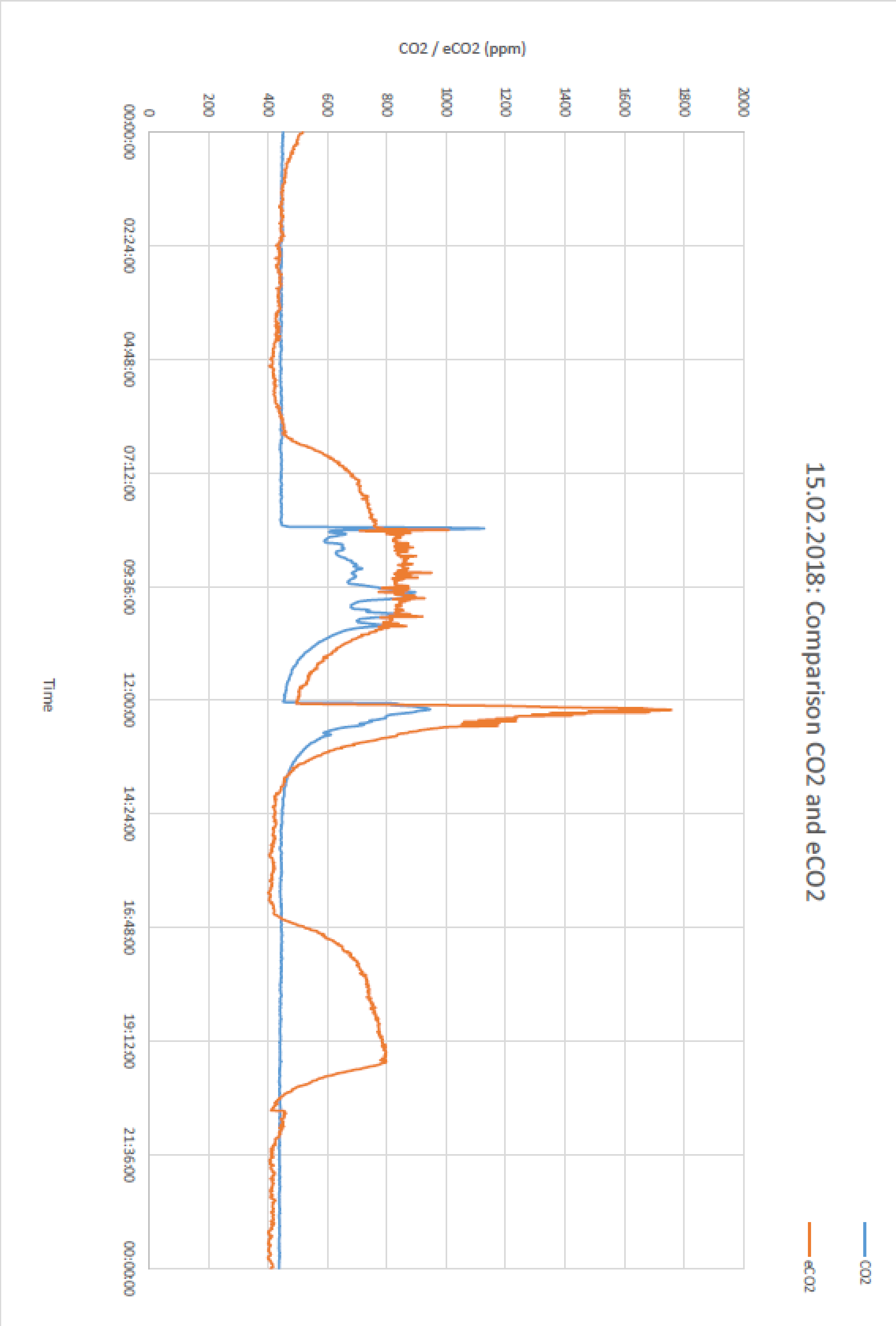
- First of all, we can notice an increase of the VOC level between 3 and 6 am while the room is unoccupied which is confirmed by the constant level of CO2. This increase clearly shows that human is not the only source of VOC, they can be emitted by furniture, paint, cleaning products, etc. Moreover, we can see that VOC level decreases when the ventilation starts around 6:30 am.

