Norwegian University of
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Influence of Occupant Behaviour Regarding Use of Area on Indoor Air Quality in Residential Building

Virkningen av Beboeratferd Vedrørende Bruk
av Areal på Inneklima i Bolighus

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Master of Energy Use and Energy Planning
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MASTER THESIS

for

Student Majd Adnan Ahmad

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Influence of occupant behaviour regarding use of area on indoor air quality in residential building

Virkningen av beboeratferd vedrørende bruk av areal på inneklima i bolighus

Background and objective

Energy related occupant behavior in buildings is a key issue for building design optimization, energy diagnosis, performance evaluation, and building energy simulation due to its significant impact on real energy use and indoor environmental quality in buildings. However, the influence of occupant behavior is under-recognized or over-simplified in the design, construction, operation, and retrofit of buildings. Having deep understanding of occupant behavior and being able to model and quantify its impact on use of building technologies and energy performance of buildings is crucial to design and operation of low energy buildings.

The aim of this project is to study the interaction between occupants and their surroundings in residential buildings, particularly on the issue of furniture settings, as well as heater location and its power. In the concept of the building and equipment design, it is always difficult to establish exact knowledge about how the space and the equipment will be used by occupants. An important element to know is how users preferred device and furniture setting will influence the room environment in terms of surface temperatures and air flow patterns. The thesis is following the work done in the project assignment where the main purpose was to analyse and visualize such effects, and achieve awareness how it can be compensated by design measures. The main objective of the master thesis is to perform a series of measurements and numerical CFD simulations, analyse simulation errors and check if simulations are converged.

The following tasks are to be considered:

1. Preform thermal measurements of the selected room of the apartment, with a various setting of the furniture
2. Recreate a geometrical representation of this room using SOLIDWORKS software. Use the developed geometrical model in Ansys simulation software. Boundary conditions should be set with the bases of performed measurements.
3. Conduct investigation regarding thermal comfort sensation with a use of newly developed occupant behaviour bot. Obtained results will show identification of an existence of potential discomfort zones in side selected room apartment.

4. Make a draft proposal (6-8 pages) for a scientific paper based on the main results of the work performed in the master thesis.
5. Make proposal for further work on the same topic.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 17. January 2018

Vojislav Novakovic

Vojislav Novakovic
Academic Supervisor

Research Advisor: PhD candidate Jakub Wladyslaw Dziedzic, NTNU

Preface:

This thesis is accomplished at the Norwegian University of Science and Technology (NTNU), Department of Energy and Process Engineering, spring semester 2018. Based on the specialization project done in the autumn 2016.

Studying the influence of occupant behavior regarding use of area on indoor quality in residential building is the objective of this thesis. The goal is to study the interaction between occupants and their surroundings, by performing a series of measurements and numerical CFD simulations, analyze simulation errors and check if simulations are converged.

I would like to thank especially my main supervisor Vojislav Novakovic, associate professor at the Department of Energy and Process Engineering at NTNU, and Jakub Dziedzic as cosupervisors for professional guidance, support and advice through this work. Finally, I would also like to thank the University (NTNU) for giving me access to equipment, computer, and a work place.

Trondheim, 11.06.2018

Majd Adnan Ahmad

Sammendrag

Energiforbruket i husholdningene står for ca. 30% [1] av det totale energiforbruket i Norge, dette er knyttet til en rekke faktorer, noe som innebærer at energibruk i bygninger også kan optimaliseres på ulike felt. Beboerens oppførsel anses å være en av faktorene som påvirker både energiforbruket og innemiljøet. Imidlertid er innflytelsen fra beboernes atferd komplisert og vanskelig å forutsi, og dermed undervurdert eller overforenklet i de fleste tilfeller.

Denne oppgaven fokuserer på samspillet mellom beboere og deres omgivelser i boligbygg, hovedsakelig på tema om møbler plassering. Øke vår kunnskap om hvordan boliger og utstyr vil bli brukt av beboere, hva deres foretrukne enhet og hvordan møbel plassering vil påvirke romtilstanden i forhold til temperatur og lufthastighet.

Studien foregår i en leilighet plassert i Trondheim, Norge, nærmere bestemt i stuen. Bruk en ventilasjonsmåler og termisk kamera for å ta en rekke tester og målinger i dette rommet, som da gir bedre forståelse om innemiljøet, størrelsen på møbler og rommets dimensjoner. Vedtar data programmene Solidworks og ANSYS for å gjenskape en geometrisk representasjon av det valgte rommet og utføre en serie med numerisk CFD-simulering basert på disse målingene. Ulike innstillinger av møblene er simulert (fire for å være nøyaktige), hver av dem er forskjellige fra den andre, men har det samme grensevilkårene.

Introduserer Microsoft Kinect for overvåkning av okkupant bevegelsen i den valgte stuen, utføre etterforskning vedrørende termisk komfortfølelse. Denne enheten ble plassert i stuehjørnet i nesten en uke, og registrerte beboernes bevegelse gjennom alle fire forskjellige romscenarier. Opptaksdata oppnås i form av klokkedata (Y / M / D / h / min / s) og punktplassering (25 punkt i 3D [X, Y, Z]) avstand fra enhet [m]. [2]

Behandlede data fra Microsoft Kinect-enheten demonstrerte hvordan plasseringen av møblene hadde merkbar påvirkning på beboerens bevegelse (i rommet). Microsoft Kinect lyktes i å oppdage okkupantens foretrukne møbler og hans plasseres samtidig.

ANSYS numeriske CFD-simulering oppnådde 88-98% resultatnøyaktighet, i henhold til de fastsatte grensevilkårene og metoden som ble brukt. Flere figurer, diagrammer og tabeller presenteres i kapittel 6, som beskriver temperatur, lufthastighet og luftvolum i alle fire utvalgte romscenarier. De fleste av resultatene samlet fra CFD-simuleringene støtter ideen om at møbel plasseringen kan påvirke overbevisningsflyt i stuen, selv om det er marginalt. Personen som brukt den leiligheten, godkjente også at noen romscenarier var mer praktiske enn andre, med hensyn til mobilitet, tilgang til andre rommøbler og luftkvalitet. Hans ide om et bedre romscenario er i samsvar med den som ble forutsatt av CFD-studien.

Abstract

Energy consumption in households stand for approximately 30% [1] of the total energy consumption in Norway, this is related to a number of factors, implying that energy use in buildings can also be optimized in various fields. Occupants behavior is considered to be one of the factors influencing the energy consumption as well as the indoor environment. However, the influence of occupants' behavior is complex and hard to predict, thus under-recognized or over simplified in most cases. This thesis focus on the interaction between occupants and their surroundings in residential buildings, mainly on the issue of furniture settings. Increasing our knowledge about how the space and the equipment will be used by occupants, what their preferred device and furniture setting will influence the room condition in relation to temperature and air velocity.

The study takes place in an apartment located in Trondheim, Norway, more specifically the living room. Using a ventilation meter and thermal camera to perform a series of tests and measurements to gain information about the indoor environment, size of furniture and the rooms dimensions. Thereby adopting software such as Solidworks and ANSYS to recreate a geometrical representation of that selected room and preform a series of numerical CFD simulation based on these measurements. Various setting of the furniture is simulated (four to be exact), each one is different from the other but has the same boundary conditions.

Introducing Microsoft Kinect for occupant migration monitoring in the selected living room, conduct investigation regarding the thermal comfort sensation. This device was placed in the living rooms corner for almost a week, recording occupants' movement throughout all four different room scenarios. Recorded data is obtained in form of clock data (Y/M/D/h/min/s) and point location (25 points in 3D [X, Y, Z]) distance from device [m]. [2]

Processed data from the Microsoft Kinect device demonstrated how the furniture setting had a noticeable influenced the occupant behavior (pattern). As it successful managed to detect occupant preferred furniture and place accordingly.

ANSYS numerical CFD simulation achieved 88-98% result accuracy, according to the set boundary conditions and method used. Several figures, charts, and tables are introduced in chapter 6, describing temperature, air velocity and air volume across all four selected room scenarios. Most of the results gathered from the CFD simulations support the idea that furniture settings could impact conviction flows in living room, even if its marginal. The person living in that apartment also mentioned that some room scenarios where more convenient than others, in terms of his mobility, access to other room furniture and air quality. His idea of a better room scenario also matched the one predicted by the CFD study.

Contents

Figure list:

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Definitions and Acronyms:

IAQ	Indoor Air Quality
IEQ	Indoor Environmental quality
Met	Metabolic rate
Clo	Clothing insulation
CFD	Computational Fluid Dynamics
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
COPD	Chronic Obstructive Pulmonary Disease
IHD	Ischemic Heart Disease
Occupant	Referring to people in residential buildings, building users.
Velocity	Refers to the air speed
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BC	Boundary Condition
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
HVAC	Heating, Ventilating and Air-Conditioning

Introduction:

Throughout history, humans have adjusted to protect themselves against extreme climatic conditions or other being. At first, we resorted to caves which is relatively safe compared to open environment. From then managed to establish dwellings to provide a comfortable internal atmosphere. Building all types of designs and structures to improve on what can be considered a "home" today. As many have tried do define the meaning of "home" away from the physical structure, it is clear for us that safety and comfort plays a huge role. [3] [4]

In modern society people spend majority of their time indoors, either home or at work, which increased the interest in building design optimization, building performance, and indoor environment quality studies [5]. Making sure that consumers live in a good healthy environment, as well as keeping employees in optimal condition.

Energy related occupant behavior in buildings is a key issue for building design optimization, energy diagnosis, performance evaluation, and building energy simulation due to its significant impact on real energy use and indoor environmental quality in buildings. However, the influence of occupant behavior is under-recognized or over-simplified in the design, construction, operation, and retrofit of buildings. Having deep understanding of occupant behavior and being able to model and quantify its impact on use of building technologies and energy performance of buildings is crucial to design and operation of low energy buildings.

The aim of this project is to study the interaction between occupants and their surroundings in residential buildings, particularly in terms of furniture settings/placement. In the concept of the building and equipment design, it is always difficult to establish exact knowledge about how the space and the equipment will be used by occupants. An essential element to know is how users preferred device and furniture setting will influence the room environment in terms of surface temperatures and air flow patterns. The thesis is following the work done in the project assignment where the main purpose was to analyses and visualize such effects and achieve awareness how it can be compensated by design measures. The main objective of the master thesis is to perform a series of measurements and numerical CFD simulations, analyze simulation errors and check if simulations are converged.

1.1. Process:

The interest in topics such as energy utilization, human comfort and buildings optimizations are constantly increasing. Which led to issues related to occupant behavior in buildings and human interaction with their surroundings. Furniture setting appears to influence the humans psychological and physical comfort (satisfaction) [6]. Both the psychological and physical qualities are considered subjective, vary from person to person. To gain a better understanding of furniture settings and occupant behavior in a selected living room, several tasks are considered:

- Perform thermal measurements of the selected room of the apparent.
- Recreate a geometrical representation of the room using various computer software. Based on the measured data, the boundary conditions should be set.
- Conduct investigation regarding the thermal sensation with a use of newly developed occupant behavior bot.
- Obtained results should be analyzed to identify potential discomfort zones where occupants are exposed to.

A number of room settings (room scenarios) are tested as well, to explore how furniture placement could potentially affect the occupants comfort.

1.2. Location of study:

Selected room of the apartment is located in Stavset, found in Trondheim, Norway, as marked in the figure below.

Figure 1: Street view of selected apartment [7]

It's a relatively small (12 m^2) loft living room, with typical furniture, such as: TV-set, sleeping-sofa, chair, simple table/desk and a shelf. As most loft apartment, the ceiling height is lower than usual (along with a decline in roof height). Having one window and two doors. One considered to be a main entrance door, the other leads further to a bedroom and kitchen.

1.3. Limitations:

Time is always a limiting factor in most cases, longer period time would most likely deliver more precise results and improved report over all. In terms of the task in hand, it is limited to the following:

- Lack of apartment/room options to perform this study on.
- Few established projects covering this topic (lack of knowledge within this topic).
- Subjects such as indoor environmental quality and occupant behavior are very complex and hard to predict using today's computer software. Resulting to a slice of assumption or generalization.

Software limitations: accurate representation of reality, choosing color of furniture, furniture material, functional (reliable) human model, floor covers, window covers, etc.

1.4. Tools and software:

Temperature and air velocity are measured manually with the help of two different equipment; TSI velocicalc multi-function ventilation meter 9565-p and FLIR E60 thermal camera. While SolidWorks and ANSYS Workbench helped on delivering furniture model, room geometry and CFD Calculation.

- **SolidWorks**: Is a CAD and CAE computer software, widely used for 3D modeling. SolidWorks was used in this project to create geometries representing the component used in the living room. From a simple 3D representation of single design component "Part" was used, then inserted into "Assembly-files". [8]
- **ANSYS**: Very important CAE software for studying fluent dynamics and simulate fluent flow in various environments (e.g. a living room as in this project). ANSYS got many different options under "toolbox", but the main components needed to complete the task are; Geometry, Mesh, Fluent and Results. [9] [10]

Microsoft Kinect used to collect body movement/pattern inside of the selected living room at different furniture settings.

Computer properties used throughout most of the work:

- Windows Edition: Windows 10 Enterprise © 2018 Microsoft Corporation
- Processor: Intel(R) Core(TM) i7-2600, CPU @ 3.40 GHz 3.40GHz

1.5. Rapport structure:

The first part of this project include previous results, literature and research, covering topics related to energy consumption in buildings, low energy houses, thermal comfort and occupants' behavior in buildings. Main aim is to establish a foundation and give a better understanding of our knowledge today.

Chapter 3 covers all tools and software adopted in this project work, followed by Chapter 4 which holds most of the measured values (furniture size, temperature and air velocity). Chapter 5 describes primary the method used to model the furniture, later on develop a geometrical representation of the living room. Contains other important steps such as mesh method, boundary conditions, fluent setup, and more. Followed by chapter 6 that contains most of the data delivered out of SolidWorks, ANSYS Mesh, Fluent and CFD-post results. The final part of this project includes two chapters (Chapter 7 and Chapter 8) for the analyses and conclusion respectively. Ending with the last chapter (Chapter 9) proposing ideas for further work.

→ *Attachment: includes some of the data/figures/charts that didn't make it into Chapter 6*

2. Building design and occupant behavior:

Buildings design optimization and occupant behavior are dependent on a variety of conditions, such as indoor environment quality and furniture setup. This chapter reviews some of the literature studies related to building design optimization, energy use in buildings, low energy buildings (mainly homes), occupant behavior in buildings, furniture placement as well as indoor environment.

2.1. Building design optimization:

Sustainable low energy residential buildings should not be on the cost of IEQ or the occupant's natural behavior in the building (should not control the behavior of humans or the lifestyle). At the same time, it must keep in mind not wasting resources or disturb the ecosystem by itself.

Building design, investigates the energy consumption and minimum-cost a building can possibly demand, having indoor environment quality (IEQ) in mind as well. By doing studies on optimizing what we have today of buildings. It's considered very complex, because it demands that engineers (designers) will be working with too many factors and parameters that are not necessarily set in stone. [11]

2.2. Energy use in buildings: directed towards Scandinavian/cold environments

As of 06. June 2017, there are 2 515 589 inhabited residences in Norway. The properties are collected and consist of several types of homes from different ages and different grades. According to SSB [12], the average energy consumption in Norway per household is 20 230 kWh in 2012. While according to SINTEF [13] [14], buildings stand for about 40% of the total energy consumption in Norway. Energy consumption in buildings can be divided into two main sections:

- Thermal section - Heating and tap water
- Technical section – Light and other electrical equipment

Technical components require energy in the form of electricity, while thermal section only require heat with a certain temperature which could be provided by electricity.

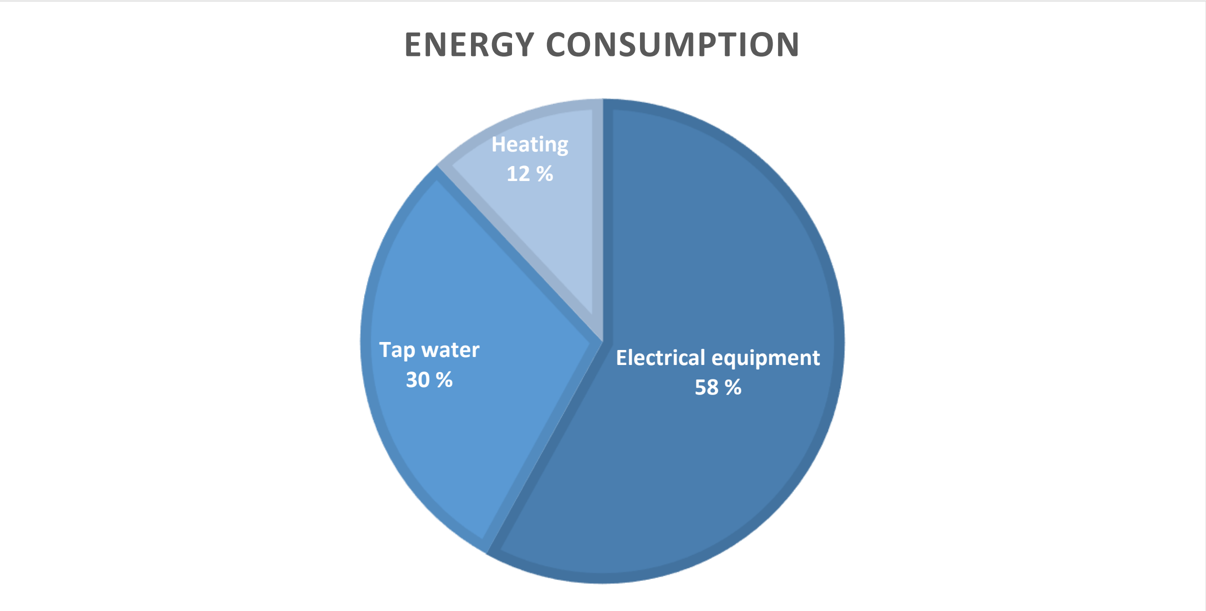


Figure 2: Energy consumption in Norwegian buildings [15] [16]

Most of the energy consumed (heating, tap water, light…) is aimed toward sustaining a high level of comfort, and the lifestyle of the occupant (behavior). The energy consumption buildings can be dependent on several factors:

1. Climate 2. Structural state 3. Installations 4. Technical facilities
5. Use of electrical equipment

The use of electricity varies over the day, over one week and over a year. Variation over the day may be due to the patterns of use and use in the household. Climate plays a key role in energy use. The energy consumption report for NVE from 2012 refers to studies that estimates that energy for heating rooms in Norwegian homes accounts for about two thirds of energy consumption. 2010 was a cold year, and the energy consumption of households totaled 51 TWh. In 2009 and 2011, energy consumption in households was approximately 46 and 45 TWh, as it has also been in the late 1990s [16] [17].

Type of housing and size affects energy consumption. The table below shows average energy consumption in kWh by house type: 1995, 2001, 2004, 2006, 2009.

Table 1: Energy consumption in Norwegian buildings according to house type and year [16]

Building type	**Energy consumption (kWh)**				
	1995	**2001**	**2004**	**2006**	**2009**
Farmhouse	31 911	31 315	31 136	32 900	30 599
Single house	28 912	27 327	26 414	26 680	25 705
Townhouses	18 818	18 731	16 850	17 033	17 726
Block, etc.	12 817	11 941	11 367	12 589	10 541
In total	23 633	22 399	21 143	21 644	20 415

This table shows that in 1995 total energy consumption in a single house was 28,912 kWh, while in 2009 it was 25 705 kWh. As in total, energy consumption in 1995 hit 23,633 kWh and 20,415 kWh in 2009, a decrease of approximately 3,200 kWh [16] [12].

The number of people in the household will affect the consumption. There were 2.2 people per household in 2011, whereas in 1960 there was an average of 3.3 persons per household. This means that average energy consumption per dwelling decreases, while consumption per person increases because there are more small households that have the same need for necessary things like heating, light, etc. [16]

2.3. low energy buildings (LEB):

Low energy house meaning has changed with time, because of change in national standards. National standards differ drastically across the world, low energy consumption improvement in a country may not meet practical needs in another country.

In general, it refers to any building with the design, technology, and building materials that consumes less energy from any source than a traditional home or conventional home. Constructed with good insulations materials, thick body (reducing air leakage in walls, windows and doors), leading the transmission and ventilation loss to be low.

Ventilation is a major factor for a good climate indoors. The biggest difference between low energy buildings and buildings built according to “older” standards (BF 1997), would be in the amount of insulation material and precision.

Low energy buildings could be able to reduce the energy used on cooling, heating, ventilation and domestic hot water by 40-60 %, while keeping in mind the indoor climate quality and safety of the building. On the other hand, Passive-house standards are aiming to reduce it by 60-80%. [16] [18]

The figures below display monthly energy demand for space heating, reheating of ventilation air and water heating of semi-detached houses and flats in Norway, built after four different standards, such as:

- Buildings before 1997
- Low-energy houses, rating B
- Passive houses, rating A
- Passive house, rating A+

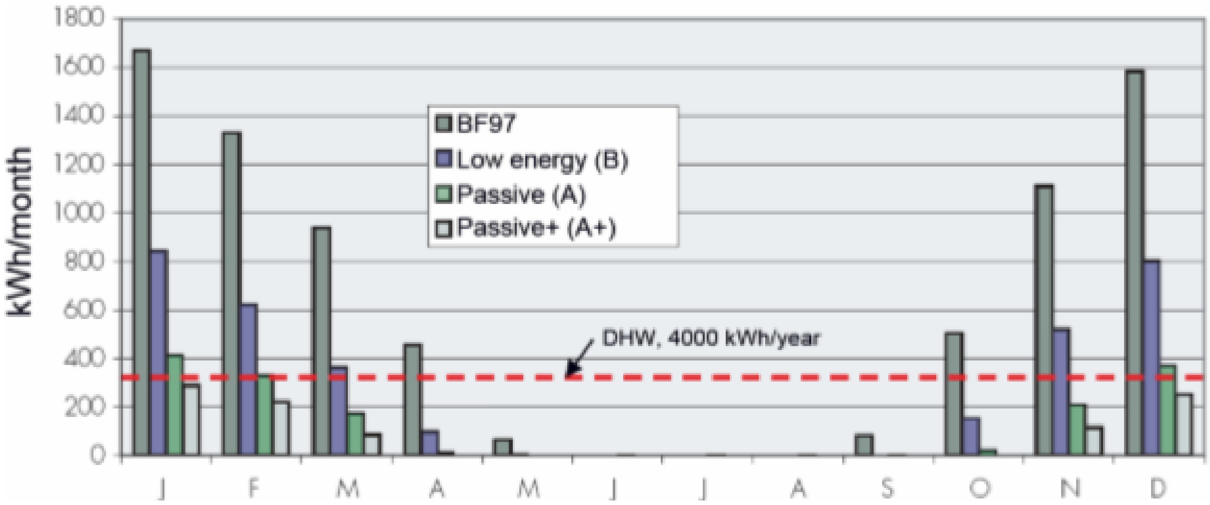


Figure 3:Monthly energy demand for space heating, reheating of ventilation air and hot water (DHW) heating for semi-detached houses of different energy standards (dakka, hermstad 2006) [18]

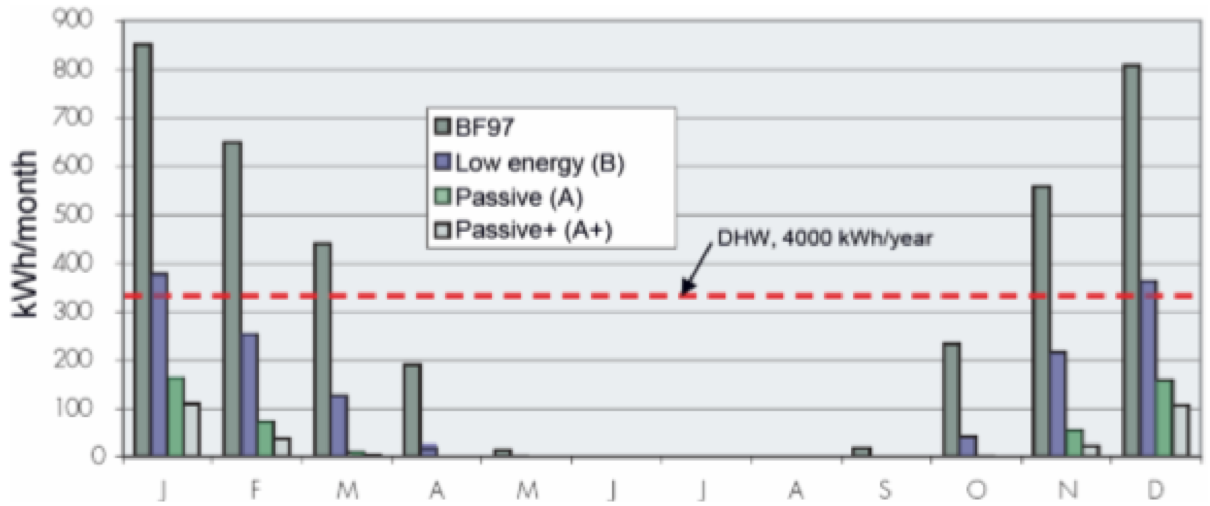


Figure 4:Monthly energy demand for space heating, reheating of ventilation air and hot water (DHW) heating for flat of different energy standards (dakka, hermstad 2006) [18]

The heating area of the semi-detached house is 104 m^2, while flats heating area is approximately the half at 60 m^2. The difference in area is can also be noticed on the monthly energy consumption in the figures above as it reflects the size difference. [18]

2.4. Furniture and heater placement:

The placement of the furniture in buildings could play a role in saving energy, general occupant comfort, as well as occupant movement/behavior inside such room. According to a study done at the university of Florida, room's physical temperature could be influenced by furniture, e.g. two identical rooms one with furniture will by default feel and appear different than empty room with no furniture [19]. Elements such as furniture color, size, texture and material all can affect the temperature besides furniture placement in the room. Other factors that can affect the room temperature and energy savings, such as:

- Window coverings
- Lighting and Energy
- Room colors and textures
- Wall and floor coverings

It is advised to place heaters near the window (outlet), most likely under the window. In most cases placing the heater under the window is an efficient way to recover heat losses through the window, saving energy as well. To solve such issues, it's recommended to increase window insulation by using blinds, roller shades draperies or shutters. When furnishing a room, avoid covering the heater or cooling source, to prevent unnecessary energy losses.

All these elements can have their effect on the building efficiency and the indoor environmental quality (IEQ). Heating and cooling system use up to 60 % (58 on heating according to NVE [20]) of the total energy consumption in Norwegian buildings, which turns the study of furniture settings a considerable key in terms of minimizing total energy consumption and obtaining thermal comfort. [19]

2.5. Indoor Environment Quality (IEQ)

One of the primary concerns of humans is to search about comfortable as well as safe environment to be in. People in ancient times used the gained experience throughout the years to achieve appropriate living conditions and make the best utilization of the naturally available resources. Buildings occupancy levels, the practices of construction (lower permeability of air of the envelope as well as the generalized heating use, (HVAC) systems of air conditioning as well as ventilation) and the expectations of users' have changed dramatically in recent decades, which leading to increase the interest in the quality subject in the indoor environment. [21] [22]

Nowadays the quality of indoor environment is actually very important factor affecting on the health, performance of populations and comfort, since people spend extended period of time inside buildings in developed areas. The indoor environmental quality concept is very important as well as depends on different variables such as relative humidity, temperature, air velocity, occupancy, air flow, concentration of pollutants, lighting, noise…

These can be divided into four primary areas that includes the quality definition of the inside space environment. [21]

- Acoustic comfort: indoor and outdoor noise pollution impacts the occupant health and quality of life.
- Thermal comfort: the feeling of being totally satisfied with the thermal environment surrounding the human body.