- Then, when the room is occupied, we can see that CO2 and VOC behavior are really similar and dependent on the occupancy. However, we can notice that when someone enters the room, CO2 level immediately increases while VOC level seems to take some minutes before increasing. Moreover, two VOC peaks can be noticed during the day. The first one occurs around 12:30 and explains why the VOC level decreases around 12:37 while CO2 level increases according to occupancy. Indeed, this peak is certainly due to an external VOC source, different from human, and increases the VOC level for only a few minutes. The second one occurs around 15:30 and explains as well the decrease in VOC a few minutes later while CO2 level increases.

- To finish, at the end of the day, when the room is unoccupied, the VOC level increases a bit around 16:30, stays constant and then decreases around 11 pm. This is probably due to external sources of VOC as mentioned before.



15.02.2018: Comparison CO2 and VOC levels
CO2 (ppm)
0
200
400
600
800
1000
1200
VOC (ppb)
-50
0
50
100
150
200
250
Time
00:00:00
02:24:00
04:48:00
07:12:00
09:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
00:00:00
8:20
10:25
12:00
12:30
No one
1 person
No one
1 person
No one
CO2
VOC



15.02.2018: Comparison CO2 and eCO2
CO2 / eCO2 (ppm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
00:00:00
02:24:00
04:48:00
07:12:00
09:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
00:00:00
Time
CO2
eCO2

Comments:

- From 00:00 to 8:20, the room is empty that is why CO_2 and VOC levels are constant and really low, close to the minimum values detectable by the sensors (400 ppm for the CO_2 sensor and 0 ppb for the VOC sensor). We can notice however that VOC level increases around 6:30 when the ventilation starts.
- The rest of the day, VOC and CO_2 levels are really similar and dependent on the occupancy of the room. However, another exception, really similar to the one the day before, occurs around 16:30. Indeed, the VOC level suddenly increases before decreasing again around 19:44.
- Except for the two behaviors mentioned previously, the equivalent CO_2 calculated by the VOC sensor is really close to the CO_2 level. Indeed, when there is no external source of VOC disturbing the measurements, we can clearly see the link between the two quantities.

Appendix B: VOC and CO_2 Measurements in the Apartment

Author: Marie Cabau

VOC and CO_2 measurements

Accommodation

Description:

20 m² apartment, one room with bed, kitchen and a big window.
Bathroom separated.

Place:

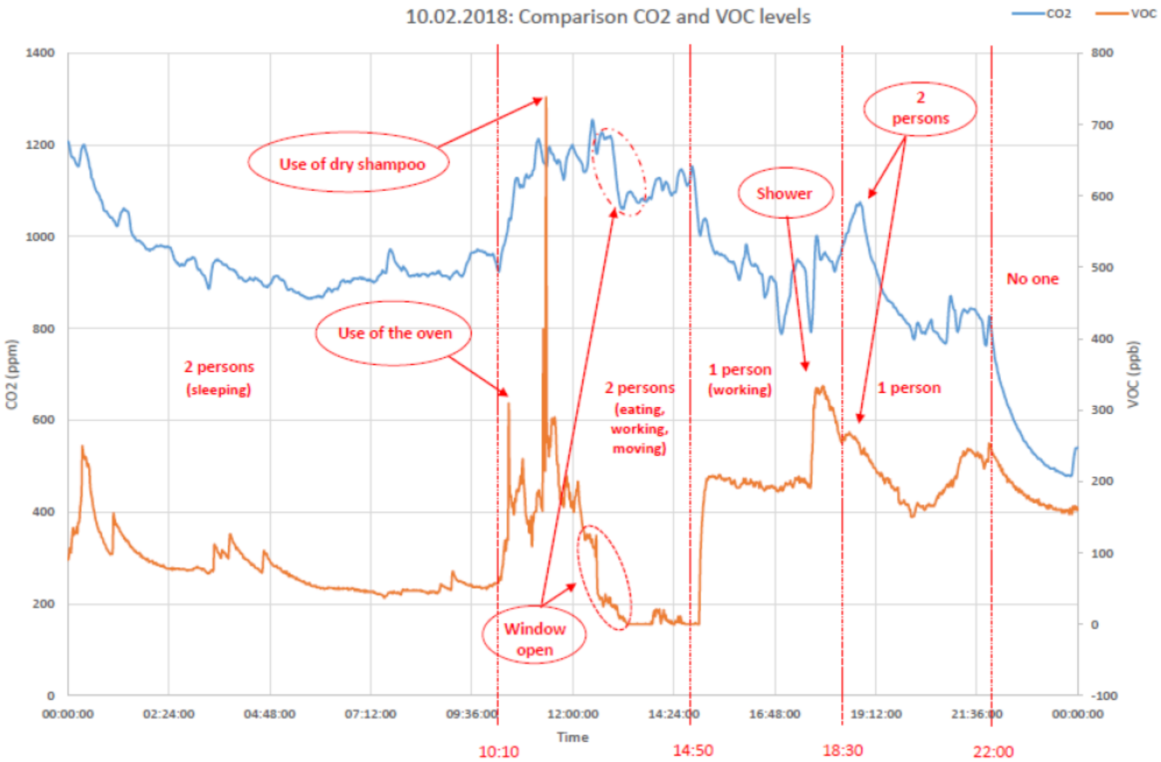
Osquldas väg 16, STOCKHOLM

Sensors location:

Close to the window, in the kitchen room.

Ventilation:

Always on. Additional cooker hood.



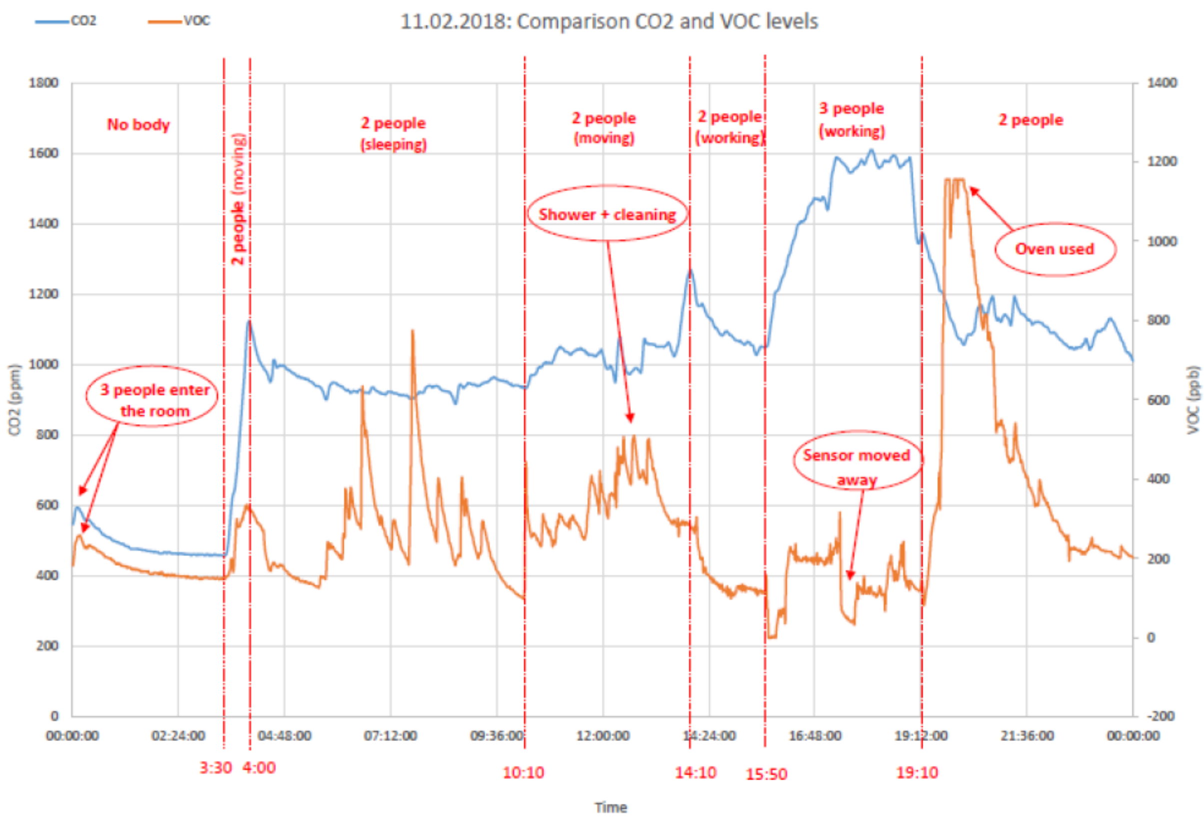
Comments:

- From 00:00 to 10:10, two people are sleeping. No special disturbance occurred that is why CO2 and VOC have approximately the same behavior.

- From 10:10 to 14:50, the levels of CO2 and VOC increase as two people are in the flat and they don't sleep anymore. However, two peaks of VOC can be noticed, due to the use of the oven and the use of dry shampoo. Then, when the window is open, both CO2 and VOC decrease. However we can notice that around 14:50, the level of VOC increases suddenly while the CO2 level decreases according to the occupancy. This could be explained by the fact that, when the window is open, the level of VOC close to the window decreases a lot (the sensor is close to the window) reaching 0 ppb. Consequently, when the window is closed, it takes a few minutes before the VOC level becomes homogeneous (the VOC particles far from the windows have not been eliminated). An increasing after air mixing (when the window is closed) is also observed for CO2 but it is more gradual.

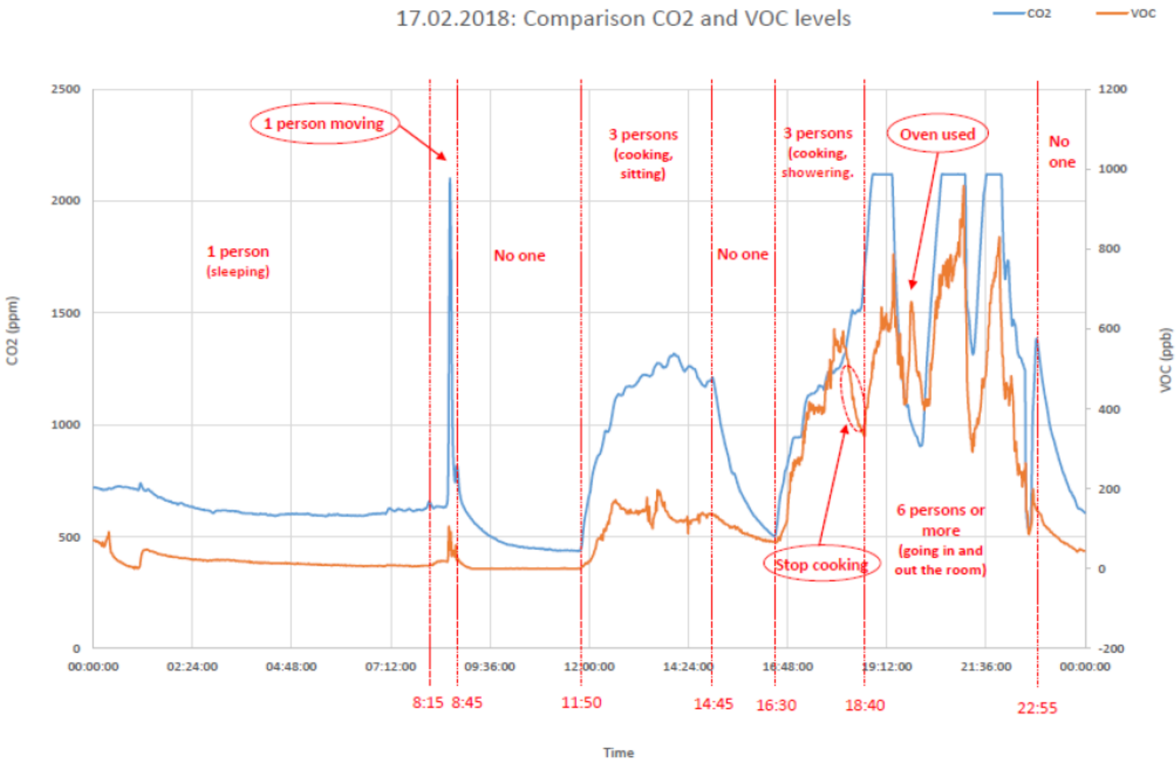
- From 14:50 to 18:30, one person is working which implies a decrease in CO2 level and a VOC level almost constant. However, a VOC peak occurs around 18:00 because of the use of the shower.