- Visual comfort: the right light source and the right amount of lighting is essential to the human comfort indoors.
- Indoor air quality: Indoor environment quality (IEQ) and indoor air quality (IAQ) are often confused. In fact, the quality of the internal environment is a broader (bigger scale) concept that includes the concept of indoor air quality as a key element. IAQ is mainly focused on the air quality itself.

2.6. Indoor Air Quality (IAQ):

The term Indoor air quality usually is referred to the quality of air which is inside and outside the buildings, particularly if it is related to the health of those inside these buildings as this can be affected by various microbial contaminants or particulates, or simply gasses such as radon of carbon monoxide and lastly energy stressors, all these can put health at risk. The best methods used to better the indoor air is by ventilation, filtration or simply by controlling the source of pollutant in additional to the people those residents which can frequently clean carpets and rugs more often. [23]

Air cleanliness is expressed by the amount and type of pollution found in the air, that causes trouble and damage the occupant health. Here is some of the factors that effects the IAQ:

- Material emissions
- Number of people per $m2$ and their activity level
- Different processes (type of work done in the room)
- Outdoor air quality
- Location of the outdoor air intake
- Filtration of intake air
- Cleaning/ vacuum cleaning

A report issued by the medicine institute stated that there were three factors which can affect the pollution of the indoor air which are the human behavior, the characteristics of the buildings and the pollutants properties. The first factor is considered a component that can affect the IAQ to affect in form of increase in the presence of the pollutants. Those would include, cooking where the level of carbon monoxide in addition to the nitrogen dioxide lead to a dangerous level. Behavior would be the interaction/actions/lifestyle existent in the environment like opening windows or closing them since it affects the air exchange rate leading to a decrease in the level of the polluted air indoors. [23]

Indoor pollution can be caused by various sources as mentioned, evoking a number of diseases such as lung cancer, stroke, IHD and COPD [24]. That's what makes it important to understand and take these factors into consideration when planning for IEQ. [25] [26] [27]

2.7. Thermal Comfort:

Satisfaction of the inner mind regarding to the environment is called the "Thermal comfort" which gets assessed by ASHRAE 1996 [28], and defined as:

"That condition of mind which expresses satisfaction with the thermal environment"

Once people feel discomfort in their surroundings (indoor environment), it will eventually influence their behavior. One of the most important goals for them to maintain the comfort of residents by sticking to the level specified by the HVAC to include air condition, ventilation in addition to heating when designing, as this comfort is maintained by heat coming from the human body through metabolism which sees to create a balance with the outer surroundings. Air temperature is generally the main indicator when it comes to determine thermal comfort, being easy to use and relate to, however it's not the only element. Thermal comfort is influenced by six primary factors according to most studies [29] [28], often divided into two sections [30]:

A. Environmental factors:

- Air temperature [°C]
- Mean radiation temperature [°C]
- Air velocity [m/s]
- Humidity [Pa]

B. Personal factors:

- Clothing Insulation [Clo]
- Metabolic heat (activity level) [Met, W/m2]

* *Met: Is the unit used to measure the activity level of a person* [29].

* *Clo: 1 clo describes a person with activity level of one met (seated, relaxed), in a room with these conditions; 21 C, 50% RF and 0.1 m/s air velocity* [29].

Looking at the factors above, shows that thermal comfort is linked to both environmental and personal factors. Not considering the age of each individual, sex, time spent inside the room, health statue, and many more individual influences. Today there is two popular methods to examine thermal comfort: PMV/PPD Model and the Adaptive Model. [28] [29]

Developed by P.O Fanger, the PMV/PPD model is one of the most recognized models to provide thermal comfort since it was developed by experimental data and rules of heat which was gathered in a controlled environment and conditions. Fanger brought the idea of "thermal load (L)", as it was defined [28] [30]:

"the difference between the internal heat production and the heat loss to the actual environment for a man hypothetically kept at the comfort values of the man skin temperature and the sweat secretion at the actual activity level"

In other words, thermal load must be close to zero for achieving thermal comfort conditions by this model. Nevis (1996), McNall (1968), Fanger (1970) and others, where able to collect and provide a seven-point scale of thermal sensation (running from Cold to Hot), as well as an equation for PMV. [29] [28]

Table 2: Scaled rated sensation [28] [31]

Hot	**+3**
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

Equation used for the predicted mean vote (PMV):

$$PMV = (0{,}303e^{-0{,}036M} + 0{,}028) * [(M - W) - 3{,}05 * 10^{-3}$$

$$\{5733 - 6{,}99(M - W) - P_a\} - 0{,}42\{(M - W) - 58{,}15\} - 1{,}7 * 10^{-5}M(5867 - P_a)$$

$$-0{,}0014M(34 - t_a) - 3{,}96 * 10^{-8}f_{cl}[(t_{cl} - 273)^4 - (t_r - 273)^4] - f_{cl}h_c(t_{cl}t_a)]$$

Where "t_{cl}" is:

$$t_{cl} = 35{,}7 - 0{,}028(M - W) - 0{,}155I_{cl}$$

$$[3{,}96 * 10^{-8}f_{cl}\{(t_{cl} + 273)^4 - (t_r + 273)^4\} + f_{cl}h_c(t_{cl} - t_a)]$$

PPD is the Predicted Percentage of Dissatisfied, anticipating the percentage of people that would complain about their thermal conditions (as a function of PMV) [28]:

$$PPD = 100 - 95e^{(-0{,}03353PMV^4 - 0{,}2179PMV^2)}$$

The relationship between Predicted Percentage of Dissatisfied (PPD) and Predicted Mean Vote (PMV) is shown in the figure below (Figure 5)

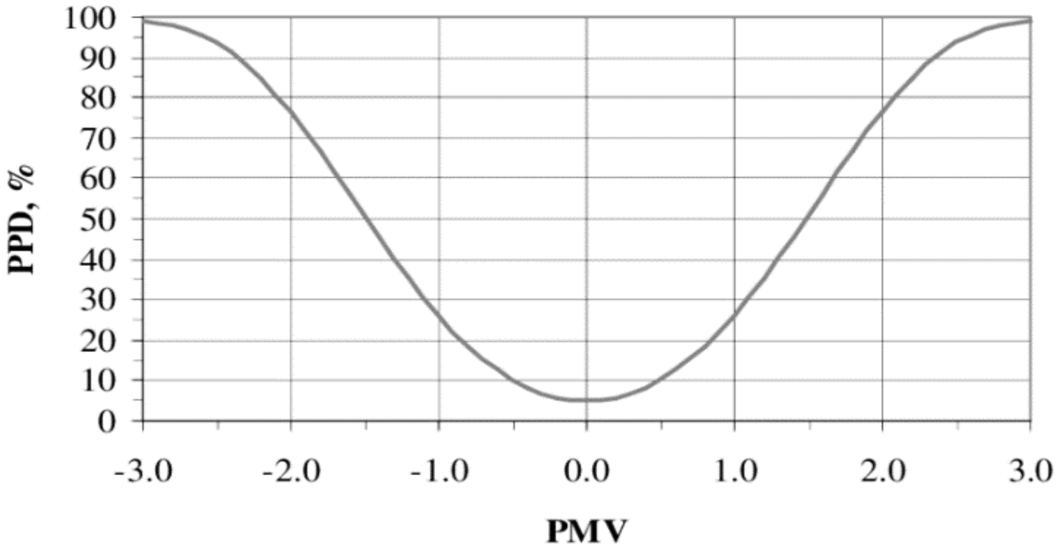


Figure 5:Practical evaluation of the thermal comfort parameters [28] [32]

However, the adaptive model was created by recording hundreds of field studies (sponsored by ASHRAE) and how people interact with their environment. With the intention that outdoor climate effect indoor environmental quality (comfort) as people constantly adapt to change in climate throw-out the year.

The thermal comfort in the adaptive model, was suggested by Brager and De Dear (1998) [33] to include a newer version of the EN 15251 standard in addition to the ASHRAE standard 55, that would include a regression equation in order to relate the maximum and minimum indoor temperature to the outdoor temperature on average, on a monthly basis. Regarding the EN 15251 (2007) [34] that is provided in the Figure 6, such a model would be implemented in the buildings that do not contain mechanical cooling, and ones that are have operable windows controlled by ease. This model would be based on the idea that the level of expectation and adaptation of the occupants would be much related to the conditions of the outdoor climate.

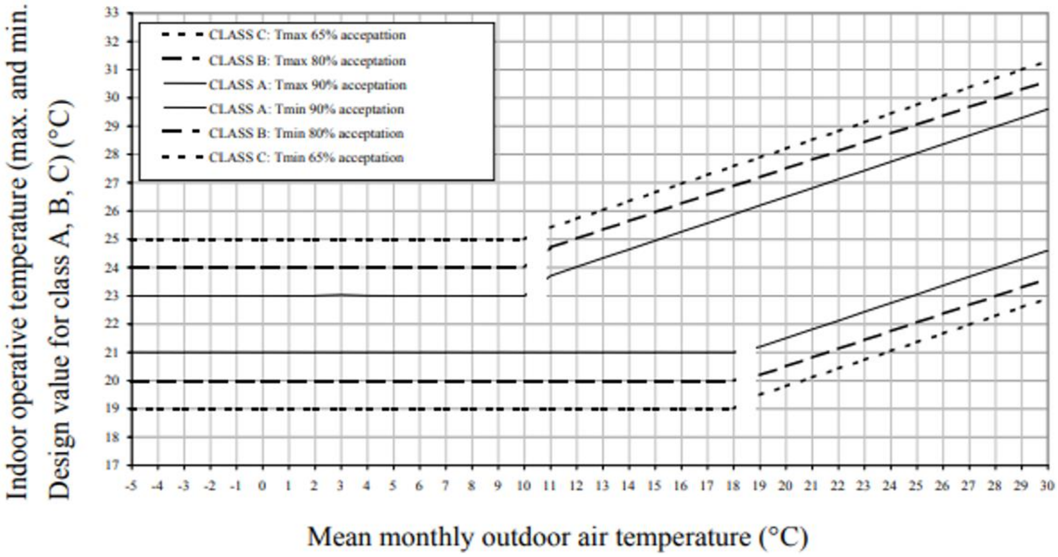


Figure 6: Minimum and maximum design values for the indoor operative temperature according to EN 15251(2007) [34]

A study in 2009 [35] did a simulation study regarding how occupants' behavior would affect the energy consumed in such buildings to reach a conclusion that the assessment nowadays involving a very simple approach of applying numerical data would be regarded as “not enough” (lacking) in constructions that contain close interactions among the occupants in those buildings. Upon the implementation of the adaptive model in a building's design, there's an expectation of the occupants to adapt in the atmosphere or make the latter adapt to their own desire (satisfaction), meaning that building as such would have the expectation of a close interaction regarding the controls of the buildings that are available. This lead to considering the behavior of occupants to be extremely important to determining the indoor environment quality and the performance of energy in buildings

2.8. Occupant behavior in buildings

The behavior of occupants, in addition to the characteristics of building are considered complex but should be considered when determining the energy level regarding heating inside building. Since those characteristics affecting the behavior and regulations can be determined by which are used as a full factor of variants such as the lifestyle, household characteristics in addition to the interaction and motivation between the dwelling (building) and occupant; those can simply be difficult to change by external factors since previous studies of Becker, Darley and Seligman in the 1978 in addition to a Danish study conducted by Andersen [36] found that occupant behavior effects the building's energy consumption.

Various international studies discussed the influence of the occupant behavior in addition to the building characteristics it had on the building energy consumption. The behavior or the occupants can influence the inner and outer factors, which are known as Drivers and that is why suggesting an action to be performed by them is important; since these drivers contain factors of social, physiological nature such as age and gender, contextual nature, and psychological nature. An example of the environmental factor is the inner and outer temperature, and the contextual one is by the position of the window and structure of the office [37].

Seligman et al. (1977/78) [38] researched the energy consumed in twenty-eight town houses and discovered that the variation is two to one, also the energy consumed depended on the occupants. Another researched in (2008) on what affects the consumptions of heat by using a survey where they discovered that family size, and the income in addition to the age of the owner alongside the ownership status has an impact on the oil consumed for heating [39]. This demonstrates that the (social) economical statue plays a huge role in the occupants' behavior. Though it should be noted that their behavior does not play a significant part on performance of energy [38].

There are many projects worldwide working to find a model for occupant behavior in buildings, missing a functional or consistent module for occupant behavior. This is hindering the building design optimization proses. Recently a study in 2017/2018 at the NTNU (department of energy and process engineering) in Trondheim Norway, conducted by Jakub W.D [40] [41] on occupant migration monitoring in residential buildings with the use of depth registration camera.

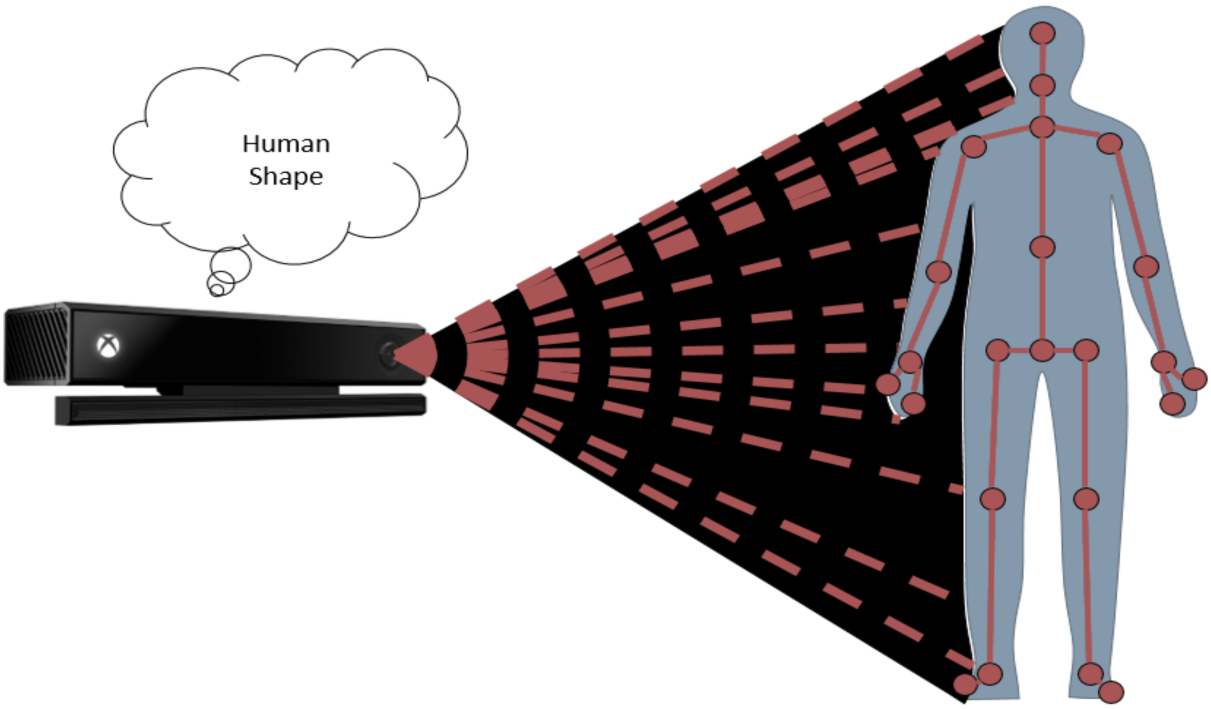


Figure 7: Simple demonstration of how the Microsoft Kinect operates [42]

Where able to use Microsoft Kinect to produce/recognize the occupant pattern successfully. With the help of Microsoft Kinects own built-in software, it was possible to link a human body shape to a skeleton model (of 25 joint points) while tracking its movement constantly (capture human activity). Collecting data of all 25 joints in 3D [X, Y, Z], as well as the data in year/Month/Day/Hour/Min/S/Frame with registration speed up to 30 Hz. The 3D information is in [meter] according to the users' distance from device. [43] [2] [40] [41]

2.9. CFD simulation:

Computational fluid dynamics (CFD) are one of the sections of fluid mechanics that use numerical methods and algorithms to solve, predict and analyze problems involving fluid flow. Most of the CFD problems are based on solving the equations of Navier-Stokes, which determine the flow of fluid in its gas or liquid state. These equations are simplified by removing some of the terms describing viscous and vorticity, a linear approximation of these equations, leads to the linearized potential equations. The CFD problem analyzed, can be expressed mathematically as systems of partial differential equations [10] [9]:

- Navier-Stokes equations
- Eulers equations
- Laplace Equations
- The full potential flow equations

L.M. Milne-Thomson in the mid-1930s published a two popular textbooks titled *"Theoretical Hydrodynamics"* and "*Theoretical Aerodynamics*" [44] [45]where he developed two-dimensional methods to solve the Linearized potential equations in (later republished by Dover Publications on the 1996. Throughout the 1960s to the 1980s plenty of studies where accomplished in this field, such as:

- Famously the work of John Hess and A. Smith in 1967, as they published three-dimensional methods to solve the linearized Navier-Stokes equations. [46]
- In 1968, Harlow and Nakayama, managed to develop some of the most important algorithms and codes used in today's CFD studies: parabolic flow codes vorticity-stream function-based codes, the k-ε model, the TEACH code and the SIMPLE algorithm. [47]
- Suhas V. Patankar published in 1980 a book in computational fluid dynamics (CFD) titled "*Numerical Heat Transfer and Fluid Flow*". Which is considered to be one of the most influential and groundbreaking textbooks in computational fluid dynamics (CFD) [48].

These calculations are mostly solved using a computer software, such as ANSYS Fluid (which is used in the thesis). CFD software such as ANSYS Fluid can be used to simulate the interaction of liquids and gases with surfaces defined by boundary conditions (BC) and completing the calculation needed [10] [49]. [50]

3. Tools:

Two main computer programs used in this project, ANSYS and Solidworks. History, specialities, functions and more is described of each software. Measuring tools such as ventilations meter, thermal camera and Microsoft Kinect, are adopted to mainly measure temperature, velocity and occupant behaviour (pattern).

3.1. SOLIDWORKS

Founded in 1993 by Jon Hirschtick graduate of Massachusetts Institute of Technology [51]and shipped its first product in 1995 called SolidWorks 95. The product ambition from the beginning was easy-to-use, affordable and available on the Windows desktop. Today SolidWorks is looked at as a computer-aided design (CAD) software, where companies worldwide use it for modelling and creating various products. As well as its considered an easier software to learn and create geometries in. [8] [52]

SolidWorks provide the choice of three separate file types at start:

1. **Part**: representation of one single module in 3D
2. **Assembly**: multiple parts can be added helping to create a new geometry
3. **Drawing**: 2D drawing of a part or assembly

The design can be implemented in 2D sketch and then converted to 3D part, using a variety of tools and features such as:

- Sketching tools:

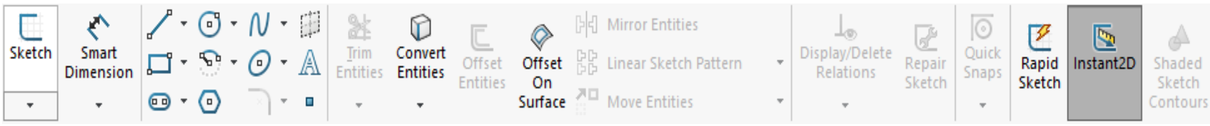


Figure 8: SolidWorks Sketching tools

- Features (base feature):

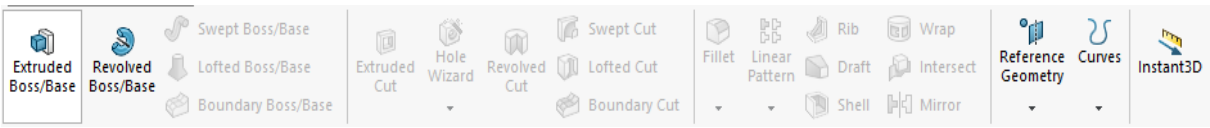


Figure 9: SolidWorks Features

Once the two-dimensional sketch is defined using the tools shown in the figures above, “Extruded” or “Revolved” can be used to form a three-dimensional design of that sketched area. These tools can operate by pulling/dragging the cursor or plotting the values directly. Solidworks “dashboard/ screen” keeps a constant graphic preview of the model in hand, which gives an idea of how the final product would look like.

3.2. ANSYS:

ANSYS is an engineering software simulation company founded by software engineer John Swanson. Flourishes as a finite component analysis and fluid dynamics software, serving a vast variety of engineers, designers, researchers and students. [53]

ANSYS Workbench is an excellent simulation platform, with numerous tools and systems to be used. ANSYS Workbench project workspace is divided into two main tabs, *Toolbox* and *Project Schematic* as shown below. [10] [50]

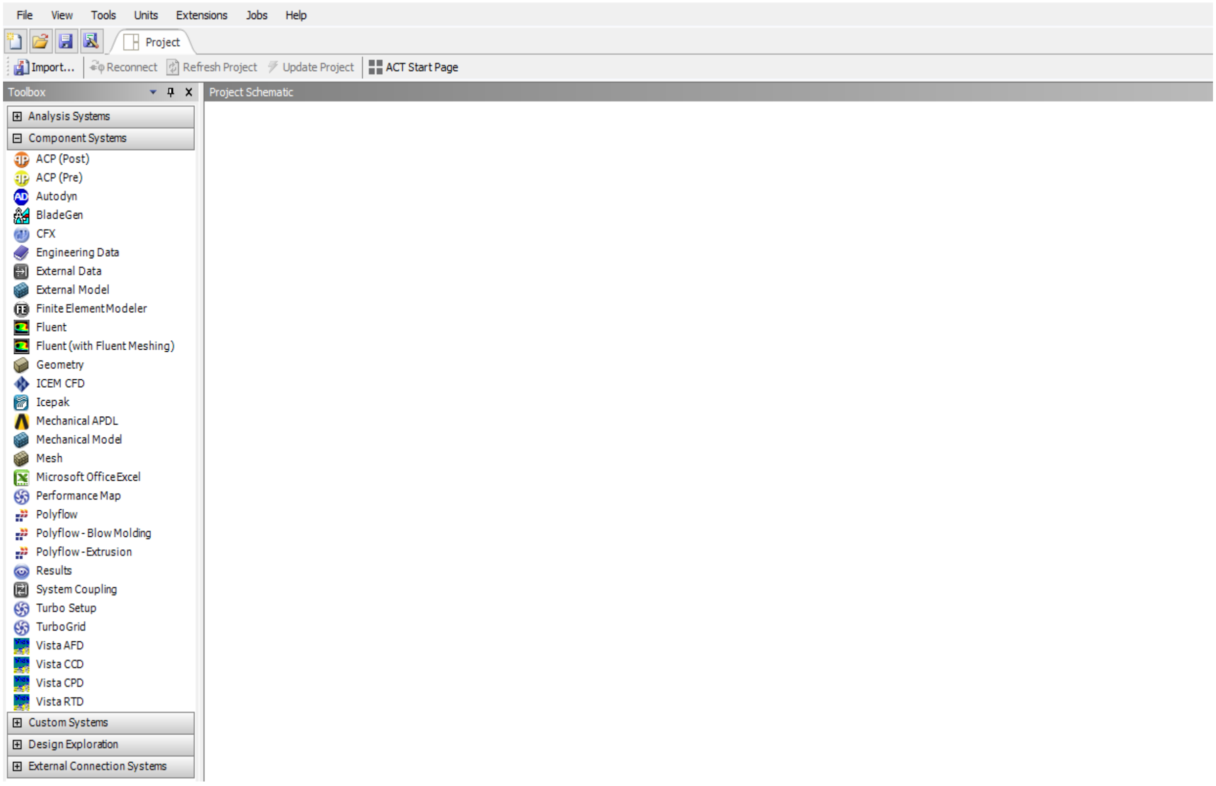


Figure 10:ANSYS Workbench Project workbench

Toolbox consists of systems such as: Analysis Systems, Component Systems, Custom Systems, Design Explorations and External Connection Systems. Each system individually contains blocks of one or more cells.

Project Schematic displays the necessary systems used for the project: systems are added and linked together simply by drag-and-drop or using the context menu.

To complete any project, the user must interact with each cell in sequence left to right, or from top to bottom. Key cells to most ANSYS workbench projects are: Geometry, Mesh and Solution (type of solver). [10]

Geometry (Model):

This cell is the starting point of all assignments, displaying the physical module to be analyzed. The geometry can be straightforward (simple) or complex (difficult), all dependent on the object in hand.

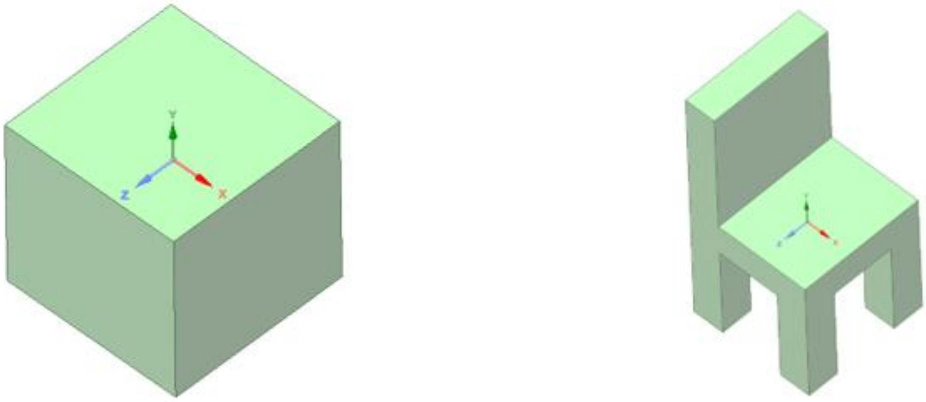


Figure 11:Three-dimensional representation of what a geometry could look like

Here is an example of what the geometries could look like, figure.1 showing a simple "cube" while figure.2 showing what is considered more complex. (each having volume, faces, edges and points).

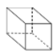
Building the geometry can be through using ANSYS DesignModler or SpaceClaim (which was acquired by ANSYS in May 2014) or simply import geometry from any other major CAD systems. [10] [9] [50]

Mesh (Grid):

A "mesh" is one of the most important stages of the simulation, having a huge impact on the solution accuracy, rate of convergence and CPU time required. (Bakker) Meshing is basically developing a mathematical representation of the geometry under study, dividing the physical module into a number of cells, nodes, edges and faces. Each cell can take a variety of shapes, depending on the geometry and the mesh technology used.