- Between 18:30 and 22:00 the two behaviors are really similar. From 18:30 to 18:50 two people are in the flat which implies an increase in both CO2 and VOC. Then, both decreases when there is only one person left in the apartment. They both increase before 22:00 and then follow the same behavior when nobody is in the room.



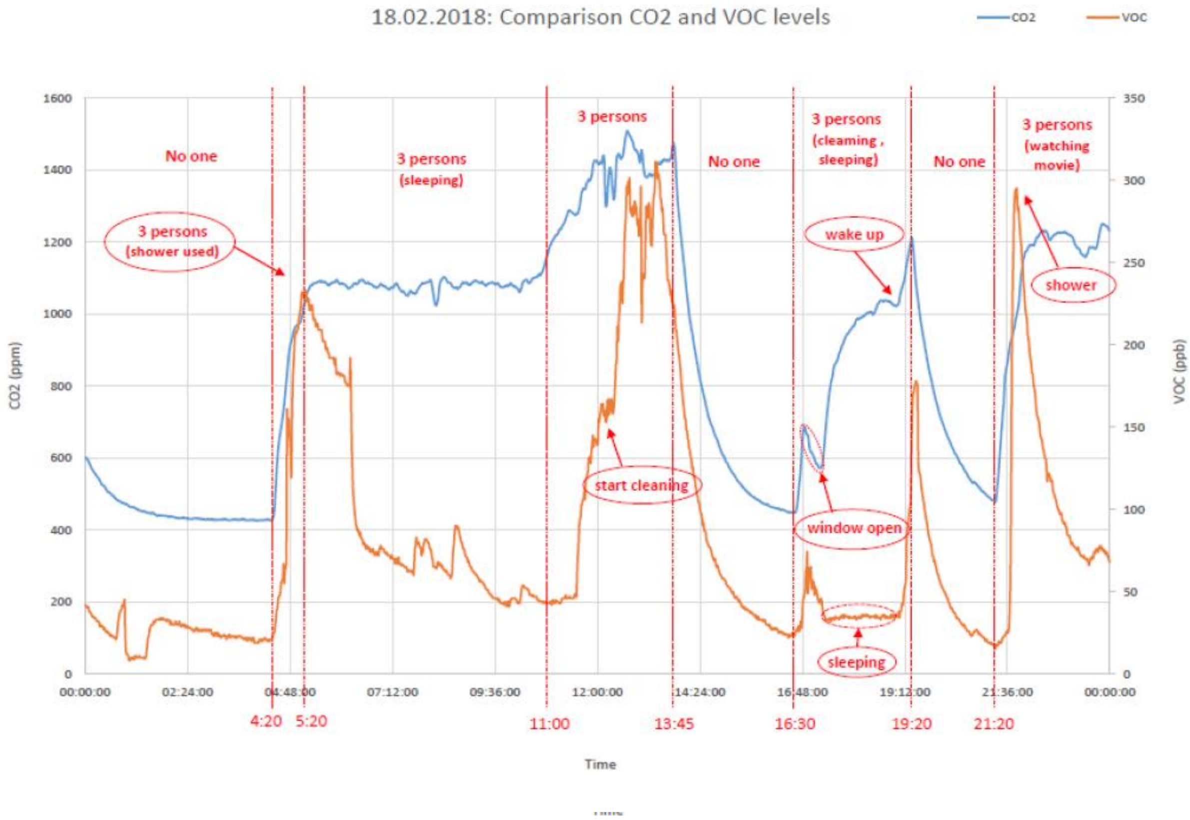
Comments:

- From 00:00 to 3:30 the room is empty and we can observe similar behavior for CO2 and VOC. Around 00:10, we can notice a small peak for both CO2 and VOC while 3 people enter the room for a few minutes.
- Between 3:30 and 4:00, two people enter the room implying an increase in both CO2 and VOC. Then, the level of CO2 is constant between 4:00 and 10:10 while two people are sleeping in the room. However, we can notice a strange oscillating behavior for the VOC level which doesn't have a direct explanation.
- Between 10:10 and 14:10 two people are moving and CO2 and VOC levels have almost the same behavior. We can notice two exceptions which are linked. First of all, around 1 pm a small increase in VOC is detected, due to cleaning and showering. Moreover, we can notice an increase in CO2 around 2 pm while VOC level stays constant. This is due to the fact that the VOC level was decreasing after the cleaning was over.
- From 14:10 to 15:50, 2 people are working and not moving anymore that is why CO2 and VOC decease until 15:50 where a third person join the room. This implies an increase in both CO2 and VOC. However, we can notice around 17:30 that the decrease in VOC is much more important than the one in CO2. This can be explained by the fact that the computer used for VOC measurements had been moved away from the people during a few minutes.
- Then only two people are in the room after 19:10. The use of the oven from 19:30 to 20:30 implies a high peak in VOC while CO2 decreases due to lower occupancy.



Comments:

- From 00:00 to 8:15, one person is sleeping in the room that is why CO2 and VOC levels are both almost constant. We can however notice a little decrease in VOC around 1 am without direct explanation.
- Then, from 8:15 to 8:45, the person wakes up and moves in the room which implies VOC and CO2 peaks. Then, both CO2 and VOC levels decrease before stabilizing between 8:45 and 11:50, while the room is empty. Until the rest of the day, CO2 and VOC levels follow similar behavior depending on the occupancy. However, we can notice two exceptions that can be explained.
- The first one occurs around 18:00 when the VOC level decreases while the CO2 level is still increasing. This can be explained by the fact that from 17:00 to 18:00, CO2 level was increasing due to occupancy while VOC was increasing due to occupancy and cooking. Consequently, when the cooking stopped around 18:00, VOC level progressively decreased before reaching the level due mainly to occupancy. The second exception is the VOC peak occurring around 20:00 while CO2 decreases. This peak can be explained by the use of the oven which increase VOC level.
- We can also notice that the CO2 sensor reaches the maximum CO2 level it can detect (2100 ppm) between 18:30 and 23:00 which explains the horizontal straight lines observed. In reality, the CO2 level in the room was higher than 2100 ppm.