The goal of meshing in ANSYS Workbench is to provide robust, easy to use meshing tools that will simplify the mesh generation process. These tools have the benefit of being highly automated along with having a moderate to high degree of user control (ANSYS.18.1. viewer)

Type of cells:

- In a 2D plane:  Triangle  Quadrilateral
- In a 3D view:  Tetrahedron  Hexahedron

 Pyramid  Wedge

 Arbitrary polyhedron

Grid types:

1. Structured grid (single-block): essentially using hexahedral cells, can be recommended for simple geometries.
2. Multiblock (Connected blocks): considered adaptive compared to a structured grid, but still not ideal for complex geometries plus it can take relatively longer time to construct.
3. Unstructured grid: The mesh has no logical representation, using cell shapes in a random manner.
4. Hybrid Grid: Applies the most useful cell type in any order whether it is: tet, hex, pyr, wed or poly. Highly flexible meshing frequently used for complex geometries. [10]

Mesh Quality:

To achieve accurate and stable calculations, a high mesh quality is vital (essential). In order to minimize errors in the simulation and improve the accuracy, quality of the mesh needs to be studied. Mesh quality is mainly measured by: Element quality, Skewness, Smoothness, and Aspect ratio.

- Element quality:

  Presents a quality measure, ranging from 0 to 1. A value of 0 is considered poor quality while a value of 1 indicates a flawless cube/square (excellent). This value can be expressed in two different equations;

  1. Two-dimensional elements (quad/tri): The ratio of the area to the sum of the square of edge lengths for 2D elements.
     $$Quality = C\left(\frac{area}{\sum(EdgeLength)^2}\right)$$
  2. Three-dimensional elements (bricks): The ratio of the volume to the square root of the cibe of sum of the square of the edge lengths for 3D elements.
     $$Quality = C\left(\frac{volume}{\sqrt{\left(\sum(EdgeLength)^2\right)^3}}\right)$$

  The value of C for each element type is listed in the table below:

Table 3: C value for each type of element [10] [9]

Element	Triangle	Quadrangle	Tetra.	Hexagon	Wedge	Pyramid
C value	6,928203	4,0	124,707658	41,5692193	62,353829	96,0

- Skewness:

  Considered to be one of the main and most important quality checks for a mesh. There is two popular ways to measure grid skewness (dependent on cell shape): [9] [10]

  1. Based on the equilateral volume: to test only triangles and tetrahedral cell shapes.
     $$Skewness = \frac{Optimal\ cell\ size - Cell\ size}{Optimal\ cell\ size}$$
  2. Based on the deviation from a normalized equilateral angle: Can be used to test any cell/face shape. Works for prisms, pyramids, and more.
     $$Skewness = \max\left[\frac{\theta_{max} - \theta_e}{180 - \theta_e}, \frac{\theta_e - \theta_{min}}{\theta_e}\right]$$

     Where; θ_{max}: Largest angle in the face cell
     θ_{min}: Smallest angle in the face cell
     θ_e: angle for an equiangular face/cell

  It's important to keep this value as low as possible, as it affects the calculated results massively. Most of the equations solved, consider the cells to be equiangular, a reality low skewness value is therefore important. [10] [9]

Table 4: Cell quality according to skewness value [10] [9]

Cell quality	Degenerate	Bad	poor	fair	good	excellent	equilateral
Skewness value	1	0,9→1	0,75→0,9	0,5→0,75	0,25→0,5	0→0,25	0

The best skewness value to possibly achieve is 0 (equilateral) and 1 (degenerate) as worse skewness.

- Smoothness:

When comparing cells sizes, its preferred to have a gradual change, not large jump in size. Not higher than 20%

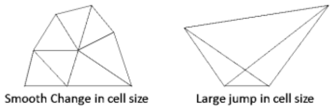


Figure 12: Smooth Change in cell size and Large jump in cell size [9] [10]

- Aspect ratio:

Aspect ratio of any cell shape is the ratio of its longer side (edge) compared to its shorter side. A ratio of 1 is considered ideal. This ratio is usually divided into two branches: Aspect ratio for triangles and Aspect ratio for quadrilaterals.

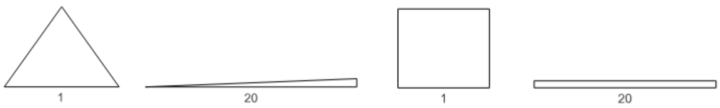


Figure 13:A) Aspect ratio for triangles B) Aspect ratio for quadrilaterals [9] [10]

Figure 13 describes the Aspect ratio with two different shapes; A) One Triangle with an ideal ratio of 1, while the other has an aspect ratio of 20. B) shows a rectangular shape instead (quadrilaterals aspect ratio) [50] [10] [9]

3.3. Ventilation-meter:

TSI velocicalc multi-function ventilation meter 9565-p is the ventilation meter available for this project. This type of velocity meter is capable of measuring; air velocity, temperature, humidity, pressure and more. Is equipped with optional “smart” plug-in probes. Graphic display of instructions, variety of languages to choose from and can hold up to five measuring plots on screen at the same time. [54]

Figure 14:TSI velocicalc multi-function ventilation meter 9565-p [55]

This ventilation meter can also be connected to a PC, effortless way to retrieve test data. Table 5 contains a few of the properties/ data describing the TSI velocicalc multi-function ventilation meter 9565-p:

Table 5: TSI multi-function ventilation meter properties/data [54] [55]

Description	**Data**
Max Air Velocity (ft/min)	9999
Min Air Velocity (ft/min)	0
Air Velocity Resolution	1 ft/min (0.01 m/s)
Air Velocity Accuracy	±3% of reading or ±3 ft/min (0.05 m/s) (whichever is greater)
Number of temperature channels	1
Min Temperature (° F)	40° F (5°C)
Max Temperature (° F)	113°F (45°C)
Data Logging	Yes
Data Storage (samples)	26,500 samples and 100 test IDs
Logging Intervals	1 second to 1 hour
Width (in)	4
Height (in)	2
Length (in)	8 3/8
Battery	Four AA (included)
Description	VelociCalc Ventilation Meter with differential pressure sensor

3.4. Thermal camera:

Thermal camera is a device that catch/expose light in the infrared range (IR) of electromagnetic spectrum (EMR) to produce a visible image/sketch. These types of devices are able to function in wavelengths between 900-14000 nm. IR see/ read out/ transmit the targeted body according to their temperature value, proving images without necessarily any visible light (light source). [56] [57]

Figure 15: FLIR E60 Thermal camera [56]

FLIR E60 thermal camera offers a high-quality preforming thermal camera, which is used in collecting data for the boundary conditions. Table 6 contains some of the most unique proprieties of the FLIR E60 Thermal Camera:

Table 6: FLIR E60 Thermal Camera Overview [56] [57]

Specifications	**Data**
Built-in Digital Camera	3.1 M.pixels (2048 × 1536 pixels), and one LED light
Detector Type	Focal plane array (FPA), uncooled micro bolometer
Difference Temperature	Delta temperature between measurement functions or reference temperature
Focal Length	18 mm (0.7 in.)
IR Resolution	76,800 (320 × 240 pixels)
Laser	Activated by dedicated button
Laser Alignment	Position is automatic displayed on the IR image
Laser Classification	Class 2/Semiconductor AlGalnP Diode Laser: 1mW/635nm (red)
Temperature Range	-20ºC to 650ºC (-4ºF to 1202ºF)
Packaging Size	500 x 190 x 370 mm (19.7 x 7.5 x 14.6 in.)
Thermal sensitivity	<0,05ºC (50mK)
Field of view	25º x 19º (optional lenses available)
Spectral Range	7.5 to 13µm
Tripod Mounting	UNC - 20 (adapter needed)
Dimensions/Weight	9.7x3.8x7.2" (246x97x184mm)/<1.82lbs (825g), including battery
Accuracy	± 2% rdg. or 2ºC

3.5. Microsoft Kinect:

Microsoft Kinect is an 3D motion sensor developed by Microsoft for The Xbox 360 and Xbox One consoles, in addition to Microsoft windows PCs. This 3D motion sensing input device mainly use webcam and peripheral to control and read our signals/motions.

Figure 16: Microsoft Kinect for The Xbox 360 and Xbox One consoles [58]

Microsoft Kinect was established to help users to interact with computer/console games without using controller, keyboard or mouse. But in this project, it is used to bring readings/data of human pattern/ movement inside a room.

4. Implementation of measurements (collected data):

Any solid geometrical recreation or numerical CFD simulation is dependent on solid foundation of data and measurements, minimizing errors/miscalculations/losses in the results. Chapter 4 is divided into three sections, to describe the implementation of measurements:

1. Room and furniture size
2. Ventilation-meter
3. Thermal Camera

These preformed measurements (of velocity, temperature, room and furniture size), set the bases for the boundary conditions. Hence this chapter follows through the process of collecting data and measurements.

4.1. Room and furniture size:

The apartment selected for this study is located in Stavset, Trondheim, which happens to be a 3rd floor "loft apartment". This apartment was easily accessible by the student, having a variety of furniture to adjust, makes it a suitable candidate to work with.

To construct a high-quality mesh, and less time-consuming calculations, furniture and room dimensions are simplified. For example; most object curves are compensated with few additional millimeters and a 90° angel.

Table 7: Selected room dimensions and other fixed objects

Definition	**Length [m]**	**Width [m]**	**Height [m]**
Living room	3,7	3,23	HR: 2,3 LR: 1,55
Window	1,1	1,1	-
Door	1,98	0,72	-
Heater	0,85	0,05	0,4
Fireplace: Base Top	0,35 0,15	0,25 0,15	1,0 0,8

Most loft apartments suffer a slight decline in roof height, developing two different roof heights, High roof (HR) and Low roof as described below:

- High Roof (HR): Covers 2,42m from the door location, at height 2,3m from floor.
- Low Roof (LR): Includes the declining part of the roof, height 1,55m from floor.

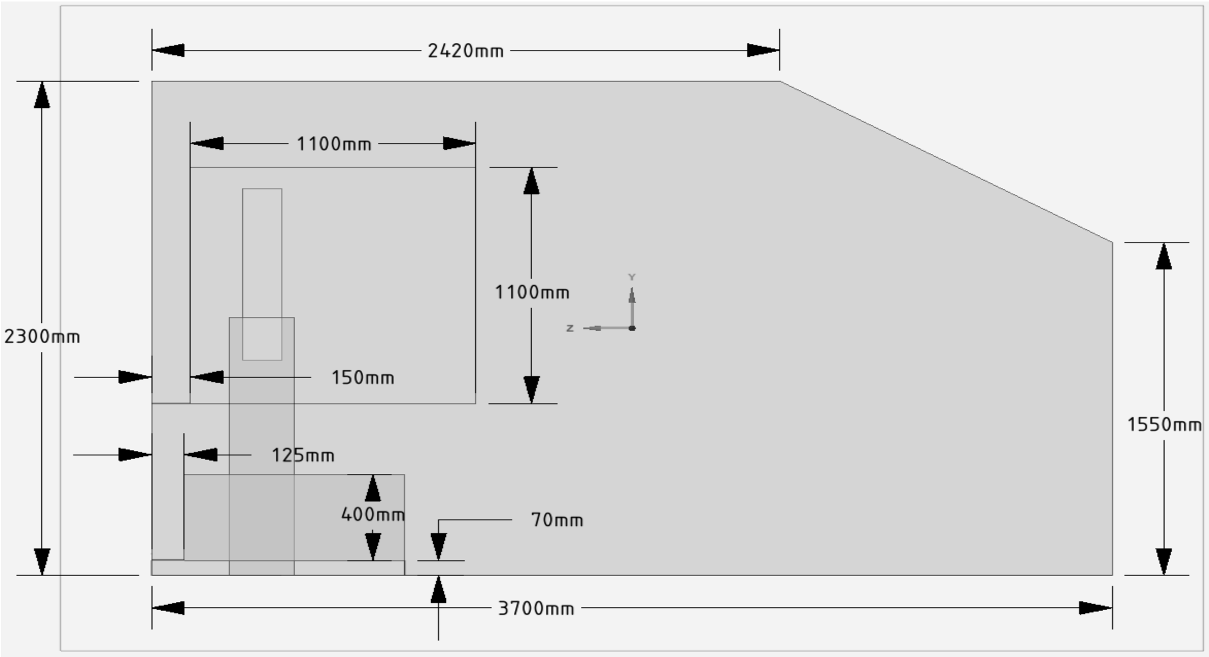


Figure 17: Side- view of the living room, showing the roof decline

The total volume of the living room (LR_v)is calculated to be:

$$LR_v = (2{,}42 * 3{,}23 * 2{,}3) + (1{,}28 * 1{,}55 * 3{,}23) + \left(\frac{(0{,}75 * 1{,}28 * 3{,}23)}{2}\right) = 25{,}9369\ m^3$$

The actual available space should be distracting the un-removable objects such as the heater and the fireplace, leaving us with the total of room “free-space” close to $25{,}8m^3$.

The word “Furniture” according to English Oxford [59] living dictionary is; Movable objects used to make a room or building reasonable for work or private life, such as; a table, chair, desk and so forth. Table 8 below, contain the size of furniture found inside the room (easily movable/adjustable furniture):

Table 8: Movable furniture size

Definition	**Length (m)**	**Width (m)**	**Height (m)**	**Description**
TV	0,8	0,05	0,57	Toshiba 32-inch LCD color TV
TV-stand	0,9	0,4	0,4	Rectangle-shaped TV-stand
Sofa	1,55	0,8	0,4 0,65	L-Shape corner sofa bed with lift up storage
Chaise longue	0,85	1,45	0,4 0,65	Chaise longue connected to the bed sofa
Table	0,75	0,75	0,8	Simple white square table
Shelf	0,84	0,4	0,8	4-Cube Organizer Shelf
Chair: Seat Back	0,4	0,4	0,45 0,85	Single chair connected to the square table

Furniture are measured from edge to edge with a measuring tape + few millimeters are added to compensate for any curves in the furniture, device, object surface.

4.2. Ventilation-meter:

Air speed (velocity) and temperature data collected below are measured manually using TSI ventilation meter 9565. Around four separate locations (points) inside of the living room:

- Point.1: Window opening (0,1*1,1 m)
- Point.2: Door opening (0,18*1,97m)
- Point.3: Center of the living room (at 1,15m height, 1,85m from door)
- Point.4: Located 3,7 m from the door at height 1,15m.

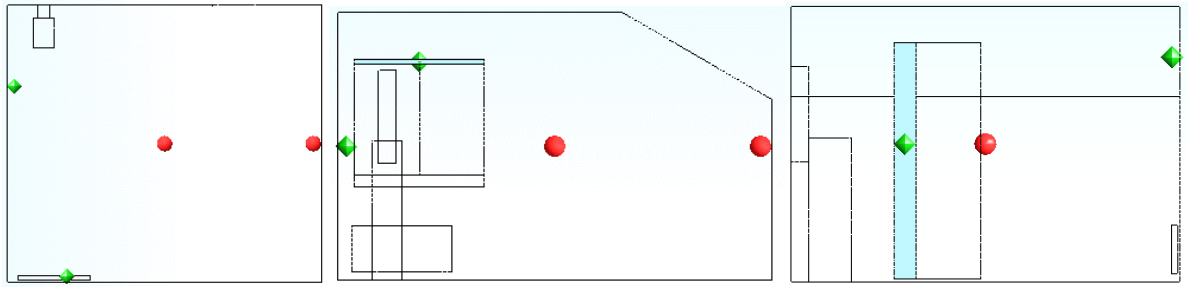


Figure 18: All four measuring points inside the selected room

Figure 18 display all four points in X, Y and Z view. Table 9 - Table 12 hold the values found at these four room locations, tested under four different conditions (states): window and door open, window open door closed, window closed door open, at last both window and door closed, to have a better idea on what is affecting the rooms indoor air movement. (for extra measures).

Table 9: Average measured values of Test.1

Test.1			
Location/point	**State (On/Off)**	**Average Velocity [m/s]**	**Average Temperature [°C]**
1	ON	0,69	16,52
2	ON	0,11	20,11
3	-	0,03	19,97
4	-	0,02	20,87

Table 10: Average measured values of Test.2

Test.2			
Location/point	**State (On/Off)**	**Average Velocity [m/s]**	**Average Temperature [°C]**
1	ON	0,71	16,99
2	OFF	0,14	20,51
3	-	0,03	19,96
4	-	0,03	20,76

Table 11: Average measured values of Test.3

Test.3			
Location/point	**State (On/Off)**	**Average Velocity [m/s]**	**Average Temperature [°C]**
1	OFF	0,27	18,35
2	ON	0,08	19,98
3	-	0,03	20,13
4	-	0,01	20,85

Table 12: Average measured values of Test.4

Test.4			
Location/point	**State (On/Off)**	**Average Velocity [m/s]**	**Average Temperature [°C]**
1	OFF	0,23	18,26
2	OFF	0,04	20,71
3	-	0,01	20,37
4	-	0,01	21,52

TSI ventilation meter is held still for approximately 30 seconds at each measuring point, while the state change (Test) is approximately 3 minutes apart. (allowing the room some time to reset from previous state).

By observing the data, it is safe to say that there is no significant change between the door on/off action, its mostly the window opening that determents velocity and temperature inside the living room.

Table 13: Average values of the four different measuring conditions.

The average of the measured data			
Location/point	**Velocity [m/s]**	**Temp. [K]**	**Temp. [°C]**
1	0,700	290,90	16,75
2	0,092	294,46	20,31
3	0,028	294,12	19,97
4	0,021	294,96	20,81

Total average value of inlet velocity is calculated to be 0,7 m/s, average inlet temperature is 290,9 K, as presented above in Table 13.

Note the measured velocity at the window “in open state” is not truly accurate or “fixed”, because of wind change at certain time. one moment it could be windy, the other is calm. Hence chosen data for boundary conditions are average value of all 6 measurements done while the window is open (0,7 m/s).

4.3. Thermal camera

Pictures of the living room where taken and then processed in MATLAB in order to identify heat maps colours and transfer the data into Celsius [C°] values, later plotted in table form (excel file). The MATLAB code used for this transaction is:

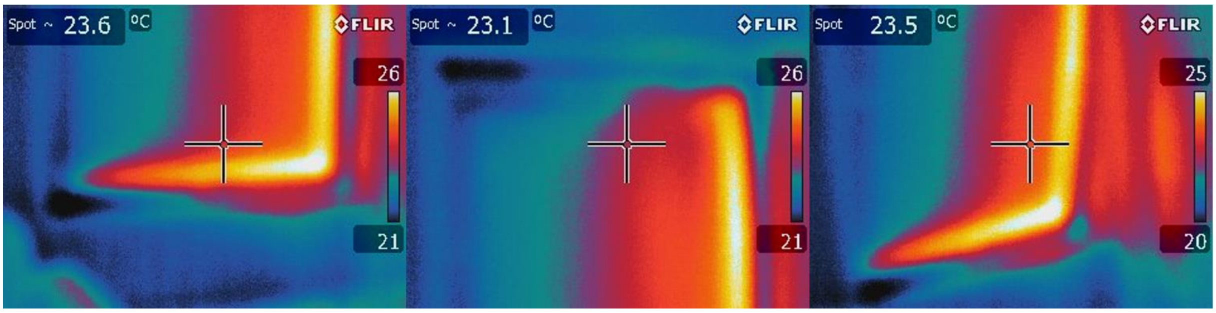
```
clc
clear
A= imread('IR_2328.jpg');

reduc=50;
[X,map] = rgb2ind(A,reduc,'nodither');
X1=imcrop(X,[0 33 278 207]);
%figure
%imshow(X1,map)
X2 = imcrop(X,[307 70 6 101]);

[n m]=size(X2);
up_range=25;
down_rang=20;

step=(up_range-down_rang)/(n-1);
temp_vect=(up_range:-step:down_rang);
temp_vect=temp_vect';
for i=1:m
    temp_map(:,i)=temp_vect;
end
figure
imshow(X2,map)
for i=1:reduc
    op= double(X2==i);
    op_s=sum(sum(op));
    op1=op.*temp_map;
    op1_s=sum(sum(op1));
    value(i,1)=op1_s/op_s;
end
[n m]=size(X1)
for i=1:n
    for j=1:m
         if  X1(i,j)~=0
        if value(X1(i,j),1)~=NaN

        X_end(i,j)=value(X1(i,j),1);
            end
        end
    end
end
```

Figure 19: MATLAB Processing Code

From analysing the photos captured by the FLIR E60 thermal camera, the first observation was that objects temperature change drastically (for instance, the window frame). Consequently, it was necessary to divide some objects into multiple surfaces (zones).

1. **Window (Inc. Inlet):**

Three photos where captured from different angels. The average temperature value and the zones are presented as follow:



The window is divided into four zones (where there is major change in temperature), top, right, left and bottom. Table 14: Average value of all four window zones.Table 14 hold the average temperature of each zone.

Table 14: Average value of all four window zones.

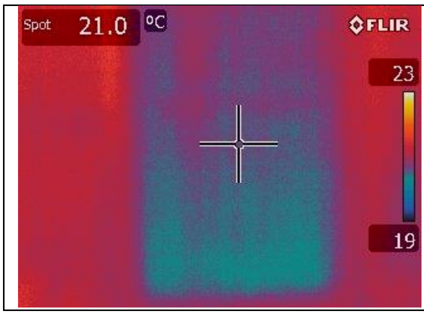
Window surfaces:	**Temperature [C°]**	**Kelvin [K]**
Top (inlet)	18,9	293,05
Right	23,64	297,79
Left	21,79	295,94
Bottom (closest to the heater)	24,04	298,19

Notice that the Temperature captured at the "inlet" is not similar to the temperature found using the TSI ventilation meter. Such difference can be explained by the fact that these measurements where not taken at the same period of time, plus the fact that the TSI ventilation meter was placed right in front of the window "inlet" and tested multiple times.

2. **Door (Outlet)**

One photo where taken for the door (outlet), the only source of data other than the values found using TSI ventilation meter. The figure below displays the surface of the door (outlet) and nearby wall.

Table 15: Door and surrounding wall temperature



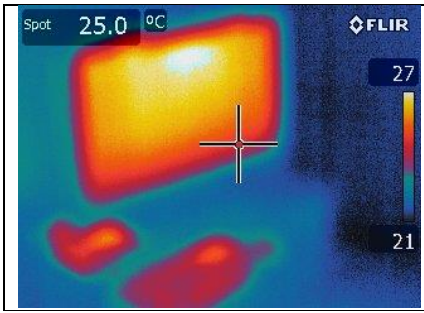
Surfaces	**Temperature [C°]**	**Kelvin [K]**
Door (Outlet)	20,31	294,46
Wall	21,18	295,33

This door is as mentioned earlier, it leads to the "wardrobe outside of the apartment", and is partly open.

3. TV-Setup

A single photo capturing the TV area, including the TV-screen and other nearby furniture (MK charger, Computer connected to MK and Apple-TV)

Table 16: TV screen and surrounding wall temperature



Furniture:	Temperature [C°]	Kelvin [K]
TV-Screen	26,03	300,18
Wall	21,23	295,38

The TV-screen is on, while the other equipment theoretically not in use (ignored).

4. Furniture (Walls)

The photos below captured three different locations/ objects in the room; shelf, sofa and lastly a wall without any furniture covering it.

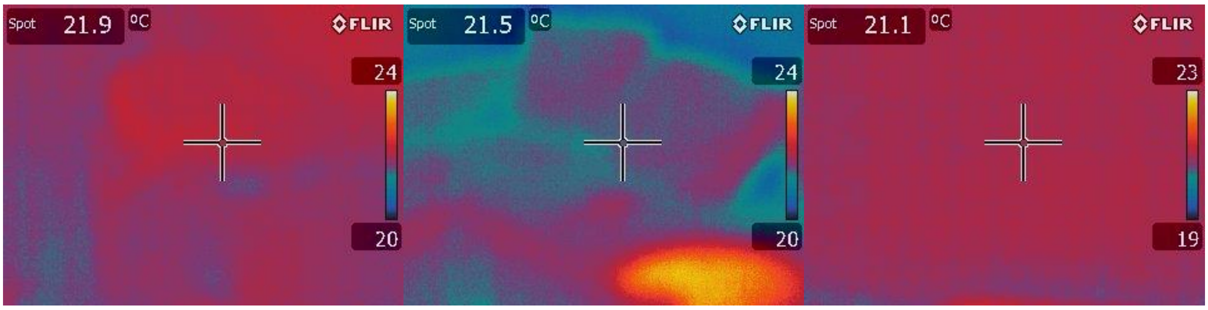


Table 17: Shelf, sofa and wall temperature

Furniture:	Temperature [C°]	Kelvin [K]
Shelf	21,82	295,97
Sofa	21,40	295,55
Wall	20,91	295,07

Note: 1. Heat spotted on the bottom right side of the sofa is generated from the heater, hence it is ignored completely. 2. The thermal photo of a wall without any furniture covering, displaying the average temperature of the wall inside the room, which is 21,1 C.

The rest of selected furniture, walls and general room temperature is set to 21 C (sense its considered to be normal room temperature regardless of season (winter/summer) as it matches most of the measurements done in this living room. Also appears to be in unison/agreement with the data collected from the ventilation meter, thermal camera in addition to the definition from both; The American Heritage Dictionary and Oxford English Dictionary sources. [60] [61]

5. Method:

In order to study the interaction between occupants and their surroundings in residential buildings, specifically on the issue of furniture settings (as well as heater locations). It is necessary to discuss a method (a strategy) for such issue. The purpose of this chapter is to describe the method adopted, leading to the results documented in chapter 6.

Building the fundamentals of this project on a case-based analyses, where different living room scenarios are simulated. By designing a living room with the inlet, outlet and heater location fixed in all scenario as well as their attributes with the help of SolidWerks and ANSYS. Furniture settings should be the main difference between each case. Subsequently, helps on analyzing and finding the influence furniture placement has on the indoor environment in terms of surface temperatures and air flow patterns. Microsoft Kinect is thereby used to gather and recreate body movement inside the selected living room. Such data can further be used to find potential discomfort zones inside the selected living room.

5.1. Room characterization

A selected $12m^2$ living room inside of a loft apartment, has an available free space volume of 25,8 m^3. Contains two doors (one is closed “wall” leads to the bedroom, the other door is leading to the outside, hence it is set as “outlet”), one window, heater and unmovable fireplace in the corner of the room. As measured in preview chapter, window opening brings fresh air at the rate of 0,7 s/m on average, while the door in open stage works as an outlet.

Figure 20 display a three- dimensional representation of the room in millimeters, mainly taking into consideration room shape, walls, window and door location. Other objects are not included yet.

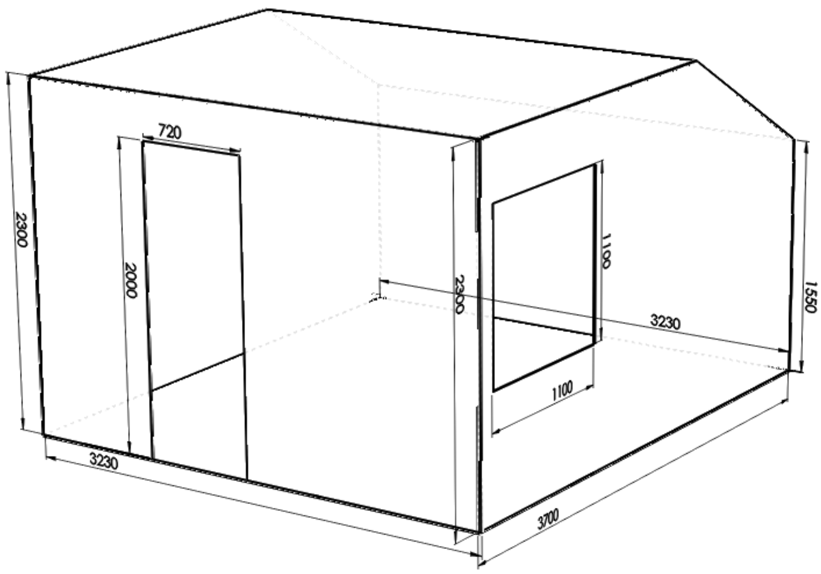


Figure 20: a simple three-dimensional representation of the living room in millimetres

Selected room length 3,7m, width 3,23m, and height 2,3m for majority of the room. with a decline at 2,42m in roof (hight.2 at 1,55m). Window length and height 1,1m, opening is calculated to be 0,1x1,1 [m] (outlet).

5.2. Furniture setting

Several settings must be tested to discover how much the furniture setting alone can influence living room environment in relation to air flow patterns and surface temperature. Accordingly, ANSYS Fluent software is used to preform numerical CFD calculations.

Each scenario should be possible to recreate in person, realistic furniture placement, allowing the occupant to interact with each object with ease. First scenario is described as "empty room scenario", as every removable furniture is taken out of the geometry. The other three scenarios consist of small adjustment in furniture placement, without removing any of them.

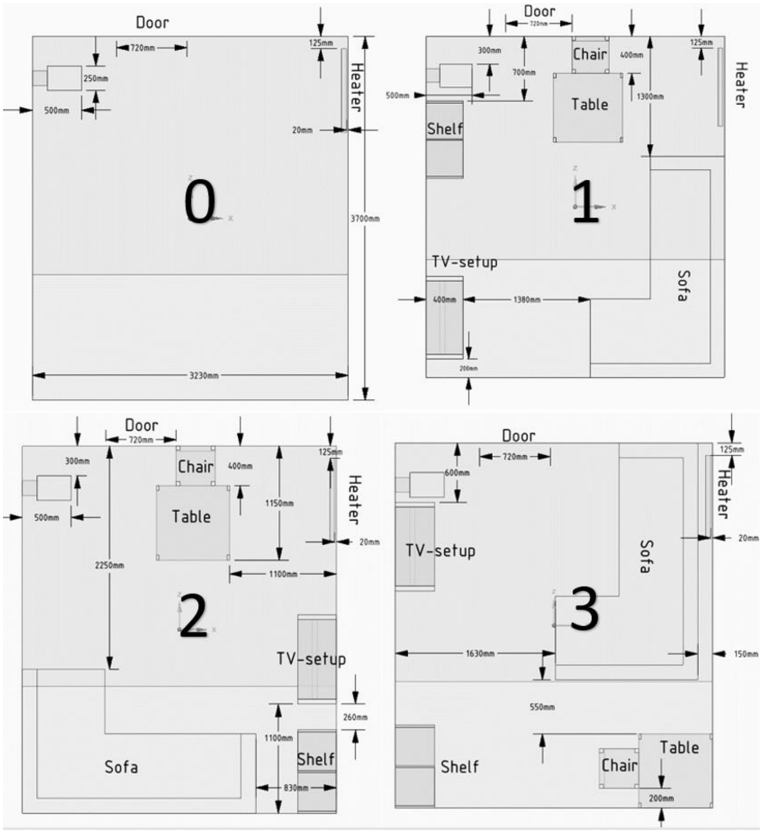


Figure 34: two-dimensional top view of each room setup. (0-3)

Figure 34 (above) shows a two-dimensional top view of all four room scenarios, displaying the furniture location as well (scaled in mm), room scenarios are followed through room setup 0 to room setup 3, from left to right.

Table 18: Description of all four room scenarios

Name	Description
Room setup 0	Simply the selected living room without any objects other than heater and fireplace. (unmovable)
Room setup 1	Includes all furniture inside the living room, as described in the figure above (Figure 34)
Room setup 2	
Room setup 3	

→ *P.S. Objects such as: the window, door and heater are all fixed in size and placement for all four scenarios.*

5.3. SolidWorks (Furniture development):

SolidWorks considered to be easy, affordable and time efficient software adopted for any type of 3D drawing. For this reason, SolidWorks helped to build a 3D module of the furniture in hand. The first step is measuring the furniture size (height, length and width), as described in chapter 4. To minimize future errors (size issues), it is important to be as accurate as possible when measuring different furniture. Once the furniture data is collected, next step would be recreating it in a geometrical model.

All furniture developed by SolidWorks are listed below:

- Table (+ chair) - L-Shape corner sofa - 32-inch TV
- TV-stand - Organizer shelf - Heater

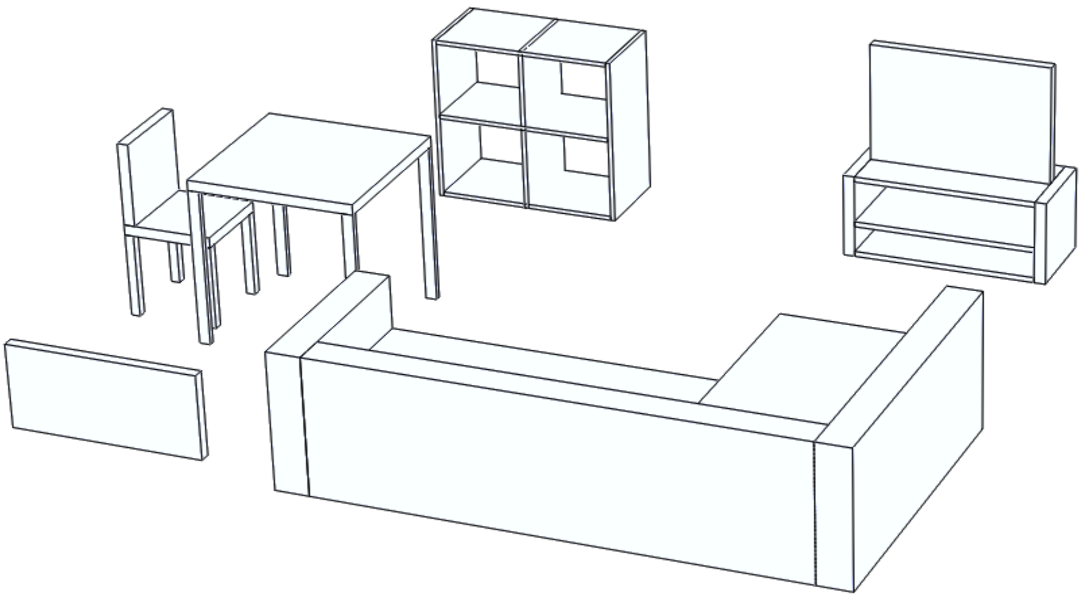


Figure 21: All furniture developed by SolidWorks

Three-dimensional representation of heater and the verity of furniture used in this project. Thereby the fireplace is recreated using SpaceClaim in ANSYS Workbench, followed by the rooms dimensions (room figure).

In theory SpaceClaim (ANSYS) could be adopted to create and developed the entire geometry from start to finish. However, SolidWorks came out to be a more beneficial (user friendly) choice. Based on the direction of this project where different room settings are simulated, moving furniture should be as easy/simple as possible, instead of developing each geometry from scratch four times, its decided to use Solidworks for the furniture model, afterwards plant it in SpaceClaim (ANSYS).

→ *To gain a closer view into each furniture and the scale of them individually, that can be found in appendix x-y.*

5.4. ANSYS Workbench:

ANSYS Workbench allows to import three dimensional models, form a grid, put boundary conditions and deliver high quality results. This project applied ANSYS Workbench cells such as: Geometry, Mesh, Fluent and results.

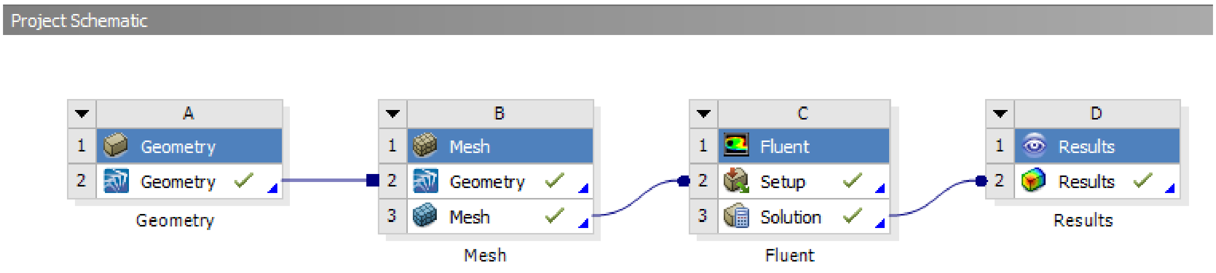


Figure 22: ANSYS Workbench, Project schematic

Every process starts with a body model (geometry), that model is then meshed into small cells, resulting in a grid with a large number of nodes. ANSYS Workbench project schematic display each sell in its right order: Geometry → Mesh → Fluent → Results. These cells are captured from the toolbox found on the left side of ANSYS Workbench's window. Each component is easily linked to the next one by holding the left button on the mouse and dragging it to the nearby component.

I. Geometry: Spaceclaim

To start of any CFD calculation, a geometry model needs to be provided (created), in this case the geometry is divided into two parts, the first is SolidWorks model (extruded area) and SpaceClaim used afterward to create the rooms shape.

First step would be, importing the furniture model developed in Solidworks to the geometry cell in ANSYS Workbench, then sketch the room dimensions according to values measured documented previously.

Toolbox "Sketch" to draw rooms dimensions, afterwards select the sketched area by pressing the "Pull" icon to bring a three-dimensional view of the living room in hand. Use of the "Combine" icon, helps on combine/split objects.

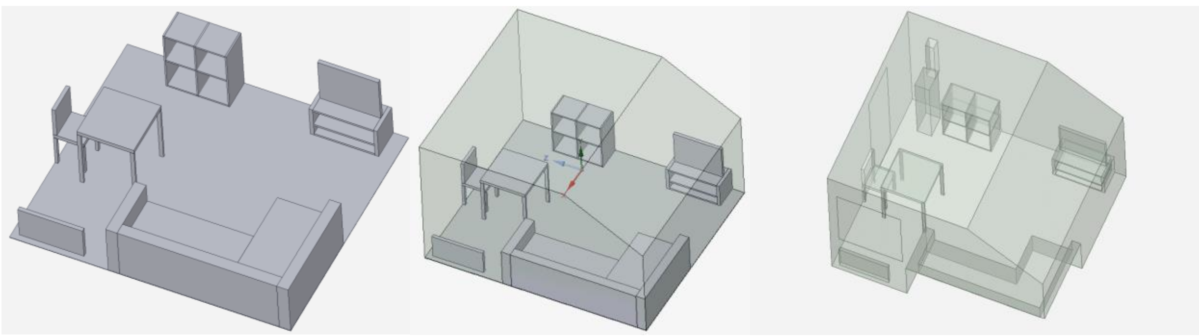


Figure 23: Geometrical representation of the selected living room

After excluding all furniture, this is the finished product (geometry of room setup 1), same process is repeated for the other room scenarios. (Figure 23: demonstrating step by step of how the geometry is created)

Create a window opening of 5*110 cm at the top, while the door opening set at 18cm from the left side of the door (25% of the door surface is considered open).

II. Grid:

"Meshing" or dividing the model/structure into smaller elements (FEM- Finite element model). As mentioned earlier (in chapter 3), a high mesh quality is very crucial in giving an accurate level of predictions (results). [9] [10]

By trying out different meshing methods, techniques and sizing values, it is possible to arrive to a high-quality grid. Judged by Aspect ratio, element quality and skewness. Assembly meshing using ANSYS Fluent, allows/provides for two algorithms: CutCell and Tetrahedrons.

As for this project, Assembly meshing method "CutCell" is very useful to provide hexahedral dominant representation considered to be more suitable for the grid in hand. To achieve that, some of the default settings needs to be changed as follow:

Table 19: Assembly meshing

ASSEMBLY MESHING	CUTCELL
Defaults	
Physics preference	*CFD*
Solver Preference	*Fluent*
Relevance	*0*
Export format	*Standard*
Sizing	
Size Function	*Curvature*
Relevance Venter	*Medium*
Curvature Normal Angel	*Default (18,0 º)*
Min Size	*0,01 m*
Max Face Size	*0,04 m*
Growth rate	*Default (1,2)*

While face sizing should include most walls in the geometry, Use Geometry Selections as the scoping method, scoping all walls (faces) (should contain: the window, inlet, door, outlet and the rest of the rooms surfaces)

Table 20: Face sizing

FACE SIZING	
Definition	
Suppressed	*No*
Type	*Element Size*
Element Size	*0,01 m*
Advanced	
Defeature Size	*0,005*
Size Function	*Uniform*
Behavior	*Soft*
Growth Rate	*Default (1,2)*

Face Sizing is selected to increase the cell number at areas (faces) considered to be interesting, such as; walls, window, heater and door.

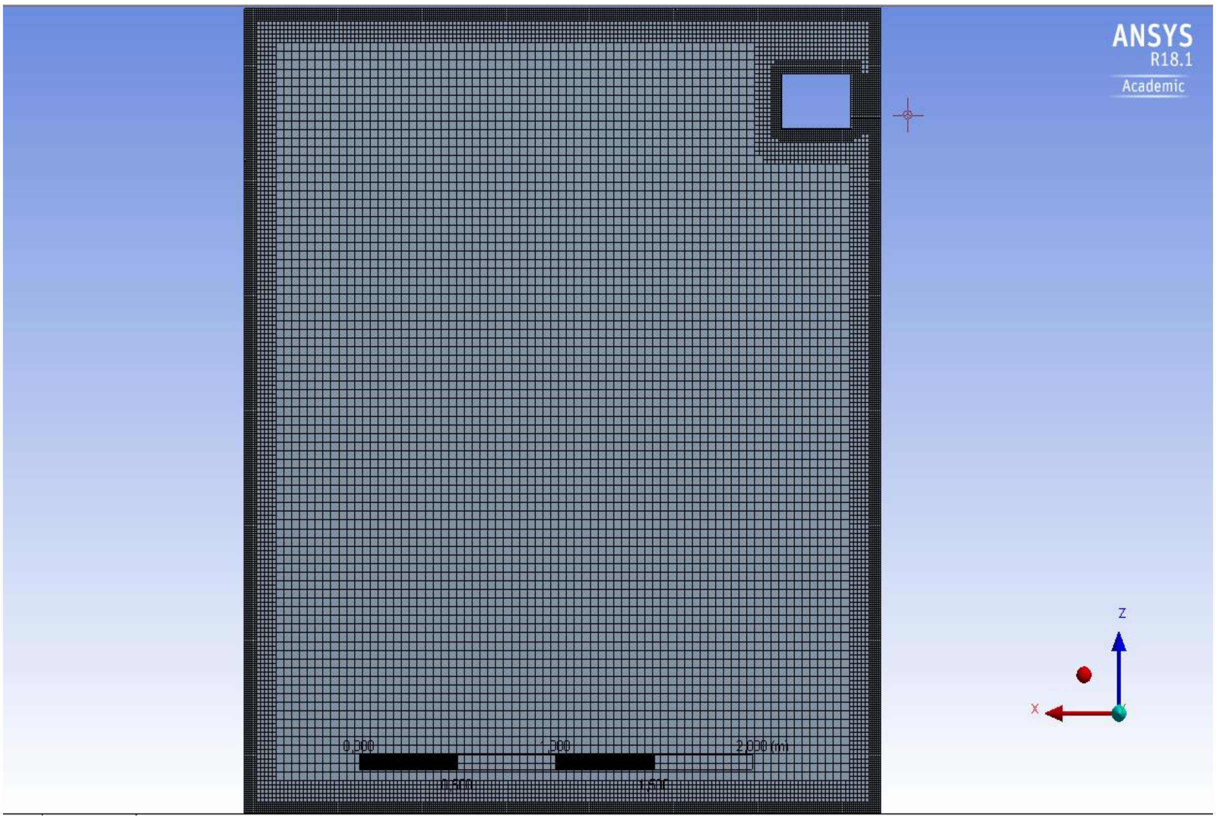


Figure 24:A cross section of the geometry (roughly at the mid of the room) of the Mesh

This figure demonstrating a cross section of the grid produced by applying the data above. The CutCell mesh consists of mostly hexahedral elements, with faces that are aligned with the coordinates axes. Displaying the gradual change/concentration of cells.

It's important here to select face(s) and create name selection according to what function each face (wall) has (defining the area of boundary conditions):

Table 21: Name Selections (BC)

Name Selection	**Description**
Window Opening	*Referring to the inlet. (top part of the window)*
Window Right	*The right half side of the window frame*
Window Left	*Is the left half side of the window frame*
Window Bottom	*Bottom area closest to the heater*
Door	*Door*
Door Opening	*Open side of the door (Outlet)*
Heater	*All six heater surfaces are selected*
TV Screen	*TV screen*
Roof/Top	*Upper surface of the geometry (Roof)*
Floor/Bottom	*Bottom surface of the geometry (Floor)*
North	*North wall (Z-)*
South	*South wall (Z+)*
East	*East wall, window side (X+)*
West	*West wall (X-)*

III. **Fluent**: set-up boundary conditions

ANSYS fluent is the a very powerful computational fluid dynamics (CFD) software, giving a lot of options and settings. Here is some of the most important setup (data) used in this project:

- General:

The General task page allow the user to select different problem settings, related to the mesh, solver or gravity:

Type “Pressure-Based” solver by default permits the pressure-based Navier-Stokes solution algorithm. Velocity Formulation “Absolute” opens the use of the absolute velocity formulation. While the time solver is set as “Steady” indicating a steady flow being solved. [9] [10]

The most significant part is to include the gravity, and make sure its directed correctly (choosing the right axis, might differ from geometry to another) at - 9,81. As the rest of the options in this task page is already correct by default.

- Cell Zone Conditions:

This task page open ups the option to set the type of a cell zone and display other dialog boxes to set the cell zone condition parameters for each zone. Type of cell zone selected is fluid (air) with constant properties. [9]

- Models:

Contains a listing of the various models available in ANSYS Fluent, such as multiphase, energy, viscous, radiation, heat exchanger, species, discrete phase, solidification & melting, acoustics, eulerian wall film and electric potential. [9]

The two main “Models” activated for this project, are “Energy” and “Viscous” (at k-epsilon (2eqn)). Activating the ENERGY gives access to determine criterion linked to energy or heat transfer in a model. while the VISCOUS MODEL dialog box is used to enable turbulent flow calculations, along with inviscid and laminar flow. Turbulent flow can be calculated using one of three - k-ε models: [10] [9]

1. Standard 2. RNG 3.Realizable

The *Standard k-ε* turbulence model is arguably the most applied model in CDF calculations as well as being the default model for ANSYS Workbench Fluent 18.1. Launder and Spalding are the founders of this model in 1974, introducing a collection of equations used for a variety of turbulent calculations. [62] [9] [10]

The transport equations for standard k-epsilon model are as follow:

For turbulent kinetic energy “k” [9] [63] [10]:

$$\frac{\partial}{\partial t}(pk) + \frac{\partial}{\partial x_i}(pku_i) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] + G_k + G_b - p\varepsilon - Y_M + S_k$$

For the rate of dissipation “ε” [9] [63]:

$$\frac{\partial}{\partial t}(p\varepsilon) + \frac{\partial}{\partial x_i}(p\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon$$

G_k: Generation of turbulence kinetic energy due to mean velocity gradients

G_b: Effects of Buoyancy on Turbulence in the k-ε Models

Y_M: The contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

While $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are all consider to be constant. Turbulent Prandtl numbers (Pr_t) are represented in σ_k and σ_ε. μ_t describes the eddy viscosity, also calculated as follow [9]:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

In the table below each changeable constant is mentioned with its default value:

Table 22: Model Constants (by default) [9] [10]

C_μ	$C_{1\varepsilon}$	$C_{2\varepsilon}$	σ_k	σ_ε	Pr_{Energy}	Pr_{Wall}
0,09	1,44	1,92	1,0	1,3	0,85	0,85

- <u>Materials:</u>

Task page can set properties for any fluid or solid (or mixture, if applicable) materials in your ANSYS Fluent simulation. In default setup this task page is divided into Fluid material and Solid material, the table below describes the properties for these materials: [10] [9]

Table 23: Fluid material (Air) and Solid material (Aluminium) properties

Materials / Properties	Fluid (Air)	Solid (aluminium)
Density $\left[\frac{Kg}{m^3}\right]$	1,225	2719
Cp (specific heat) $\left[\frac{J}{kg*K}\right]$	1006,43	871
Thermal Conductivity $\left[\frac{W}{m*K}\right]$	0,0242	202,4
Viscosity $\left[\frac{Kg}{m*s}\right]$	1,7894*e-5	-

Table 23: Fluid material (Air) and Solid material (Aluminium) properties contains properties such as density, pp, thermal conductivity and viscosity for both Fluid material (Air) and Solid material (Aluminum). These values are fix and will not be changed throughout this project.

- <u>Boundary conditions:</u>

allows the user to select the type of a boundary and display other dialog boxes to set the boundary condition parameters for all needed boundaries. Three types of BC where selected (Wall, Velocity-inlet, Pressure-outlet), for separate set of zones: [9]

Table 24: Boundary conditions

Zone	Type	Velocity/Pressure	Temperature [K]
Room walls, roof and floor	Wall	-	295,15
Heater	Wall	-	304,15
Door	Wall	-	294,46
Door opening	Pressure-outlet	0 Pascal	294,46
Window opening	Velocity-inlet	0,7 m/s	290,9
Window right	Wall	-	297,79
Window left	Wall	-	295,94
Window bottom	Wall	-	298,19
Geom-solid	Wall	-	295,15
TV-screen	Wall	-	300,18

These values are based on the data collected in chapter 4.

- Reference Value:

Reference values is the last task page on the setup of ANSYS Fluent 18.1, before running calculations. There aren't many significant changes done in this task page.

Starting with task page "Solution Methods", allowing the choice of four plans/schemes; SIMMPLE, SIMPLEC, PISO and Coupled. Going for the default scheme "SIMPLE" [9]

Table 25: Solution Methods

SIMPLE	
Gradient	*Least Squares Cell Based*
Pressure	*Second Order*
Momentum	*Second Order Upwind*
Turbulent Kinetic Energy	*First Order Upwind*
Turbulent Dissipation Rate	*First Order Upwind*
Energy	*Second Order Upwind*
Wraped-Face Gradient Correction	*On*

Next step is to decide initialization method, given two options: Hybrid or Standard. Hybrid Initialization is implemented, to solve the Laplace equations and produce a velocity and pressure fields. Other variables such as temperature, turbulence, species fractions, volume fractions, and so on, will be automatically fix/corrected/patched by this method. [9] [10]

Lastly "Run Calculation" (to start the solver iterations at Steady-State Calculations): number of Iterations can vary from file to file, for accurate results, it's advised to run calculations until the solution has converged. [10] [9] [63]

IV. CFD Convergence (Verification of CFD simulation):

Checking CFD convergence is very critical/important for all fluid flow problems, as it impact the outcome (solution). To judge if the simulation has reached a point of convergence, the residual values are typically evaluated:

As it points directly at the level of accuracy the questions have been solved at. Its advice to keep an eye on the residuals as they decrease under simulations.

Equations Residual	Absolute Criteria
Continuity	0,001
X- Velocity	0,001
Y- Velocity	0,001
Z- Velocity	0,001
Energy	$1e^{-06}$
k	0,001
Epsilon	0,001

To be considered as accurate calculations (tightly converged), the residual values has to reach a value of 1*10-3 while the energy solver could reach 1*e-6. [63] [9] [10]

V. **Results / CFD-Post**:

This cell implements a number of flexible options to display or calculate the values as required, providing an easy view of the CFD simulations results. Features that can be implemented in this cell, mainly are: Contour map, Vector, Streamlines, Table, and Location (such as: Point, Plane, Volume and Vortex) [9] [10]

Starting with recreating the four points measured inside the room. Thereby making it possible to probe the temperature and velocity values accordingly. Table 26and Figure 25 gives a better understanding of these lactations:

Table 26: Four measured room locations

Point.nr	Description	[X,Y,Z]
1.	Middle of the window opening (Inlet)	[1.57,0,725,1.15]
2.	At the doors opening (Outlet)	[0.67,0,1.77]
3.	Center of the room (Mid. Point)	[0,0,0]
4.	Middle of the furthest wall from the outlet (Point. X)	[0,0,-1.75]

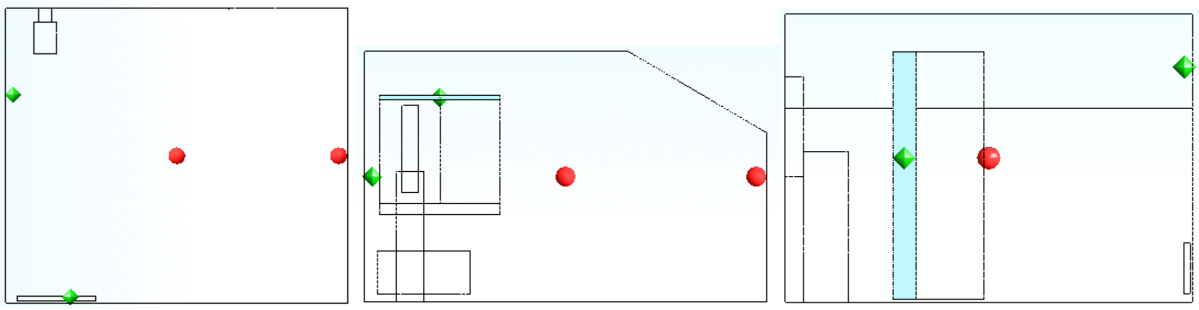


Figure 25: Two-dimensional representation of the measured points

The two Red-circular points represent Mid. Point & Point. X, while the Green-octahedron points represent the Inlet & Outlet. Furthermore, the two-dimensional contour maps, vectors and streamlines are used for a better understanding of air movement and temperature change in other points/planes inside this geometry.

In addition to these four points, two planes are selected to examine potential differences in air quality circling the room:

- Plane.1: 1,15m from ground, splitting the geometry in half.
  Selecting Location → Plane → Method: ZX Plane → Y value at 0 [m].

- Plane 2: follows across the window (inlet).
  Selecting Location → Plane → Method: XY Plane → Z= 1,15 [m].