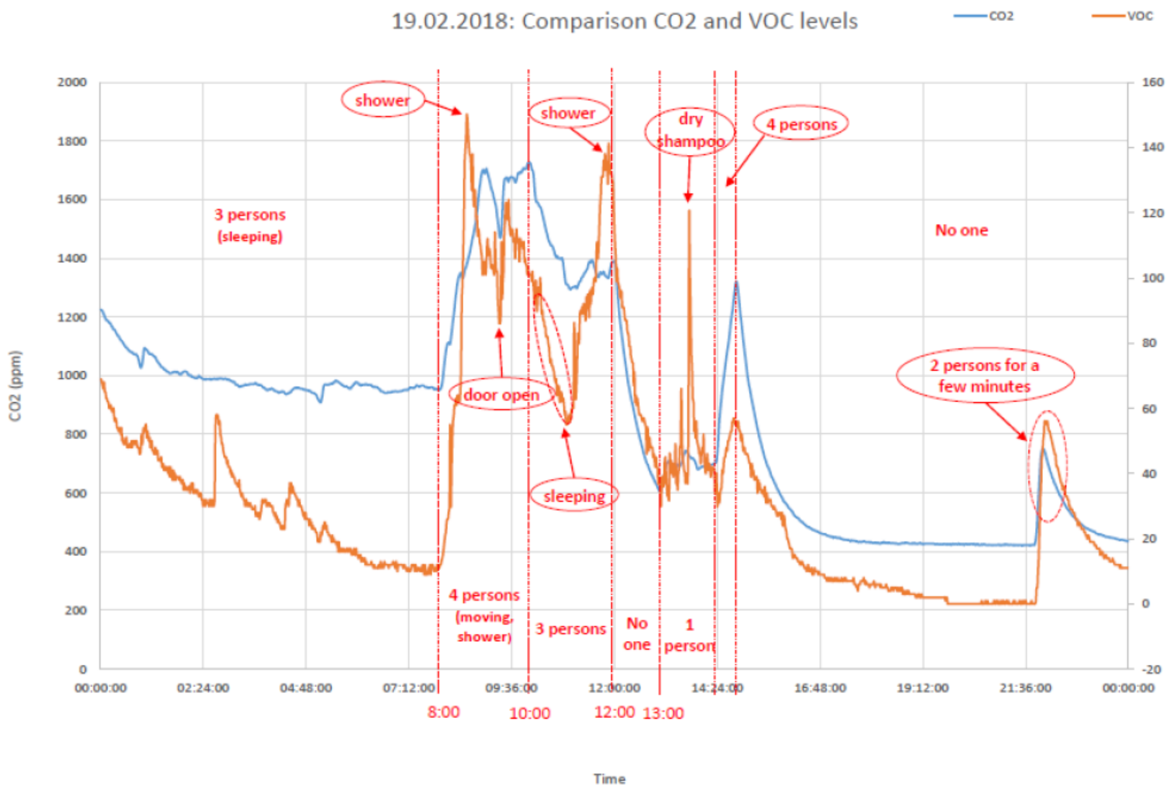
Comments:

- From 00:00 to 4:20, the room is empty and CO2 and VOC both globally decrease. However, a little VOC peak followed by a decrease is observed around 1 am without direct explanation. This peak is probably due to an external VOC source such as furniture for example. Moreover, we can notice that the VOC scale on the graph is relatively small and that the peak involves a variation of less than 40 ppb.

- From 4:20 to 5:20, three persons enter the room and use the shower which implies increase in both VOC and CO2. Then, from 5:20 to 11:00, three people are sleeping and the CO2 level stays constant while VOC first decrease before stabilization. This decrease is due to the use of the shower a few minutes before.

- After 11:00, CO2 and VOC increase while three people are awake and moving in the room. Around 12:00, people start cleaning which leads to an important VOC peak while CO2 stays almost constant. Then, from 13:45 to 21:20, CO2 and VOC follow similar behavior depending on the occupancy of the room. We can however notice that the VOC level stays constant around 17:00 while the CO2 level clearly increases. This can be explained by the fact that the window had been open during a few minutes before this strange behavior. Indeed, the sensors being close to the window, they both detect an important decrease in VOC and CO2. However, when the window is closed, CO2 level increases progressively due to air mixing and additional CO2 breathing while the level of VOC stays constant as people are sleeping and consequently not moving anymore. Air mixing, after the window is closed, doesn't increase VOC level in this case before VOC level was really low before the opening.

- Finally, after 21:20, CO2 level increases according to occupancy while VOC behavior is disturbed by the use of the shower.