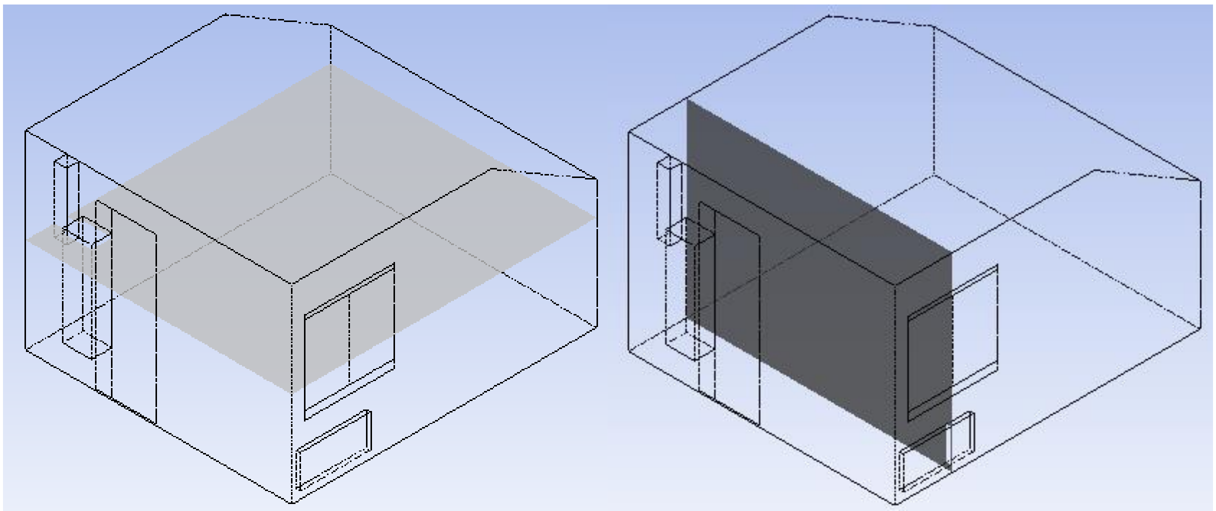


Figure 26: Plane 1 and Plane 2 respectively

Volume method “Isolovume” enables us to choose between variables such as density, pressure, velocity or temperature and more. With optional modes and values (such as; At value, Below value, Above value and Between values). Areas of temperature between 20-22 are interesting to identify, and possible to find by using Volume → Iso → Between: 20-22 C. other test could also be measured is areas of “dead are” where the velocity is considered low 0-0,01-0,02. [64] [60]

5.5. Occupant migration monitoring

Thermal measurements of the selected room should be completed at this stage, along with the furniture design, ANSYS geometrical model, mesh and CFD solution. The next step of this process would require data (information) of temperature and air velocity positioning in of the geometry (living room).

To conduct investigation regarding the thermal comfort sensation with a use of newly developed occupant behavior bot, Microsoft Kinect had to be placed in the top corner of the selected living room. The devices stayed there for one week, to capture occupant behavior in that period of time. Furniture setting is changed /switched as described previously, starting with room setup1 24-25/04/2018, then room setup.2 29-30/04/2018 and finally room setup.3 27-28/04/2018. The skeleton (limbs) works as colleting points moving across the living room collecting data in all directions.

Number	Joint name	Number	Joint name
1	Spine Base	14	Knee Left
2	Spine Mid	15	Ankle Left
3	Neck	16	Foot Left
4	Head	17	Hip Right
5	Shoulder Left	18	Knee Right
6	Elbow Left	19	Ankle Right
7	Wrist Left	20	Foot Right
8	Hand Left	21	Spine Shoulder
9	Shoulder Right	22	Hand Tip Left
10	Elbow Right	23	Thumb Left
11	Wrist Right	24	Hand Tip Right
12	Hand Right	25	Thumb Right
13	Hip Left		

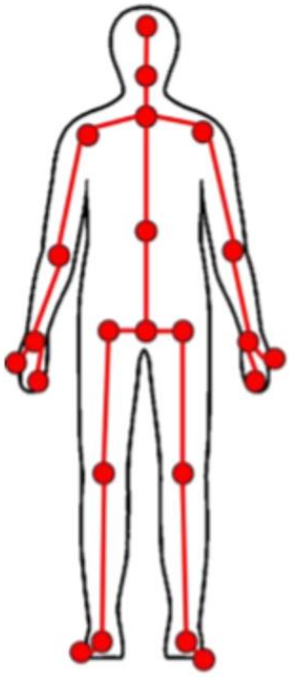


Figure 27: Skeleton model hitch points [2]

List of all 25-skeleton model (SM) joints, with a figure to the right illustrating how the limbs of the skeleton model is divided. By the help of Microsoft Kinect devise built-in software, it is possible to derive the positioning of the body in 3D (X, Y, Z). The positioning data is given from the distance between each joint and the reference point (0,0,0). Which is the measurement device (the Microsoft Kinect decide, located in a mass center of the device). Evidently the placement of the Microsoft Kinect device could affect the accuracy of recording movement within the living room. Jacub W. is credited for helping on collecting data information from the SM joints. [2] [40]

The movement where processed via Matlab, transferred as polyline into CFD-post, and then exported the value of velocity and temperature for suck points/lines! Once the data is exported from CFD-post, it can be processed once again using Matlab code.

6. Results:

This chapter hold several results collected from ANSYS and SolidWorks files. Starting with the furniture model, mesh and convergence accuracy. Followed by data gathered from comparing room setup by their temperature change, air velocity, air volume and occupant pattern. All geometries are based on the recreated furniture models found inside of the selected living room, also the four different furniture settings (placements) scenarios. To describe mesh quality figures and tables of Aspect ratio, Element quality and Skewness are included, as it plays a huge role in deciding results accuracy (reliability).

CFD calculation are compared to the measured points to establish accuracy, as described in previews chapters. Room scenarios are then studied through point probing, plane average, air quality volume as well as occupant patterns. To be able to identify discomfort zones inside selected living room. Obtained results aim to show identification of the existence of potential discomfort zones inside the selected room.

6.1. Furniture:

Figure 28 shows a three-dimensional representation of each furniture model (movable objects) found inside the living room. Not taking room setting into consideration.

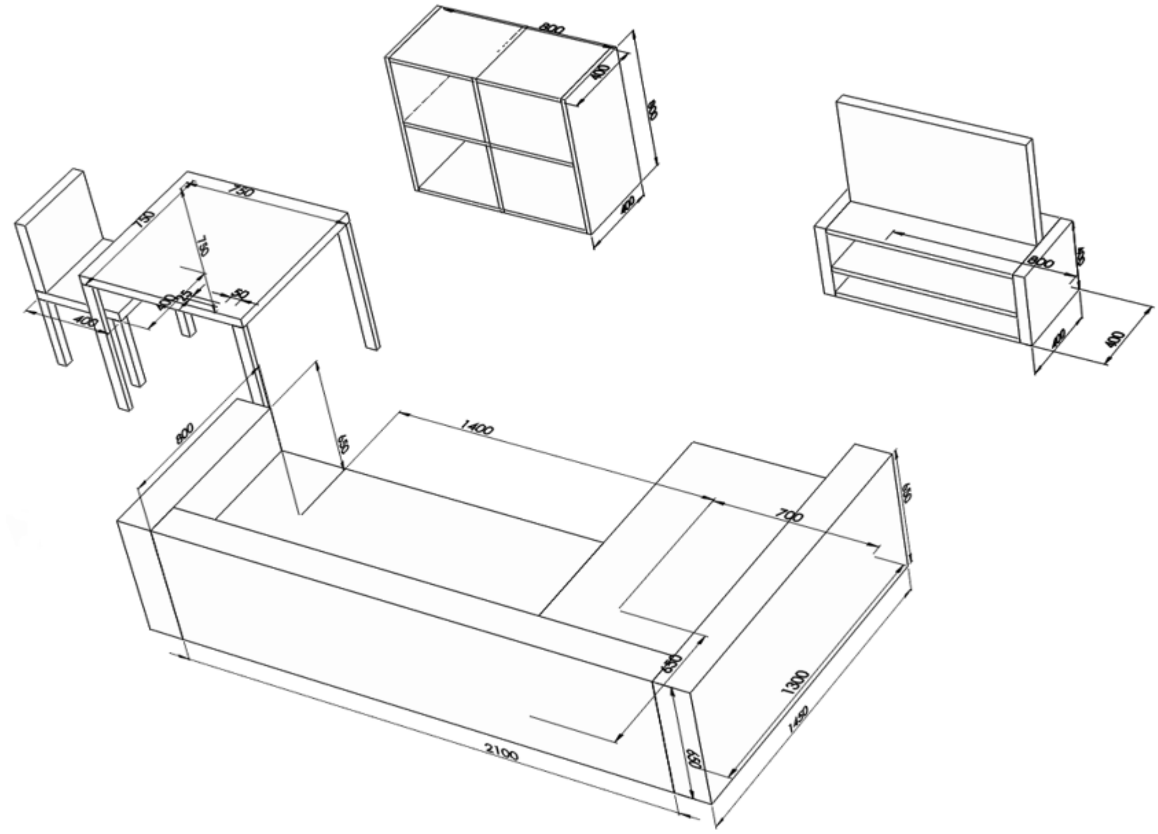


Figure 28: Three-dimensional sketch of all furniture (scaled in millimetre)

The TV is placed in the middle of its TV-stand, and then attached keeping them set as one furniture. Same method used for the chair and table, whereas the chair is linked at the midpoint of the table.

→ *Separate detailed view of each furnitrue case can be found in the appendixs.*

6.2. Mesh quality check:

Quality of mesh can be evaluated by looking at the grid at first, then by testing its element quality, aspect ratio or skewness. Figure 29 a cross-section of a random wall in the geometry, showing the different layers in the grid.

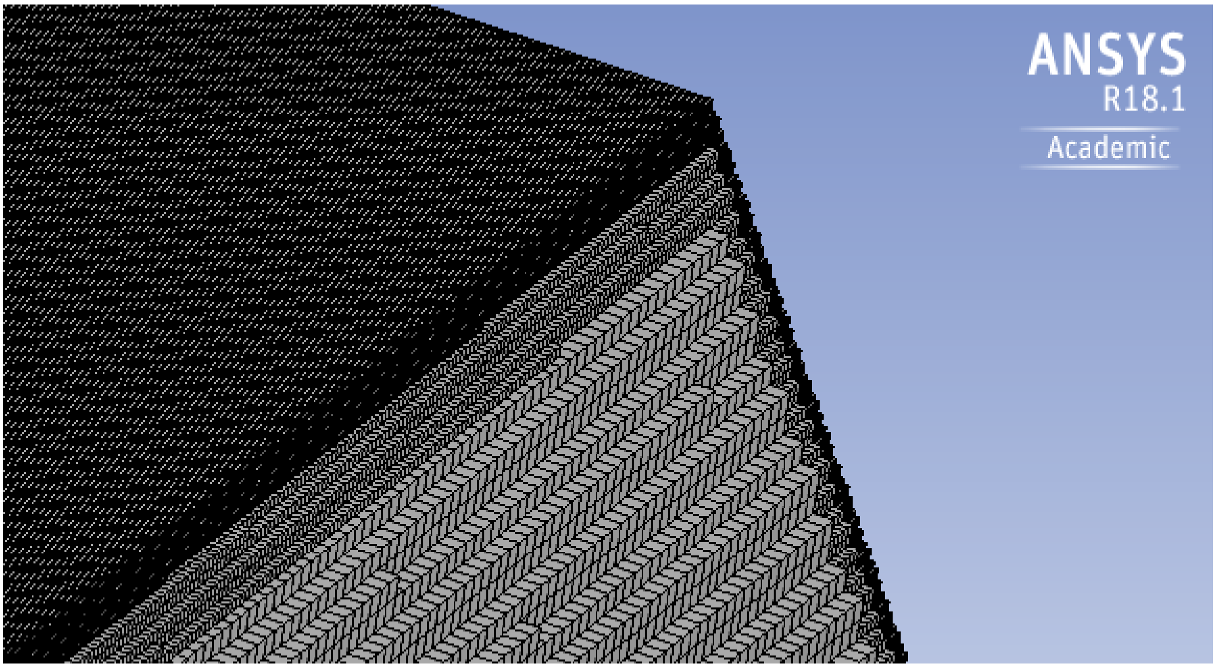


Figure 29:Cross section of geometry mesh

By visually examining the figure above, the mesh looks fine, without any noticeable/unwanted change in cell sizes or other deficiencies.

Next stage should be a more detailed one, by testing the grids validity; Aspect ratio, element quality and skewness. The tables below (Table 27-

Table 30) show max, min and average value of different mesh metrics of all four meshes (room scenarios).

Table 27: Mesh metric of room setup.0

Room setup.0 (empty room)			
Mesh Metric	Aspect Ratio	Element Quality	Skewness
Min	1,0052	0,28914	$1{,}3057e^{-10}$
Max	12,324	0,99999	0,8995
Average	1,0259	0,99804	$4{,}3797e^{-3}$

Table 28: Mesh metric of room setup.1

Room setup.1			
Mesh Metric	Aspect Ratio	Element Quality	Skewness
Min	1,0022	0,45936	$1{,}3057e^{-10}$
Max	4,5086	1,00000	0,79601

Average	1,0243	0,99713	$4{,}4963e^{-3}$

Table 29: Mesh metric of room setup.2

Room setup.2			
Mesh Metric	Aspect Ratio	Element Quality	Skewness
Min	1,0052	0,19268	$1{,}3057e^{-10}$
Max	12,324	0,99999	0,89591
Average	1,0243	0,9958	$4{,}4963e^{-3}$

Table 30: Mesh metric of room setup.3

Room setup.3			
Mesh Metric	Aspect Ratio	Element Quality	Skewness
Min	1,0052	0,28914	$1{,}3057e^{-10}$
Max	7,1511	0,99999	0,8995
Average	1,0358	0,99589	$3{,}8336e^{-3}$

Mesh metric test: [9] [10]

- Aspact ratio is recomended to be close to 1 (as ideal) cant be below the value of 1.
- Skewsness value can varey between 0-1 (0 concidered to be excellent, 1 degenerate)
- Element quality value of 1 is considerd to be “ideal”, 0 “unacceptable”.

6.3. Solution accuracy (convergence)

The figures below contain the residual scale (Continuity, X-velocity, Y-velocity, Z-velocity, Energy, K and epsilon) of each study (room scenario) on their own, as well as the number of iterations required to complete convergence.

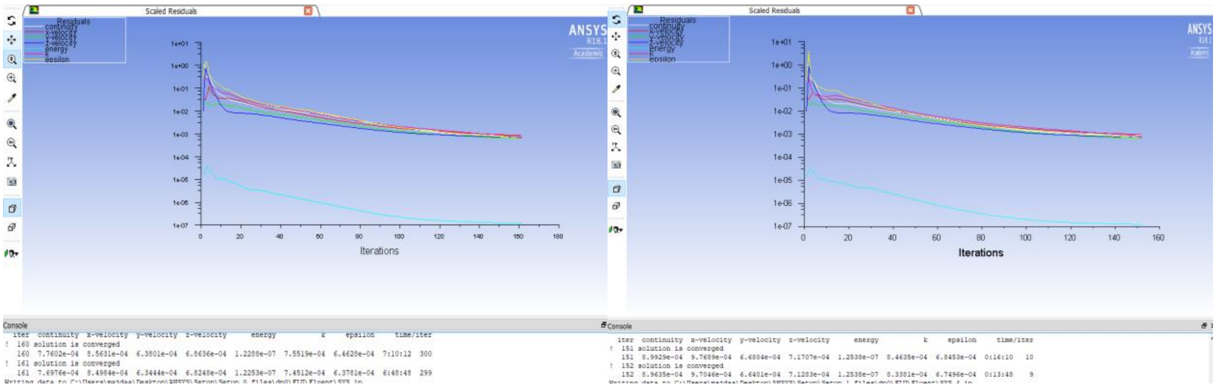


Figure 30: A) Scaled residuals for room setup.0 *B) Scaled Residuals for room setup.1*

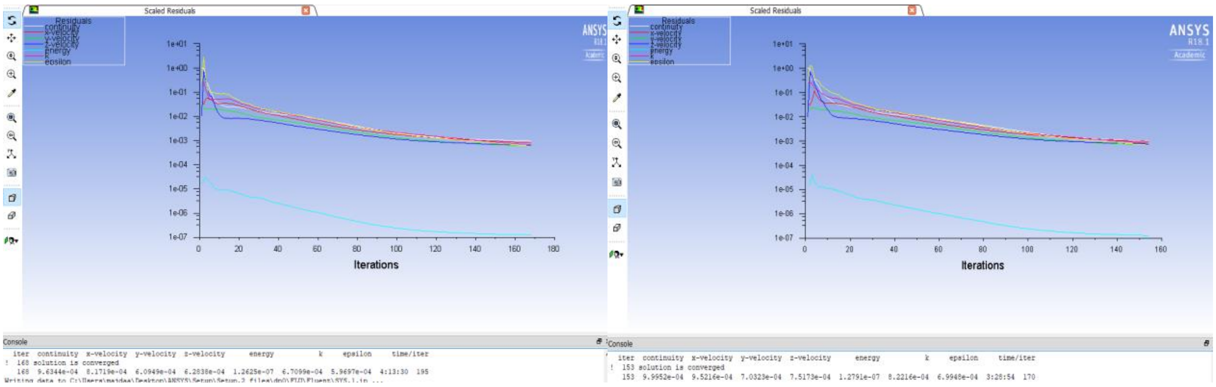


Figure 31: C) Scaled residuals for room setup.2 *D) Scaled residuals for room setup.3*

The residuals are clearly decreasing with number iterations, a healthy look for the results. The convergence happens to be completed between 150-200 iterations.

6.4. Manually measured results compared to simulated data:

Measured DATA: consist of the table below, that contans average temerature and air velocity recorded in the living room, at the four specific points/ locations. Air velocity given in [m/s], Temerature in both Kelvin [K] and Celisus [ºC].

Table 31: Measured Data for four different locations in the living room

Measured DATA			
Probing point:	**Velocity [m/s]**	**Kelvin [K]**	**Celisus [ºC]**
1. Window Opening	*0,70000*	*290,90*	*16,75*
2. Door Opening	*0,09250*	*294,46*	*20,31*
3. Mid. Point	*0,02833*	*294,12*	*19,97*
4. Point. X	*0,02167*	*294,96*	*20,81*

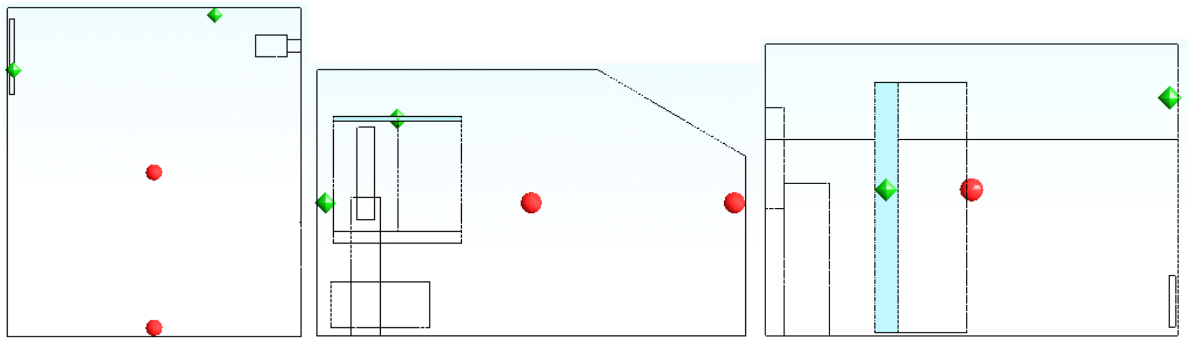


Figure 32: The four measured points represented in X, Y and Z view

The two points marked green represents the inlet and out let, while the other two are marked red and stand for mid. point and point. X.

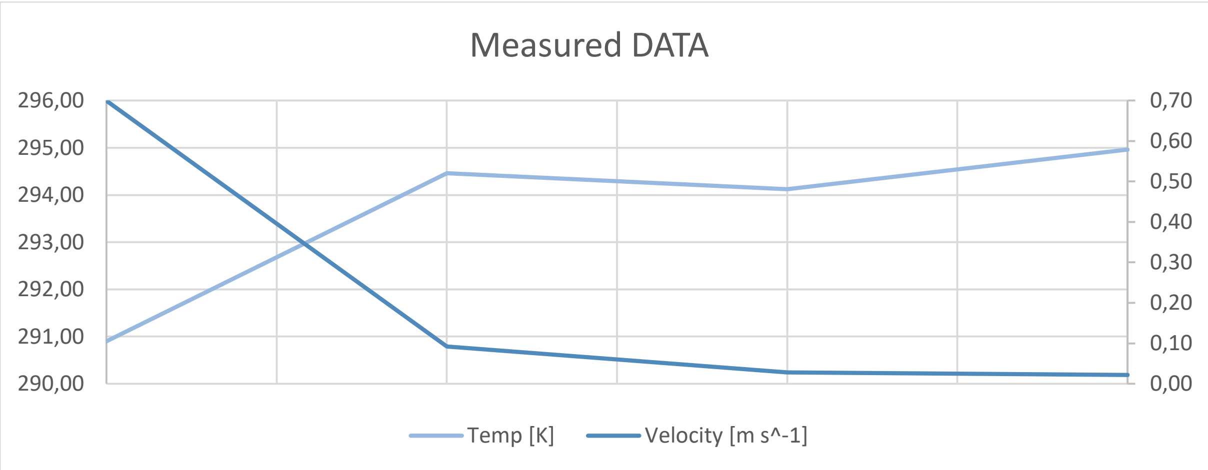


Figure 33: Chart representation of the data in Table 31

Some of these values where used as bases for the boundary conditions, later on will be used to describe program accuracy. By comparing this data to the values captured from all four different CFD-post files.

Simulated DATA: consist of four different furniture settings (CFD studies). Table 32 contains data from all four probing points according to the locations measured earlier.

Table 32: Room.setup.0. Temperature and air speed at the four selected points

Room.Setup.0	Velocity [m/s]	Kelvin [K]	Celisus [°C]
1. Window	0,7000000	290,90	16,75
2. Door	0,0863428	294,04	19,89
3. Mid. Point	0,0260691	293,44	19,29
4. Point. X	0,0241463	293,85	19,70

Table 33:Room.setup.1. Temperature and air speed at the four selected points

Room.Setup.1	Velocity [m/s]	Kelvin [K]	Celisus [°C]
1. Window	0,7000000	290,90	16,75
2. Door	0,0869158	294,15	20,00
3. Mid. Point	0,0262827	293,52	19,37
4. Point. X	0,0277373	293,83	19,68

Table 34: Room.setup.2. Temperature and air speed at the four selected points

Room.Setup.2	Velocity [m/s]	Kelvin [K]	Celisus [°C]
1. Window	0,7000000	290,90	16,75
2. Door	0,0831264	294,19	20,04
3. Mid. Point	0,0274213	293,58	19,43
4. Point. X	0,0258353	293,94	19,79

Table 35: Room.setup.3. Temperature and air speed at the four selected points

Room.Setup.3	Velocity [m/s]	Kelvin [K]	Celisus [°C]
1. Window	0,7000000	290,90	16,75
2. Door	0,0883447	293,99	19,84
3. Mid. Point	0,0304800	293,47	19,32
4. Point. X	0,0231700	293,90	19,75

Room.setup.0 contains none of the movable furniture, therefor is chosen as the reference point. By comparing it to the measured data, we are then able to judge air velocity and temperature accuracy in percent.

Table 36: Temperature and air velocity accuracy according to the simulation of Room.setup.0

Room.Setup.0	Velocity Accuracy	Temperature Accuracy
1. Window	100,00 %	100,00 %
2. Door	93,34 %	97,93 %
3. Mid. Point	92,02 %	96,57 %
4. Point. X	88,57 %	94,67 %

→ *A comparison between the measured data and the rest of the room settings are left out in appendix.*

6.5. Comparing Furniture Setting:

Once the mesh quality is checked, boundary conditions are fixed, and the convergence is completed for all four room settings, a comparison between them should be possible. This part of the project work contains a variety of methods (such as plane/volume) used to compare room settings to each other. Main concern is air velocity and temperature change inside the living room. This would potentially lead to an answer for how the furniture setup influence the air flow.

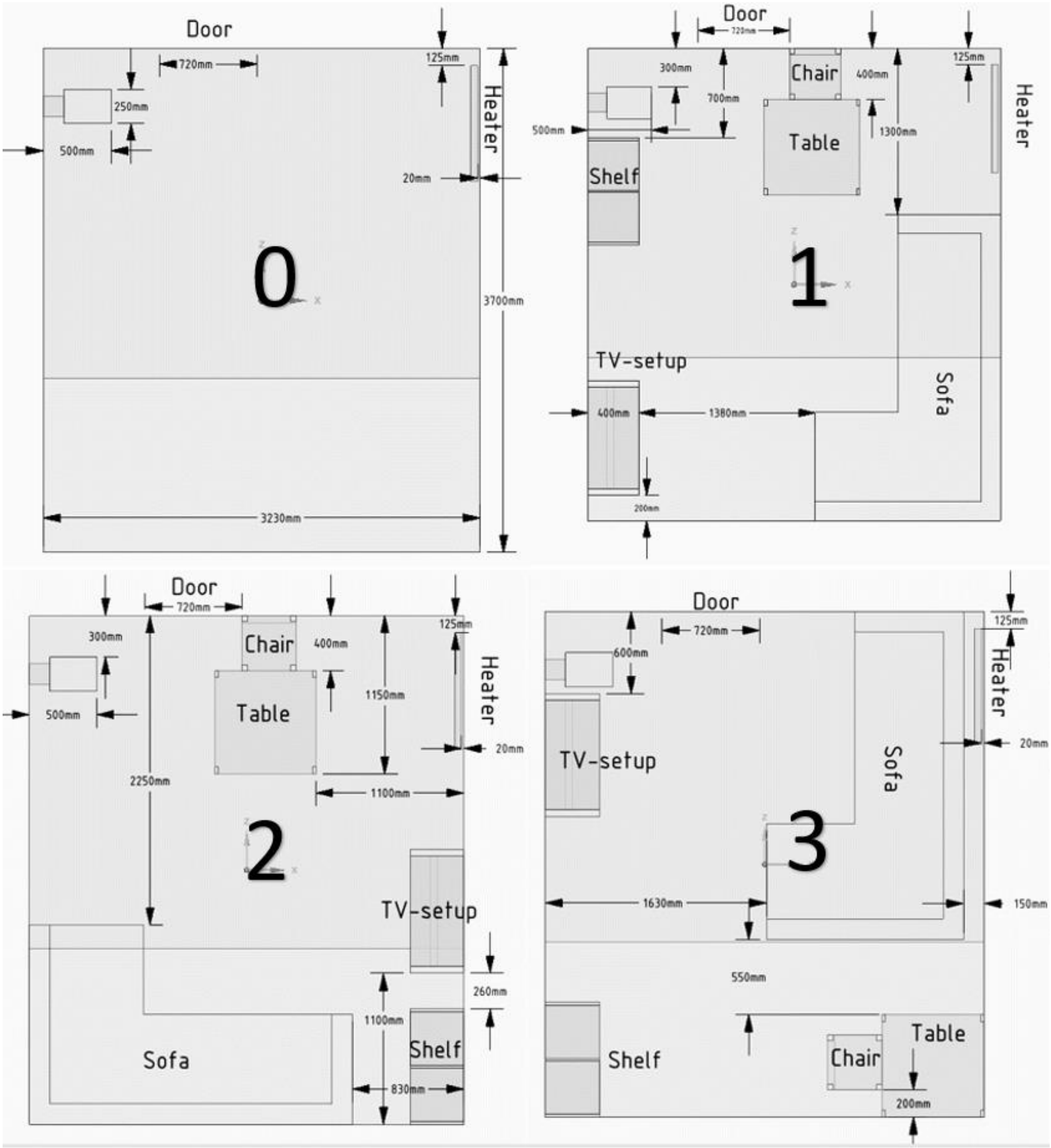


Figure 34: two-dimensional top view of each room setup. (0-3)

Figure 34 compares all four room scenarios together in terms of furniture placement. The window is located above the heater (not possible to see from this view).

Room scenario without furniture: Room.setup.0

Plane 1: Looking at the air velocity and temperature at plane 1 (1,15 m above floor, approximately human nose height while seated [65]), for room scenario 0:

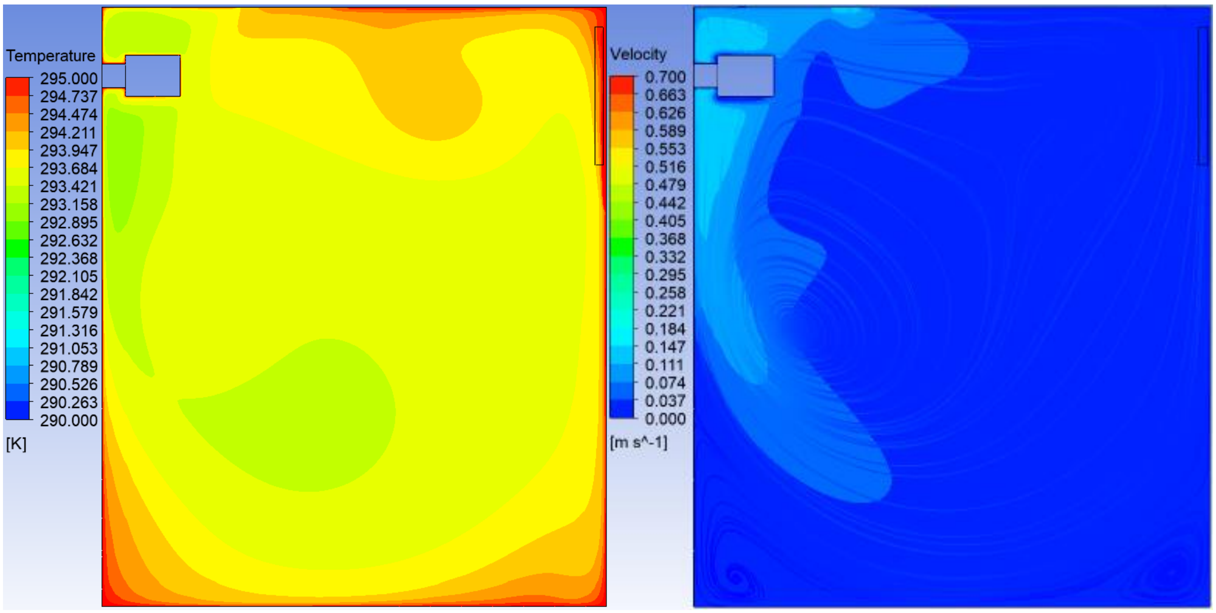


Figure 35: Temperature and Air Velocity at plane 1 (Room.setup.0)

The average temperature and velocity values at plane 1 are: 293,947 [K] (20,797 [°C]) and 0,03635 [m/s] respectively.

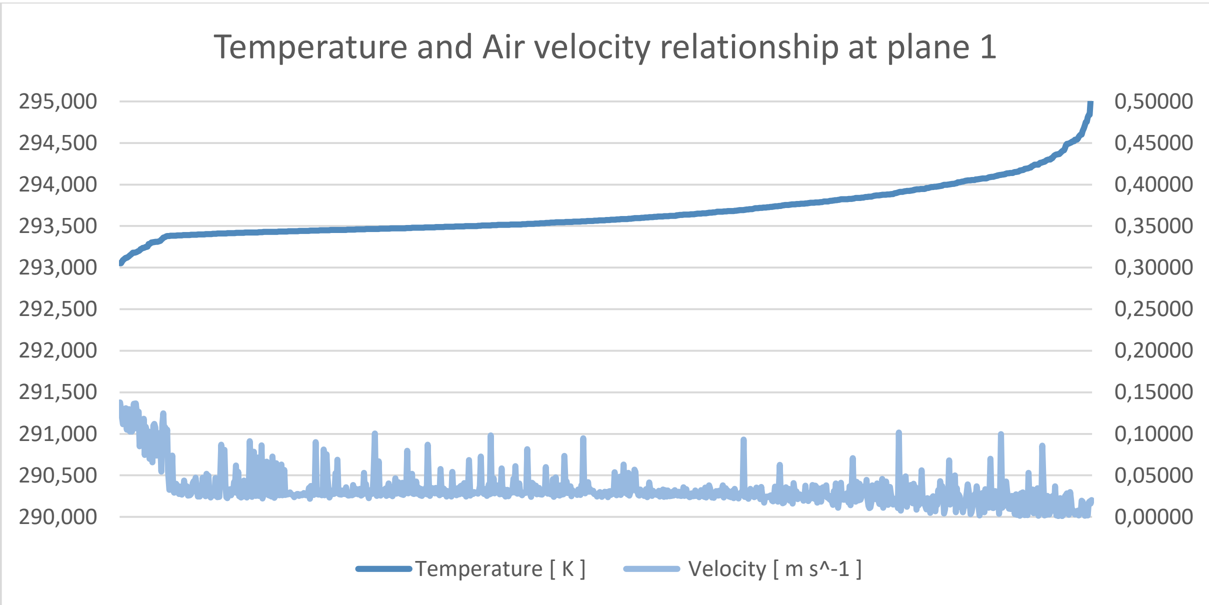


Figure 36: Relation between Temperature and Air velocity at plane 1 (Room.setup.0)

Figure 36 shows the relation between temperature and air velocity at plane 1.

Plane 2: Taking a look at the conditions across the centre of the window (inlet), showing temperature and air velocity at plane 2 (crossing through window and heater) in Figure 37.

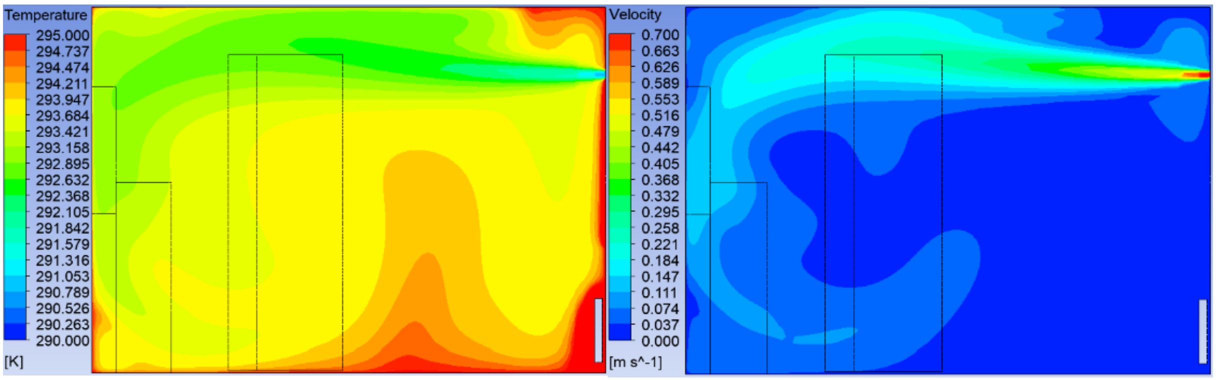


Figure 37: Temperature and Air Velocity at plane 2 (Room.setup.0)

Average temperature and velocity values at plane 2 are: 293,896 [K] (20,746 [°C]) and 0,06310 [m/s]. there is a massive difference in velocity between plane 1 and 2, but almost no change in average temperature, this is due to the heaters temperature.

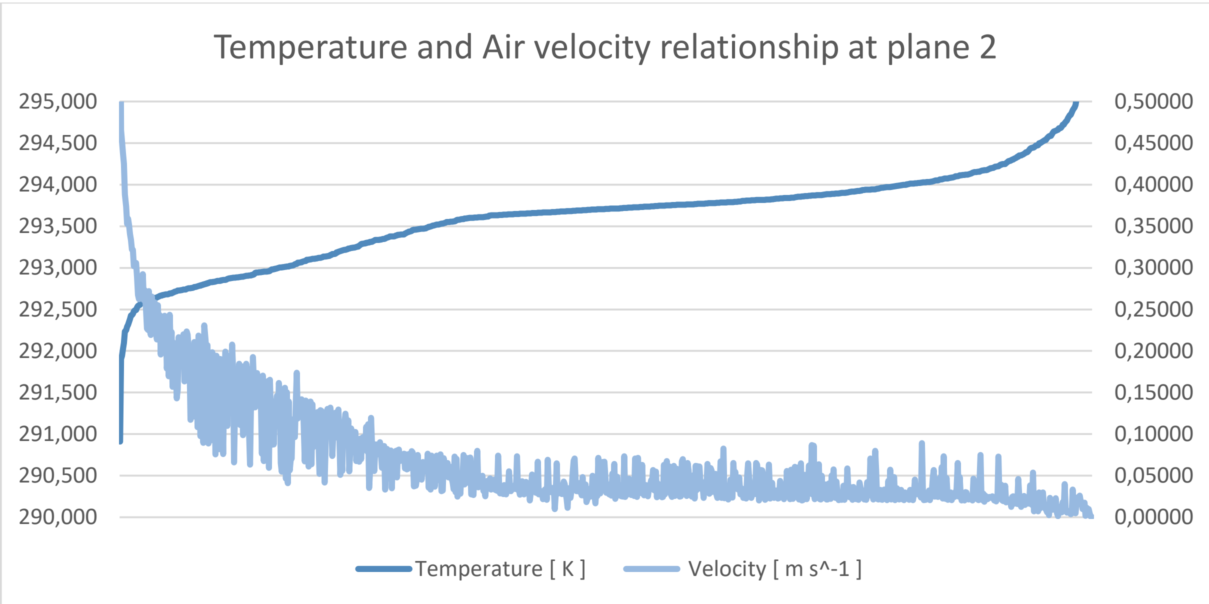


Figure 38: Relation between Temperature and Air velocity at plane 2 (Room.setup.0)

Figure 38 shows the relation between temperature and air velocity at plane 2.

Room scenarios with furniture: Comparing each scenario side by side. starting with:

Plane 1: temperature at plane 1 (1,15 m above floor, approximately human nose height while seated [65]). Room.setup.0 is also included as reference.

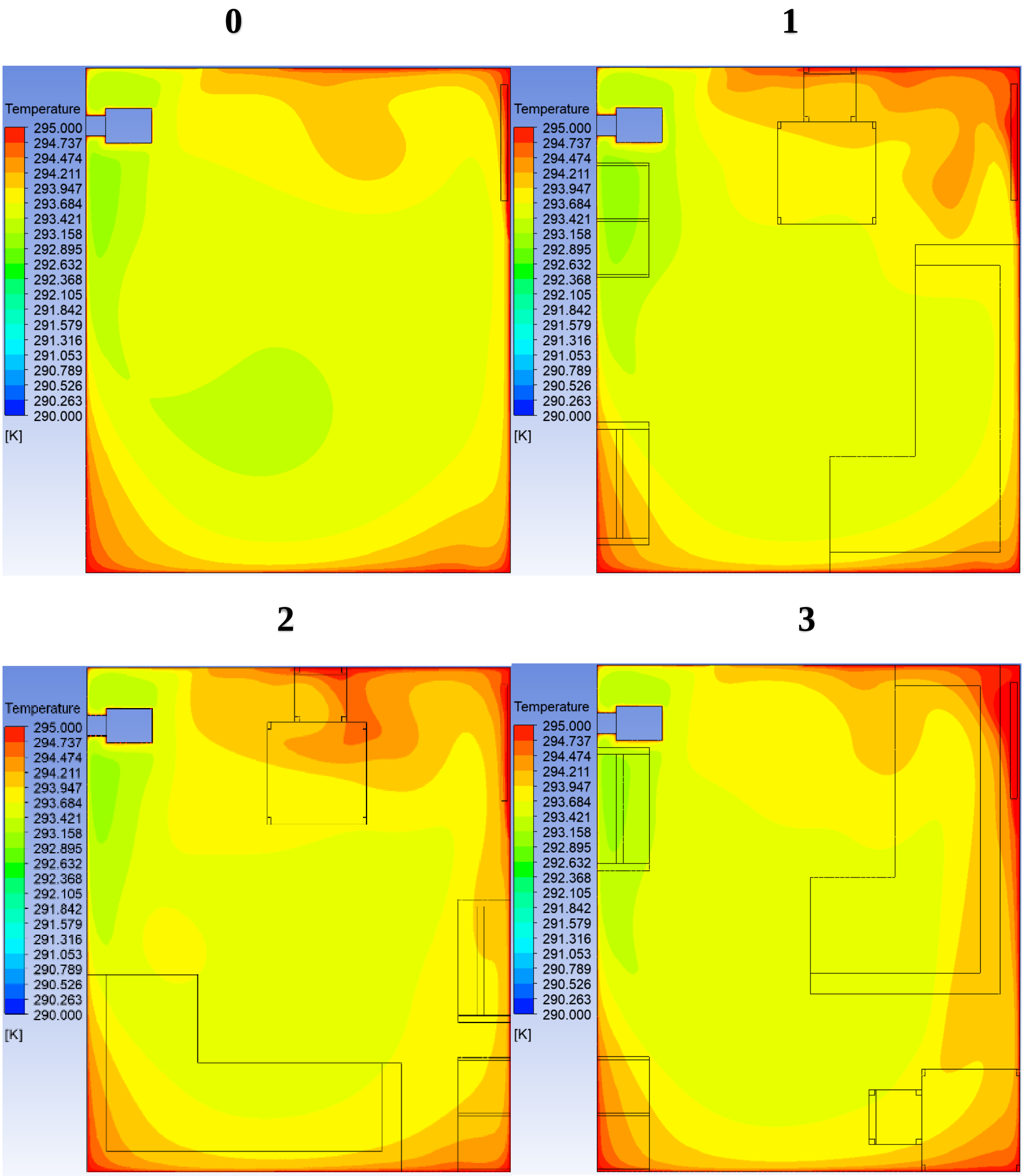


Figure 39: Temperature at plane 1 (all room scenarios)

Plane 1: Air velocity and streamlines across all four room scenarios:

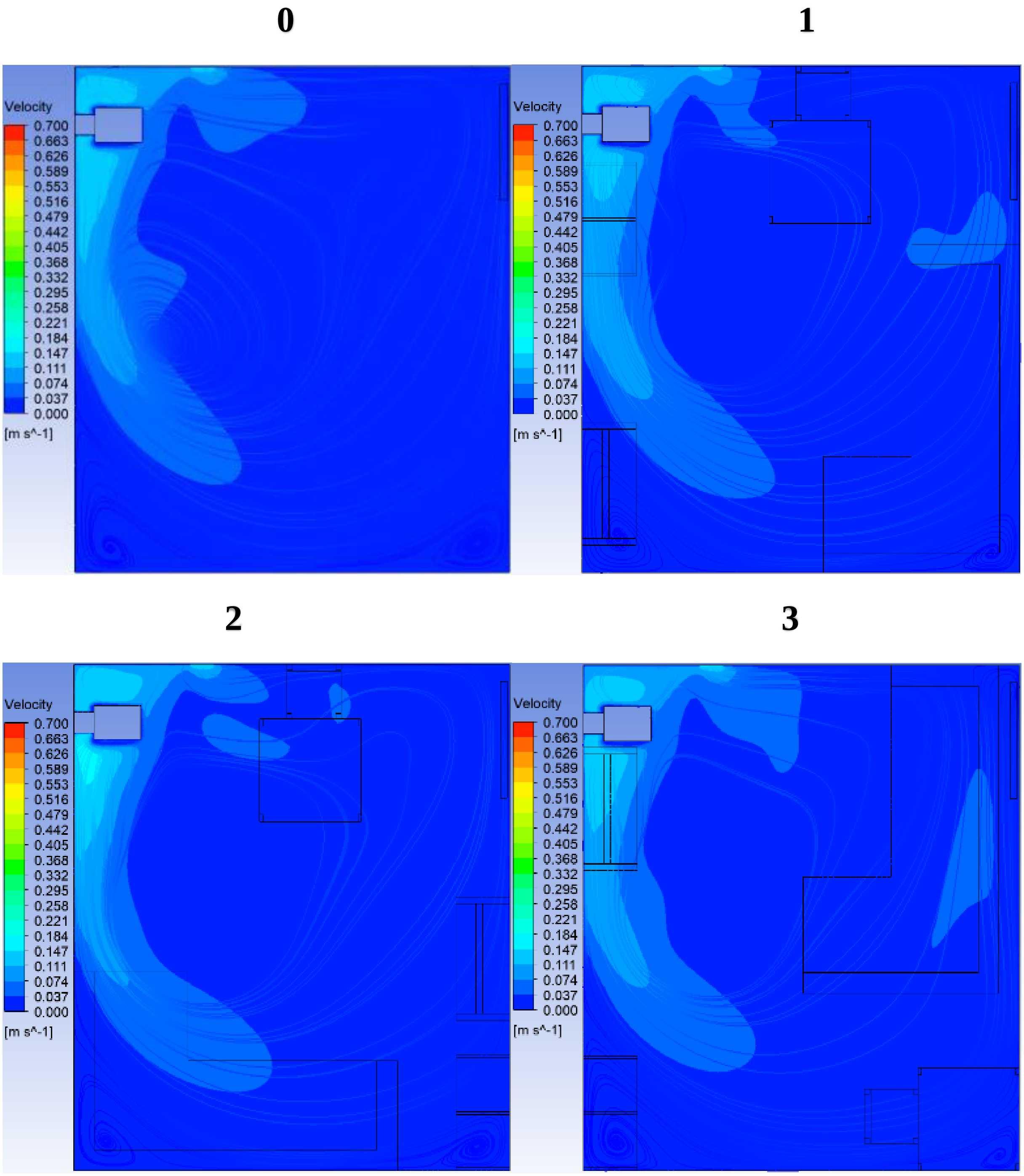


Figure 40: Air velocity at plane 1 (all room scenarios)

Average temperature and air velocity at plane 1 for each room scenario separately:

Table 37: Average temperature and air velocity at plane 1

Plane.1	**Temperature [K]**	**Velocity [m/s]**
Room setup 0	*293.947*	*0.03625*
Room setup 1	*293.995*	*0.03551*
Room setup 2	*294.042*	*0.03763*
Room setup 3	*294.057*	*0.03622*

Plane 2: Side by side comparison of temperature change for all four room scenarios at plane 2: (crossing through the window and the heater)

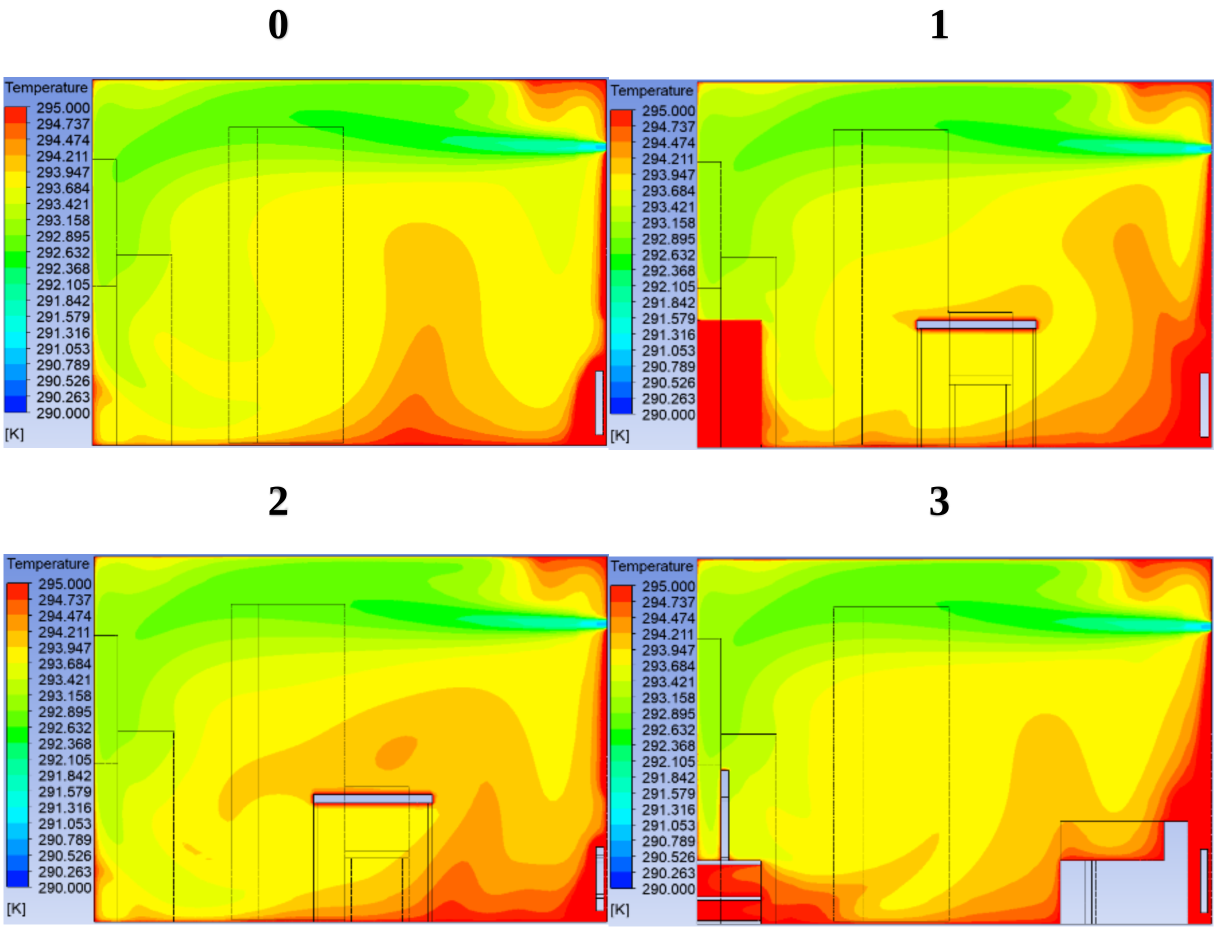


Figure 41: Temperature at plane 2 (all room scenarios)

plane 2: Air velocity across all four room scenarios.

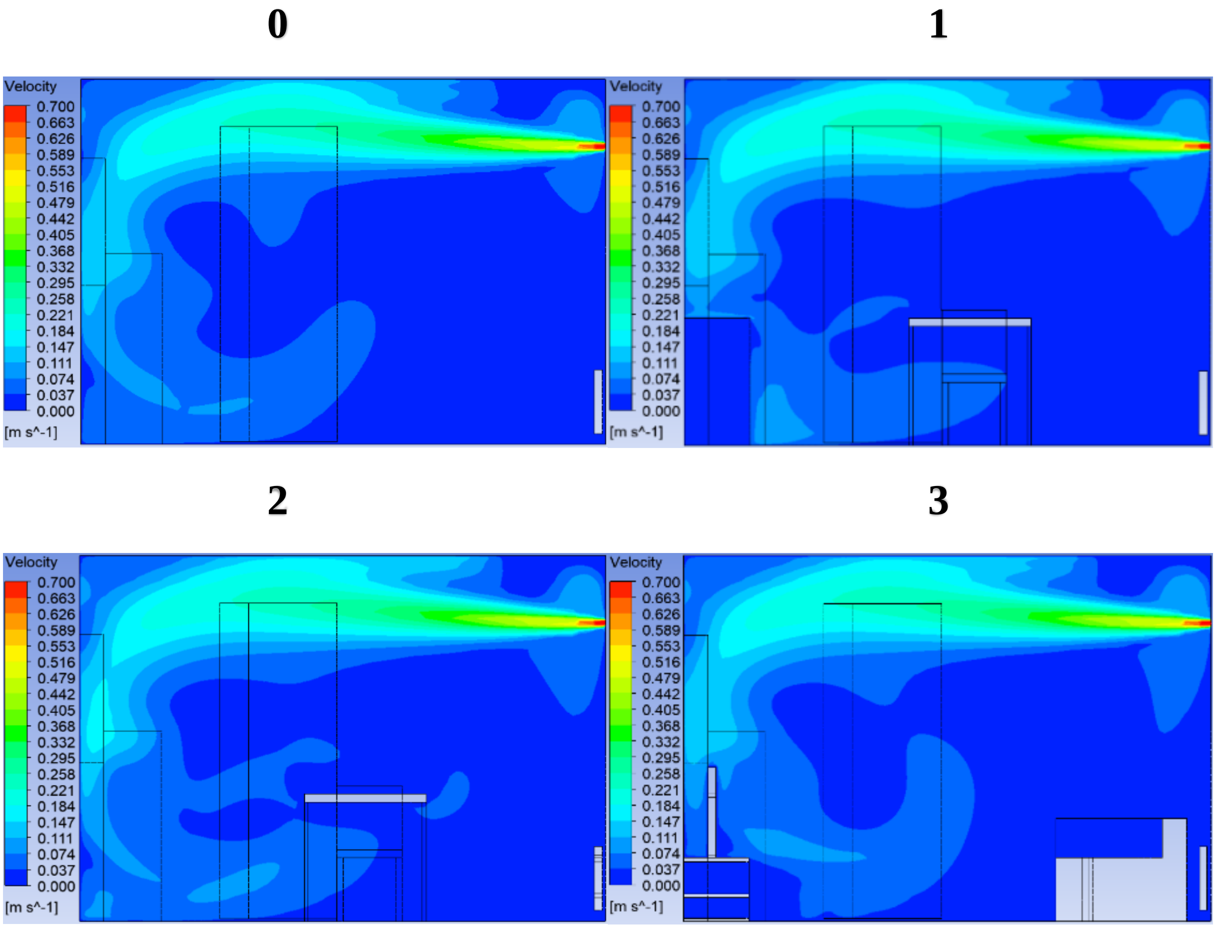


Figure 42: Air velocity at plane 2 (all room scenarios)

Average temperature and air velocity at plane 2 for each room scenario separately:

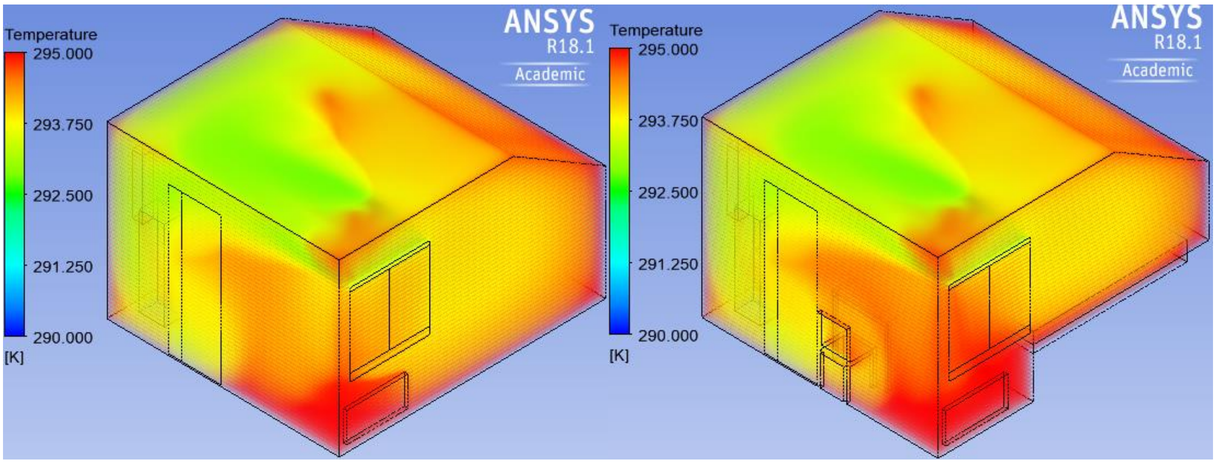
Table 38: Average temperature and air velocity at plane 2

Plane.2	**Temperature [K]**	**Velocity [m/s]**
Room setup 0	*293.896*	*0.0631*
Room setup 1	*294.049*	*0.0603*
Room setup 2	*293.944*	*0.0681*
Room setup 3	*294.189*	*0.0648*

Air volume observation:

For a different perspective of how the room indoor environment looks like, the figure below contains a three-dimensional view of the room temperature change; scaled from 290K to 295K.