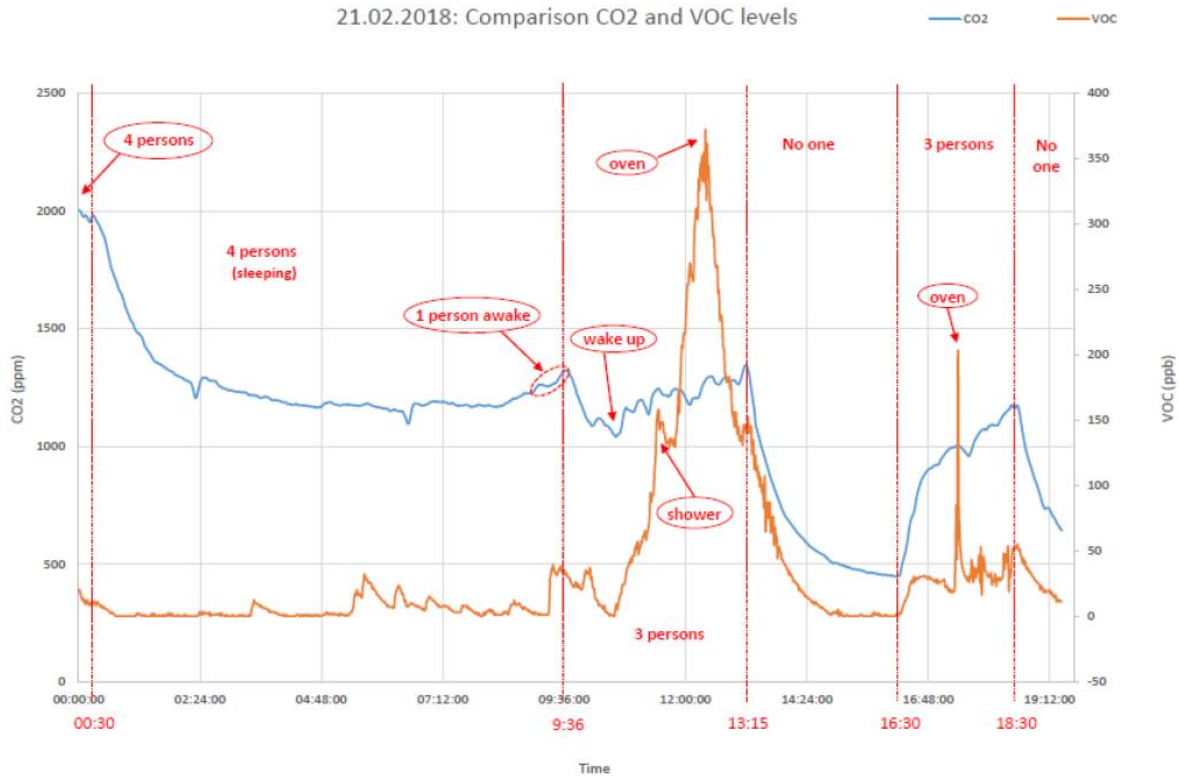


Comments:

- From 00:00 to 8:00, three persons are sleeping and CO2 and VOC are both decreasing. As noticed previously, a few VOC peaks can be observed without clear explanation but they involve variations of less than 30 ppm.

- The rest of the day, CO2 and VOC follow similar behavior mainly depending on occupancy but also activity in the room. Indeed, before 9:30, the door is open implying a decreasing peak in both VOC and CO2. Similarly, we can notice that both levels decrease around 10:00 when people are sleeping in the room.

- However, as usual, some external VOC sources disturb its behavior. First of all, we can observe two peaks around 8:30 and 11:45 due to the use of the shower. To finish, the thin peak occurring around 13:30 has already been observed in previous measurements and is due to the use of dry shampoo which contains an important amount of VOC.



Comments:

- From 8:00 to 9:30, CO2 and VOC levels decrease before stabilization while people are sleeping. When someone wakes up and starts moving around 9:15, both levels automatically increase. Then, from 9:36 to 13:15, CO2 and VOC behavior are similar, decreasing when someone leaves the room and increasing progressively when people wake up. Two VOC peaks are however noticed. The first one, around 11:30 is due to the use of the oven while the second one around 12:30 is due to the use of the oven.

- Then, the rest of the day both behavior are quite similar, except around 17:30 when the oven is used, involving a VOC peak.

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