0 **1**



2 **3**

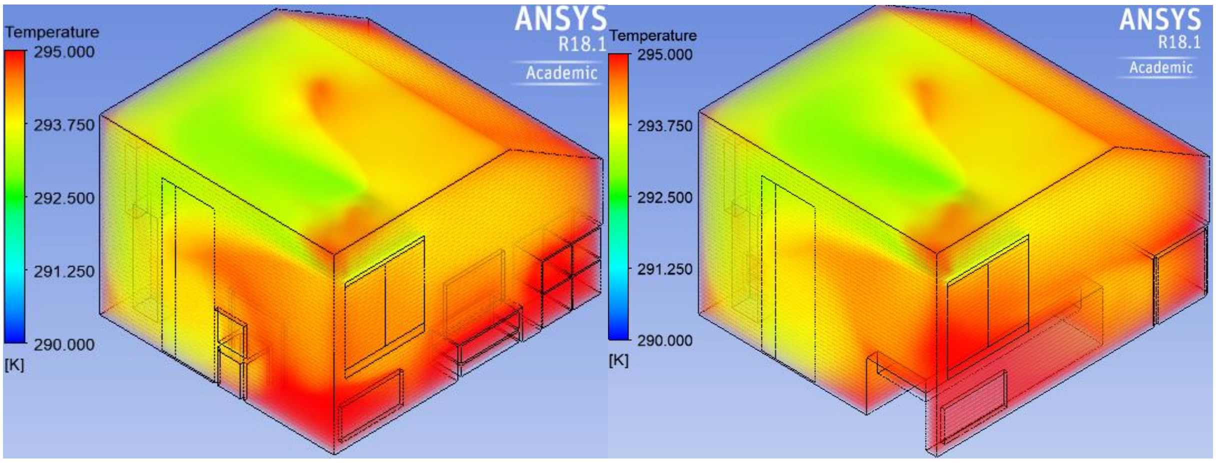


Figure 43: Three-dimensional view of the temperature change (for all four room scenarios)

Table 39 consist of the total room volume, total temperature volume between 20-22 [°C] (293,15-295,15 [K]) of each scenario, giving a better description of the air quality.

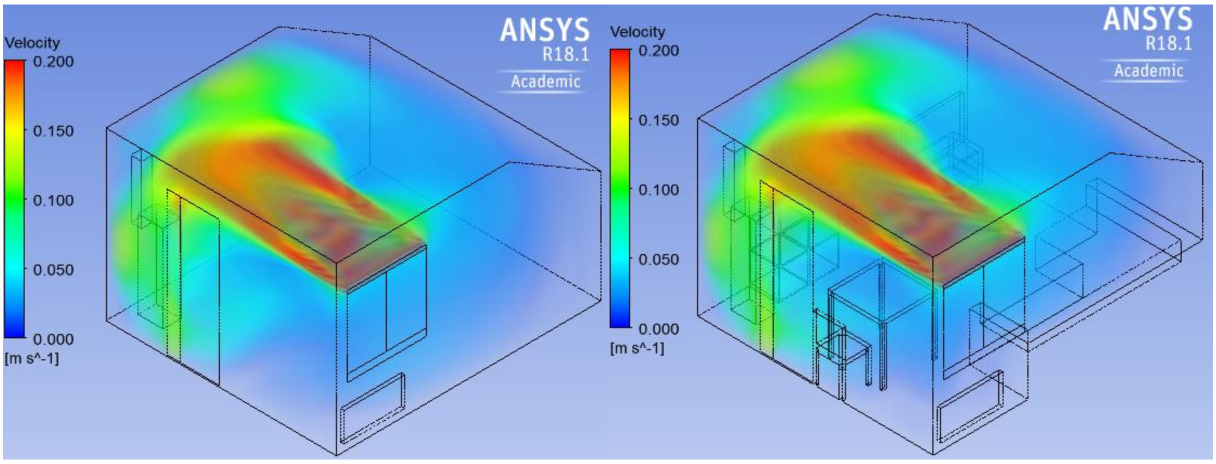
Table 39: Percentage of the temperature falling between 20-22 [°C]

	Volume [m^3]	Temperature between 20-22 °C	In percent [%]
Room.Setup.0	*25,797*	*23,362* m^3	*90,56*
Room.Setup.1	*24,494*	*21,980* m^3	*89,74*
Room.Setup.2	*24,494*	*22,153* m^3	*90,44*
Room.Setup.3	*24,494*	*22,139* m^3	*90,39*

Air volume observation:

Three-dimensional view of the room air velocity change; scaled from 0,00 to 0,20 m/s.

0 **1**



2 **1**

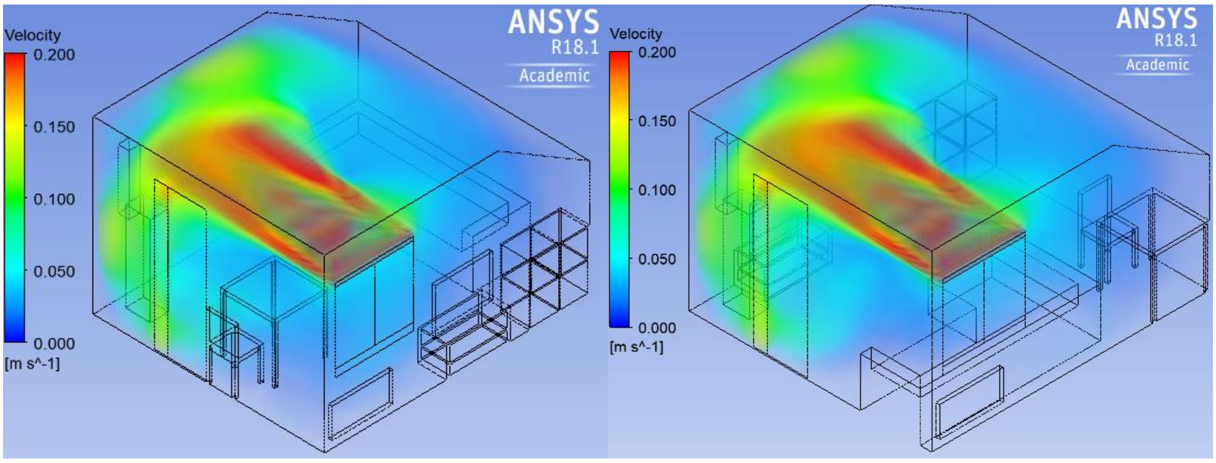


Figure 44: Three-dimensional view of the air velocity change (for all four room scenarios)

Percentage of areas with low velocity are presented in Table 40. Selected two values close to stationary; velocity below 0,01 [m/s] and velocity below 0,02 [m/s].

Table 40: Percentage of the velocity found below 0,01 [m/s] and 0,02 [m/s].

	Volume [m^3]	Below 0,01m/s	[%]	Below 0,02m/s	[%]
Room.Setup.0	*25,797*	*1,729* m^3	*6,70 %*	*4,228* m^3	*16,39*
Room.Setup.1	*24,494*	*2,315* m^3	*9,45 %*	*4,765* m^3	*19,45*
Room.Setup.2	*24,494*	*1,884* m^3	*7,69 %*	*4,035* m^3	*16,48*
Room.Setup.3	*24,494*	*2,351* m^3	*9,60 %*	*5,218* m^3	*21,31*

Occupant movement in selected living room:

Results of the body movement in different room setups, presenting all the pathways taken by the occupant during the trial (With the help of Microsoft Kinect).

Room setup.1: Temperature at all recorded nodes

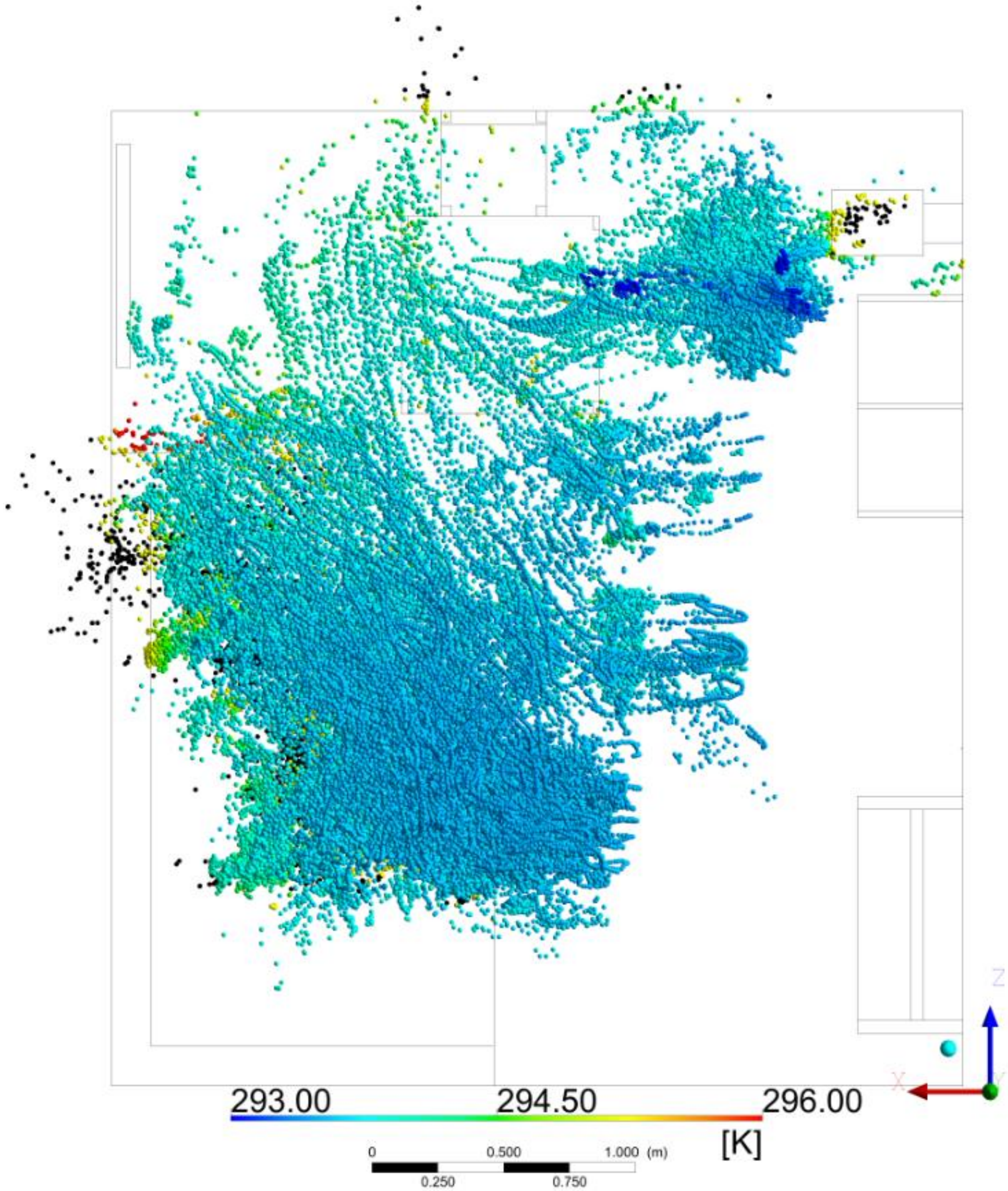


Figure 45: Temperature at all recorded nodes, room.setup.1

→ *The black points in the figure are trail mismatches; it's a low amount and shouldn't be an issue.*

Room setup.2: Temperature at all recorded nodes

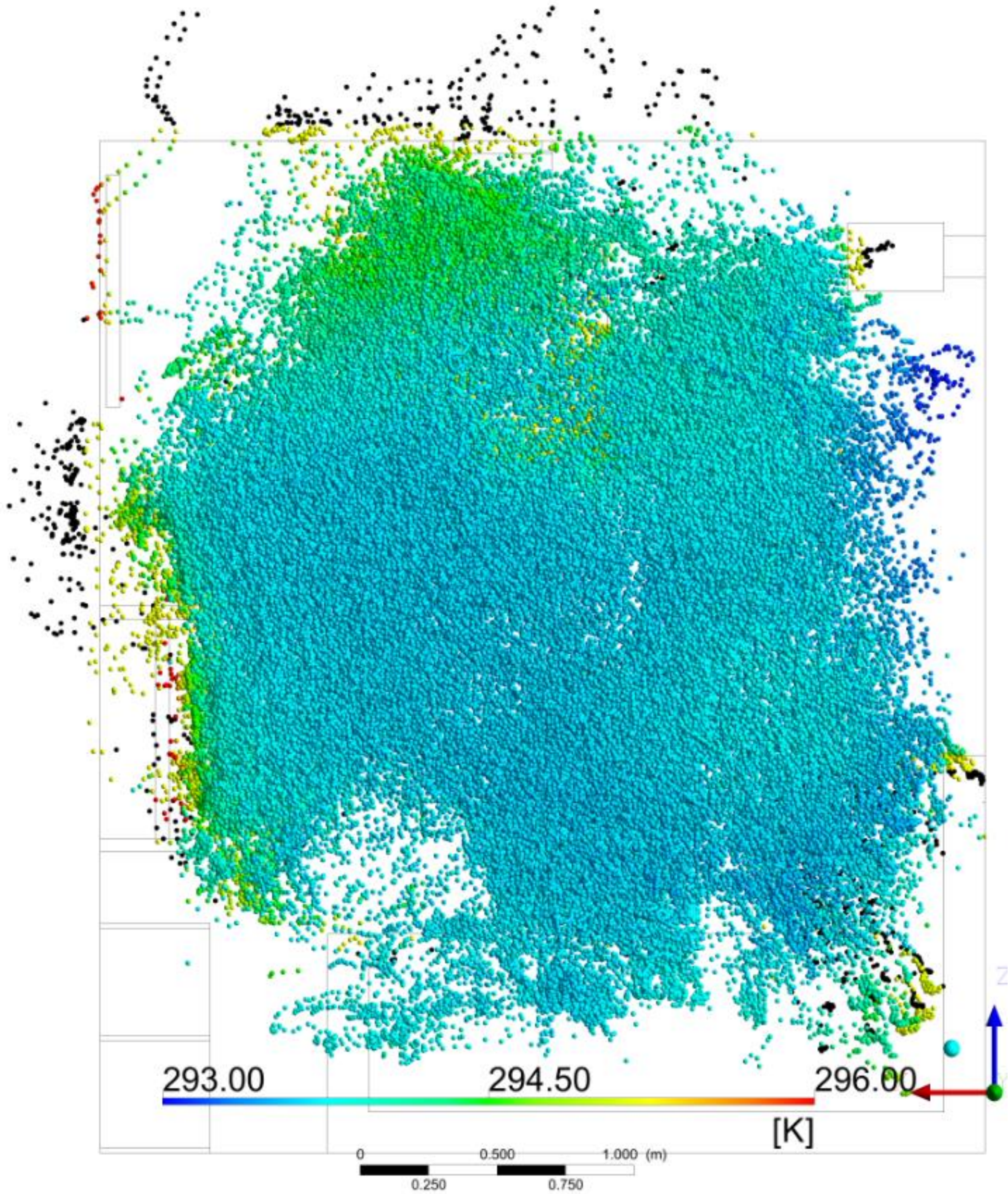


Figure 46: Temperature at all recorded nodes, room.setup.2

Room stup.3: Temperature at all recorded nodes

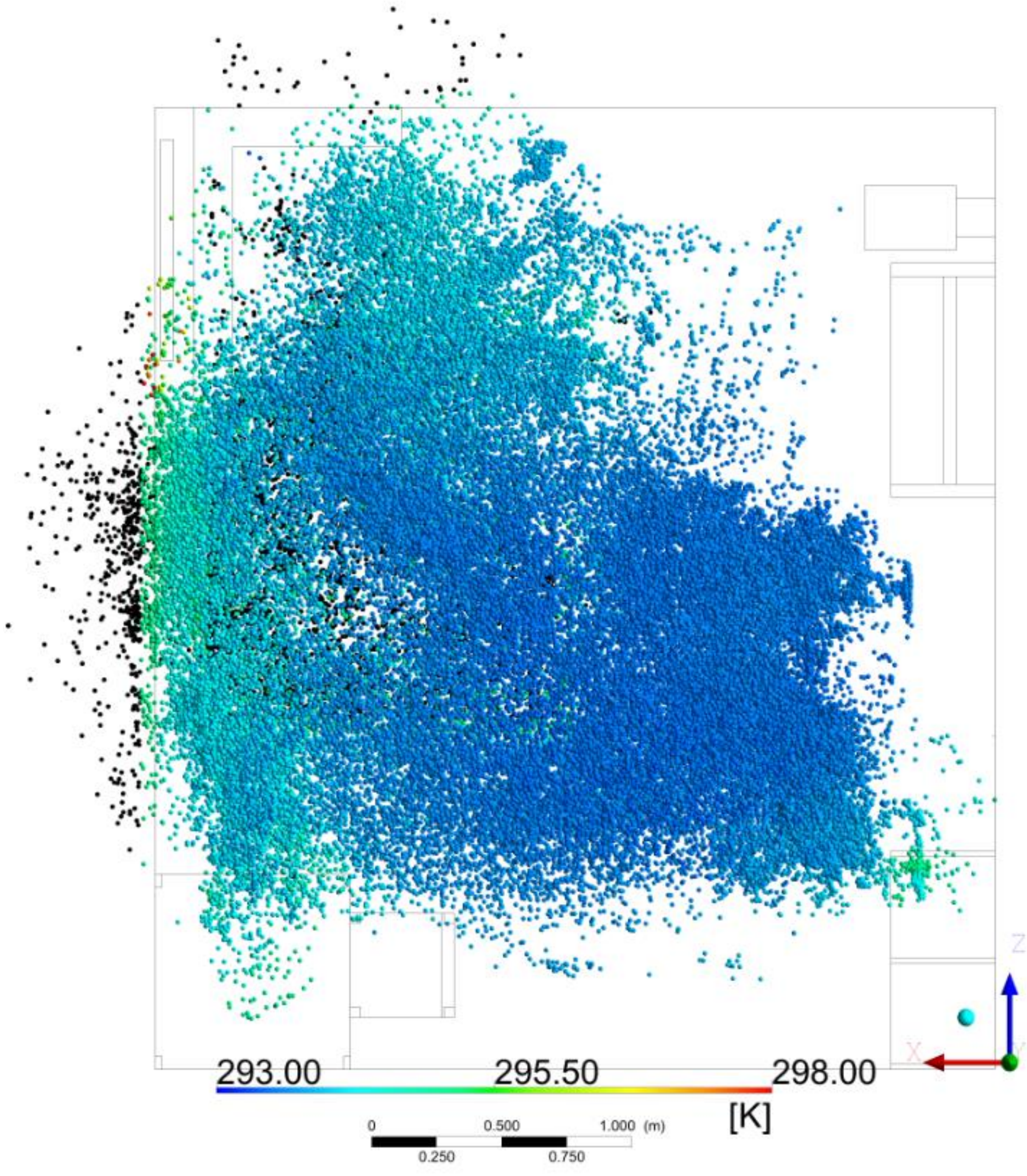


Figure 47: Temperature at all recorded nodes, room.setup.3

Room setup.1: Air velocity at all recorded nodes scaled from 0,00-0,20 [m/s]

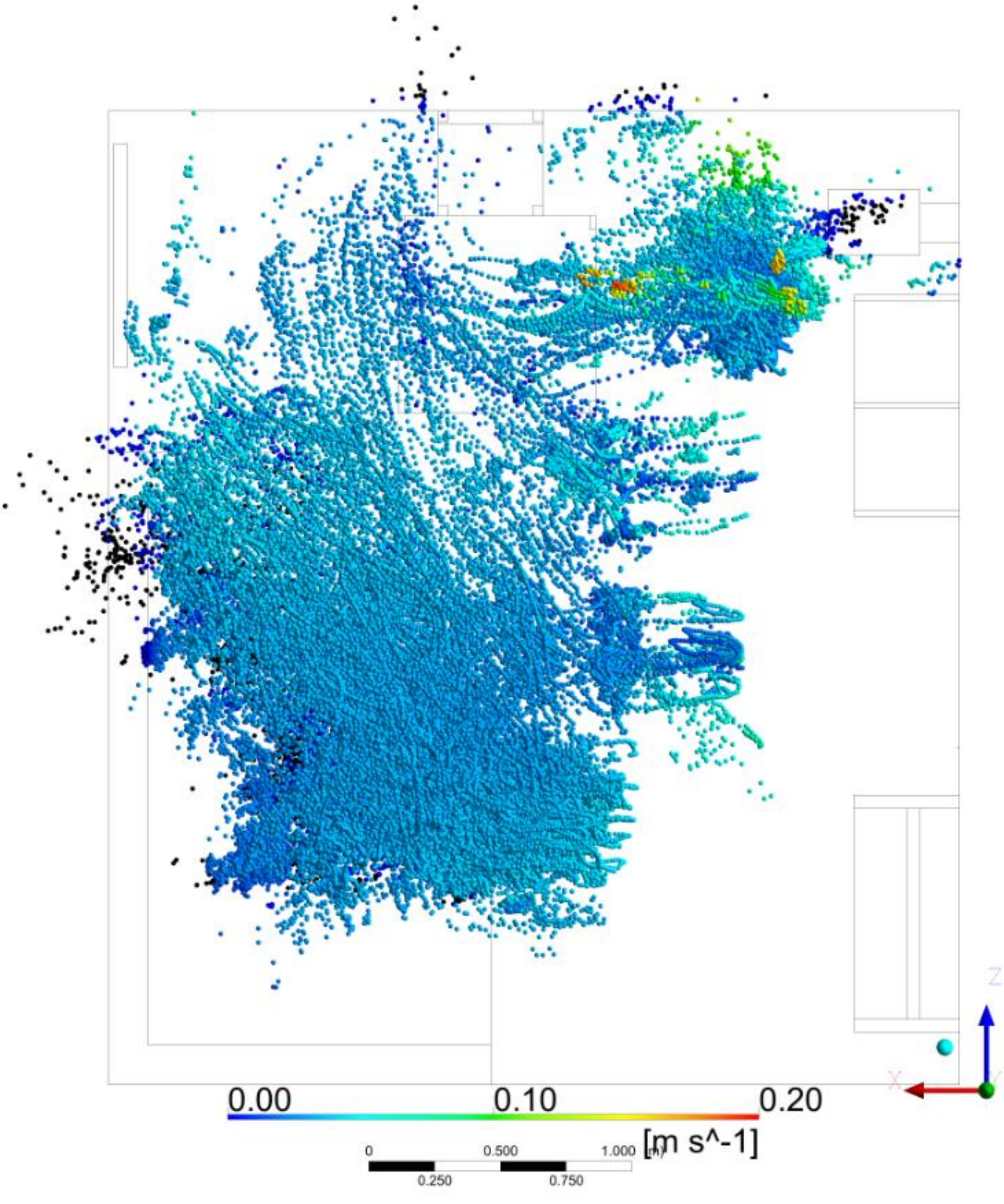


Figure 48: Air velocity at all recorded nodes, room.setup.1

Room setup.2: Air velocity at all recorded nodes

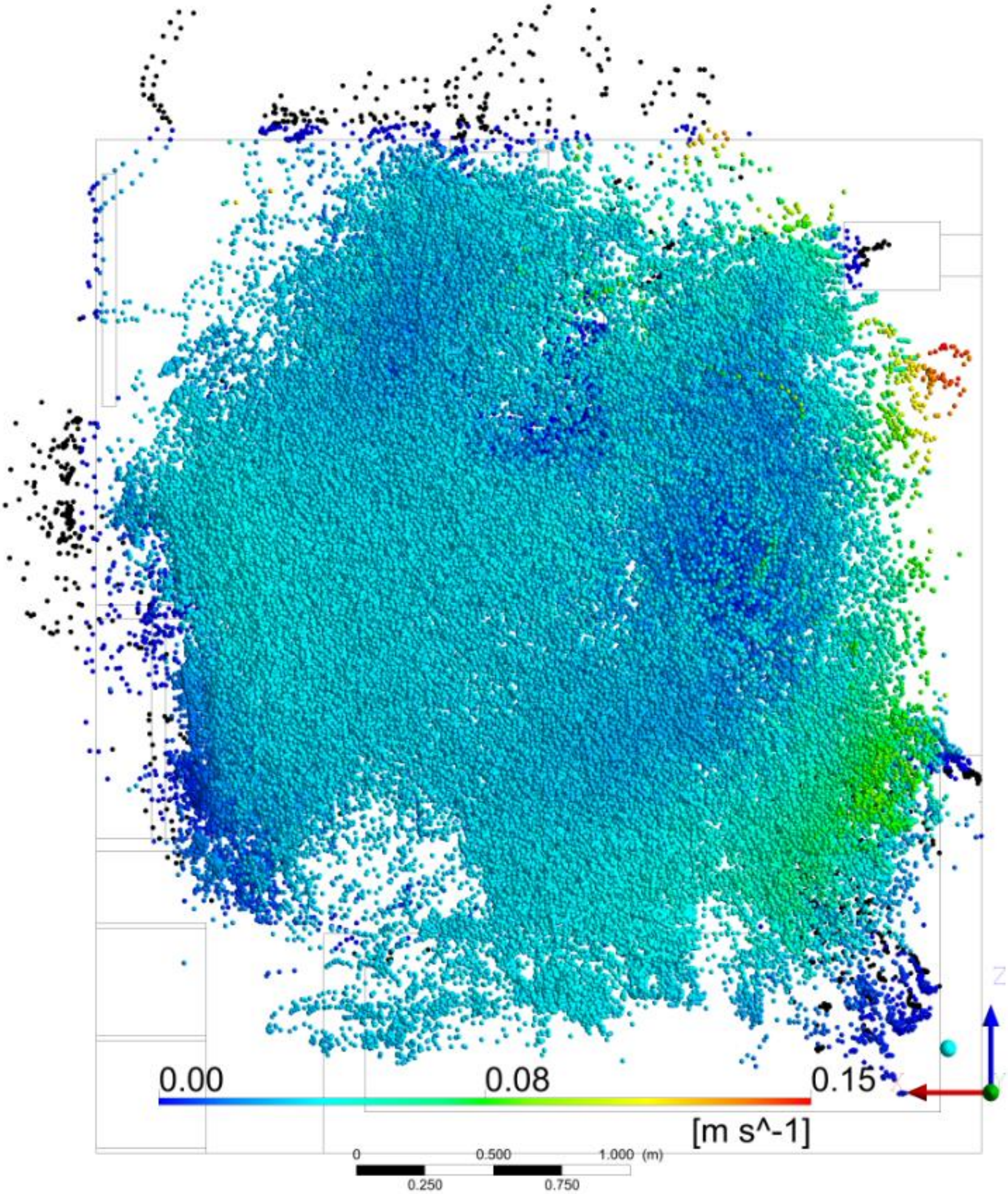


Figure 49: Air velocity at all recorded nodes, room.setup.2

Room setup.3: Air velocity at all recorded nodes

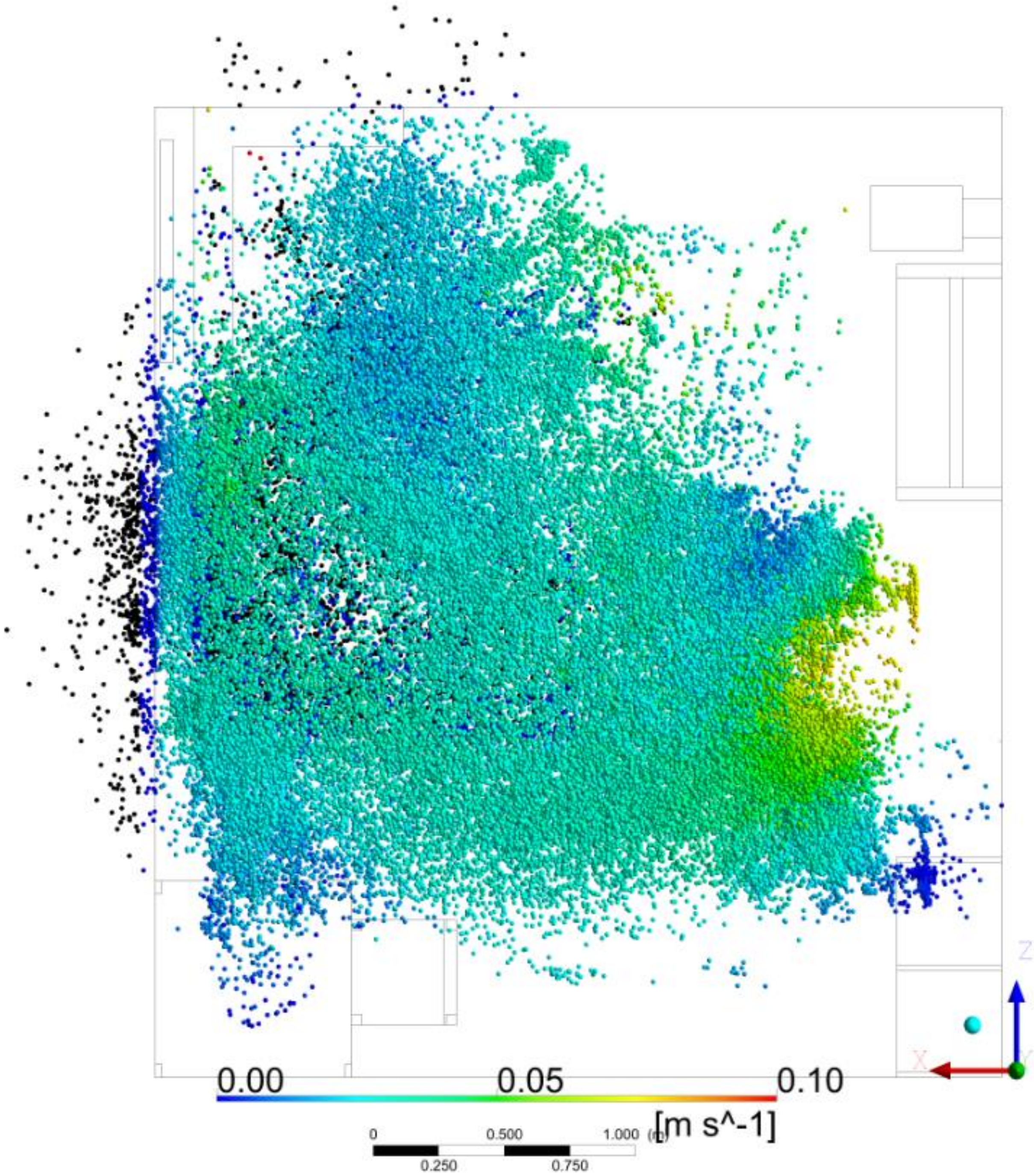


Figure 50: Air velocity at all recorded nodes, room.setup.3

→ *Similar figures for X and Z view are added into appendix*

Temperature change for spine and head (Node 1 and 4:): X axis: temperature Y axis: time. The orange line represents spine (Node 1), while the blue line represents the head (Node 4)

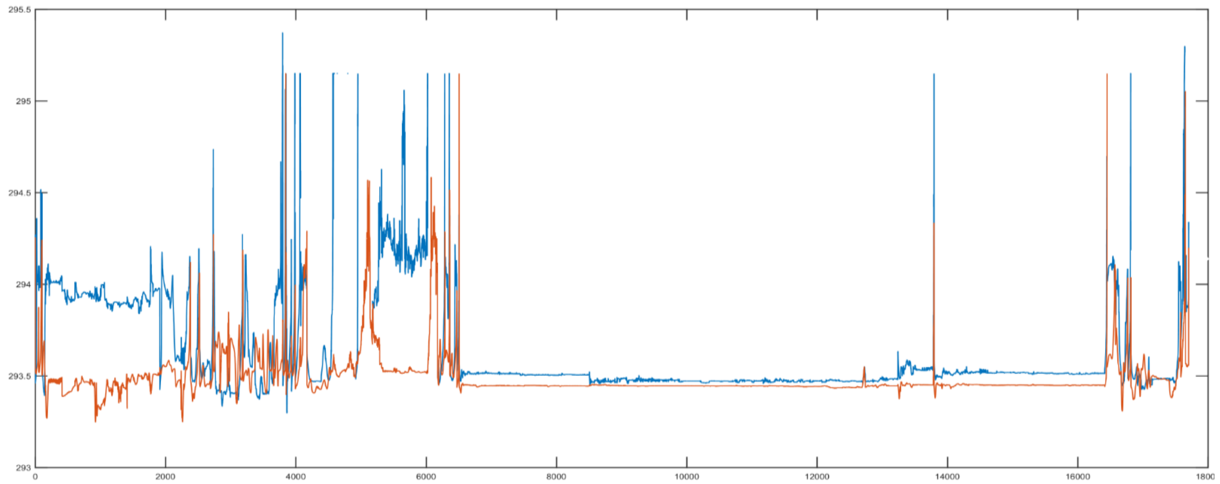


Figure 51: Temperature at node 1 and 4 (Room.setup.1)

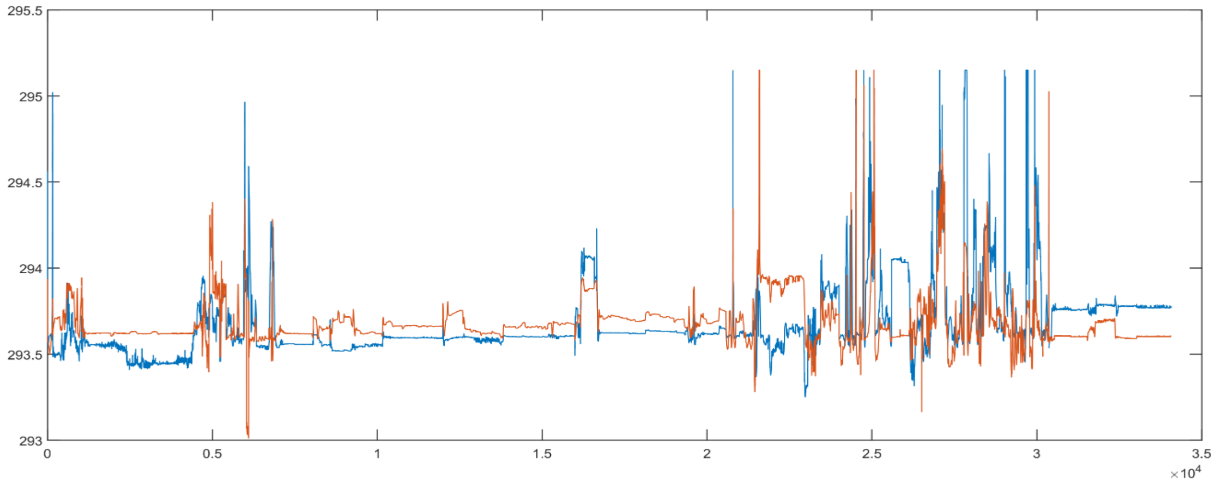


Figure 52: Temperature at node 1 and 4 (Room.setup.2)

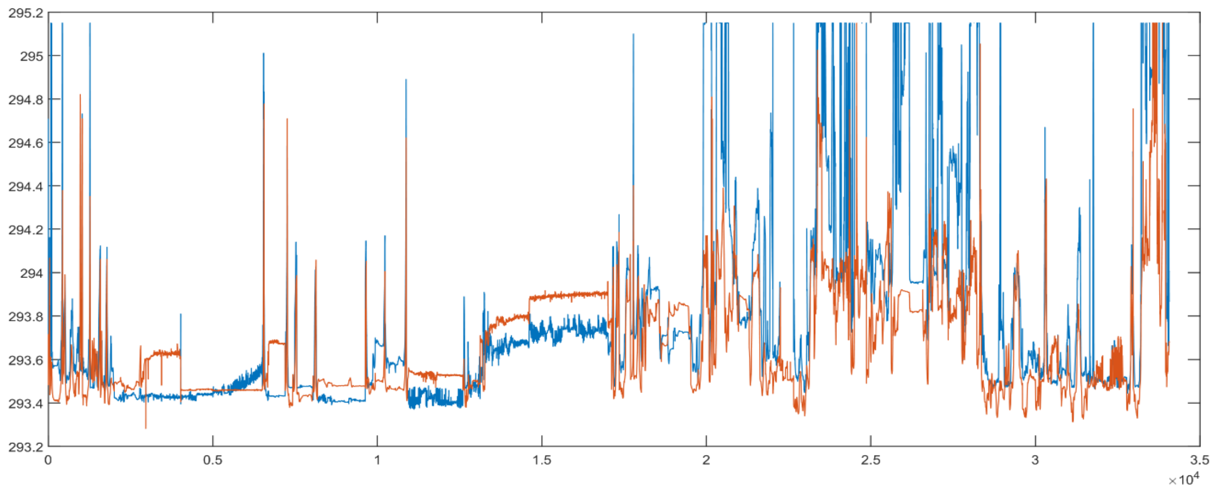


Figure 53: Temperature at node 1 and 4 (Room.setup.3)

Air velocity recorded for spine and head (Node 1 and 4:): X axis: Velocity Y axis: time.

The orange line represents spine (Node 1), while the blue line represents the head (Node 4)

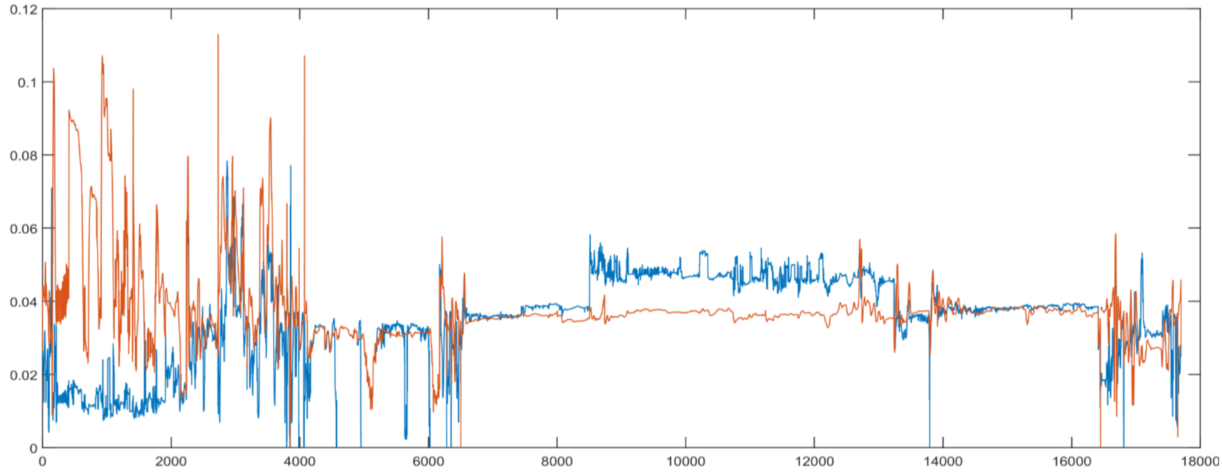


Figure 54: Velocity at node 1 and 4 (Room.setup.1)

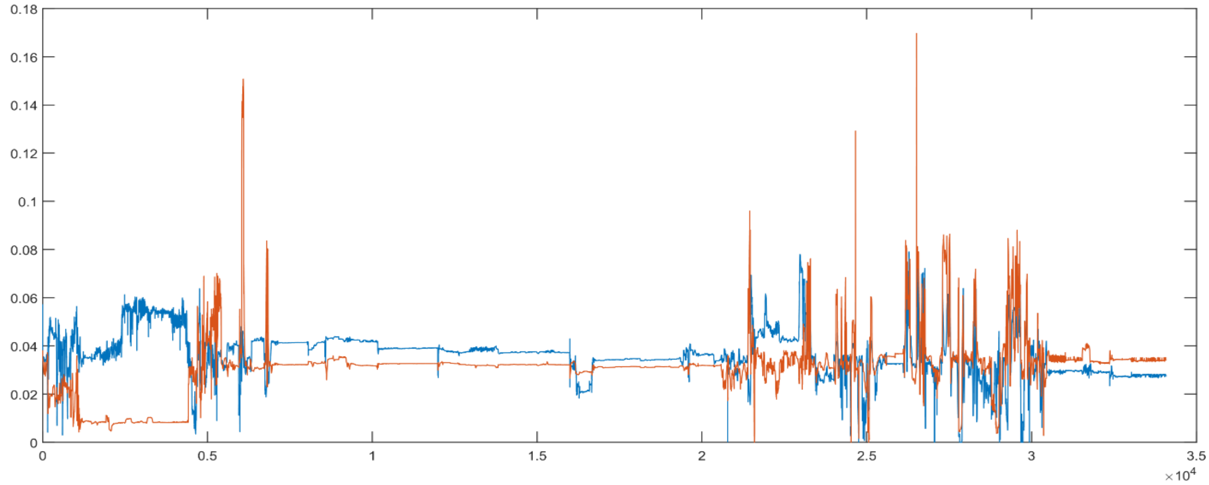


Figure 55: Velocity at node 1 and 4 (Room.setup.2)

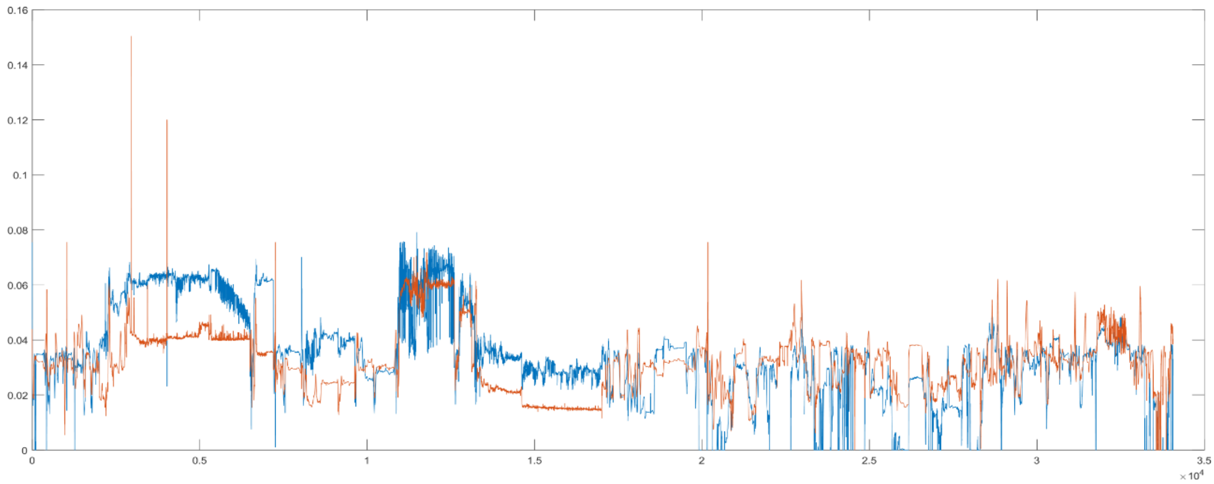


Figure 56: Velocity at node 1 and 4 (Room.setup.3)

7. Analysis and discussion:

This chapter will analyse some of the results derived from the preview chapters, in addition to some comments along the way. Mainly analysing simulation errors and assessing the impact furniture setting has on the occupant and their surroundings.

7.1. Mesh method and quality:

The assembly meshing algorithm used for this project is “CutCell”, providing a hexahedral dominant image of the grid. In addition to face sizing, specifically around the geometry walls (to increase the number of cells at interesting areas such as walls, window, door and heater). The mesh quality is hard to judge at first glance. Figure 29 demonstrate this by showing a random cross-section of the mesh without any noticeable/unwanted change in cell sizes or other deficiencies. Hence, it’s necessary to go through the mesh metric data provided in Table 27-

Table 30 to actually evaluate the Mesh validity;

Table 41: average mesh metric values; Aspect Ratio, Element Quality and Skewness

	Aspect Ratio	**Element Quality**	**Skewness**
Room.setup.0	*1,0259*	*0,99804*	*4,3797e^{-3}*
Room.setup.1	*1,0243*	*0,99713*	*4,4963e^{-3}*
Room.setup.2	*1,0243*	*0,99580*	*4,4963e^{-3}*
Room.setup.3	*1,0358*	*0,99589*	*3,8336e^{-3}*

Table 41 imclued the average value of the Aspect ratio, Element Quality and Skewness for all four room scenarios. Tested accordingly:

- Aspact ratio recomended to be close to 1 (as ideal) cant be below the value of 1. All four meshes manegade to come as close as 1,0259-1,0358 in average.
- Skewsness value can varey between 0-1 (0 concidered to be excellent, 1 degenerate according to ANSYS,Bakker). The average skewness acrooss all four scenarios hit close to 0 (X*e^{-3}).
- Element quality could be also interesting when evaluating a mesh quality, where the value of 1 is considerd to be “ideal”, 0 “unacceptable”. All four scenarios arrived at an average of 0,99.

Judging of the average value of the Aspect ratio, Element Quality and Skewness, and the standards mentioned in ANSYS help guide and Bakker website [9] [10], this is considered to be an acceptable result, even though there still is place for improvement, as the Aspect ratio hit 12 at some cells, and the skewness as high as 0,8.

7.2. Convergence:

CFD convergence should be tested by examining the residual values, as it has a massive influence on the outcome (results). The point of convergence expresses the level of accuracy the problem been solved at. A healthy setup would lead to a continuous decline in residual value, depending on the number of iteration, and is considered completed (acceptable) once all residuals hit a value of at least three order of magnitude (10^{-3}), while the scaled energy residual hits about $x * 10^{-3}$. Table 42 contains the residual data taken from Figure 30 and Figure 31, found in the previews chapter.

Table 42: Collected residual data for all four room scenarios

Residuals	**Room setup.0**	**Room setup.1**	**Room setup.2**	**Room setup.3**
Iterations	*161*	*152*	*168*	*153*
Continuity	$7{,}69*10^{-4}$	$8{,}96*10^{-4}$	$9{,}63*10^{-4}$	$9{,}99*10^{-4}$
X-velocity	$8{,}49*10^{-4}$	$9{,}70*10^{-4}$	$8{,}17*10^{-4}$	$9{,}52*10^{-4}$
Y-velocity	$6{,}34*10^{-4}$	$6{,}64*10^{-4}$	$6{,}09*10^{-4}$	$7{,}03*10^{-4}$
Z-velocity	$6{,}82*10^{-4}$	$7{,}12*10^{-4}$	$6{,}28*10^{-4}$	$7{,}5*10^{-4}$
Energy	$1{,}22*10^{-7}$	$1{,}25*10^{-7}$	$1{,}26*10^{-7}$	$1{,}27*10^{-7}$
K	$7{,}45*10^{-4}$	$8{,}33*10^{-4}$	$6{,}7*10^{-4}$	$8{,}22*10^{-4}$
epsilon	$6{,}37*10^{-4}$	$6{,}74*10^{-4}$	$5{,}96*10^{-4}$	$6{,}99*10^{-4}$
Time [h: m]	*7:47*	*7:13*	*7:55*	*7:20*

CFD convergence happens to be completed after a total of 150-200 iterations, all residuals reach a value of $x * 10^{-4}$, while the energy residual reaches $x * 10^{-7}$, which is considered acceptable for steady state calculations.

To improve solver accuracy, the CFD simulations could be run at second order discretization, it would take a longer period of time to simulate than a first order discretization.

7.3. Manually measured data compared to the CFD simulations:

TSI ventilation meter and FLIR thermal camera where used to collect data from the selected living room, related to temperature and air velocity. TSI Ventilation meter measured four selected locations of the living room, by testing the temperature and velocity three times at each location. While the Thermal Camera captured walls temperature as well as furniture, door, and window. The basis for the boundary conditions where a combination of this data.

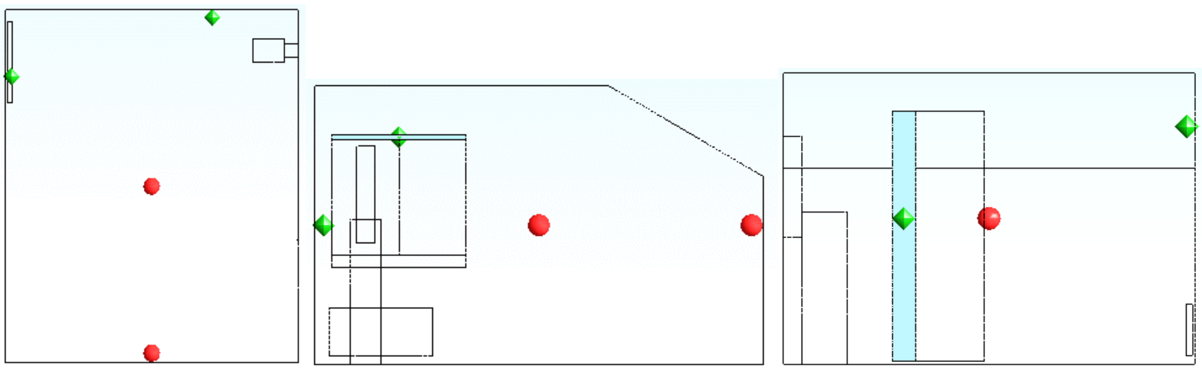


Figure 32: The four measured points represented in X, Y and Z view

The four tested locations in the room are as displayed in Figure 32 above. Green marker; Inlet and outlet, Red marker; Mid. point and Point. X.

CFD Post results establish a quite realistic evolution of the environment inside the living room, in relation to temperature and air velocity conditions. Judging from the four measured points, compared with the CFD results.

Table 36: Temperature and air velocity accuracy according to the simulation of Room.setup.0

Room.Setup.0	**Velocity Accuracy**	**Temperature Accuracy**
Window	100,00 %	100,00 %
Door	93,34 %	97,93 %
Mid. Point	92,02 %	96,57 %
Point. X	88,57 %	94,67 %

Potentially 88-98 % accuracy in across the locations/points tested, the window accuracy would always be 100% (as it reflects on the inlet BC). This is only compared to the measured data on that day and ANSYS CFD simulation, it’s not put in stone (could be questionable). The indoor air quality changes throughout the day, month and year as well.

There is a noticeable pattern in how the accuracy of the data decrease the further it is from the starting point (window/inlet). Especially velocity wise, the temperature not as much. This error could be for a number of reasons; misreading information from the equipment used in measuring the boundary conditions, the incontinency wind (inlet velocity), misleading CFD simulation (change setup), etc.

The relationship between temperature and air velocity according to the measured data:

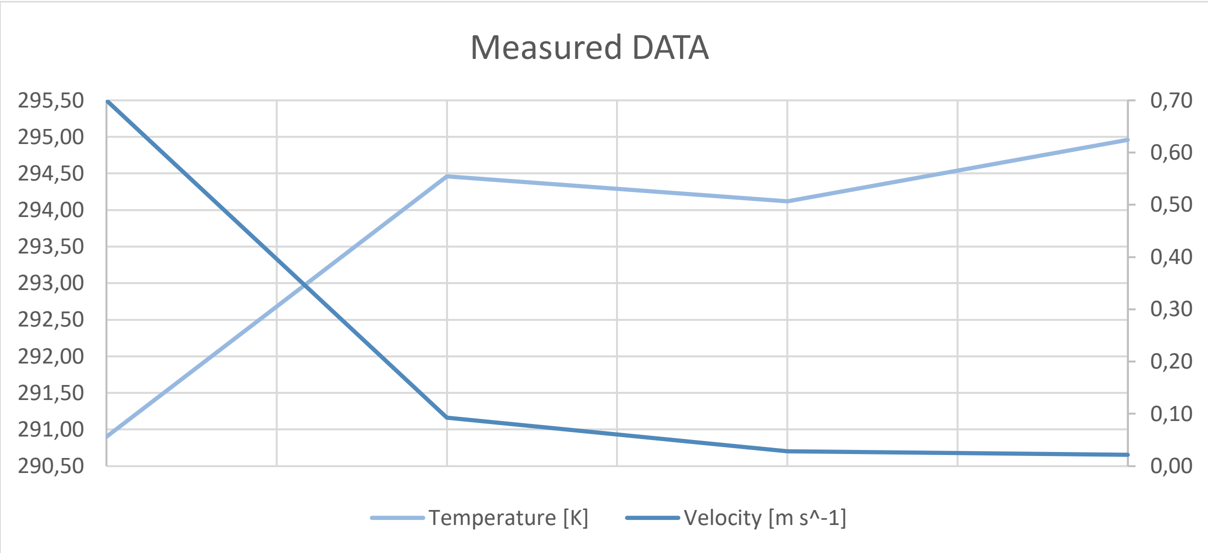


Figure 57: Rrelation between temperature and air velocity according to the measured data

Relation between temperature and air velocity according to the CFD simulation:

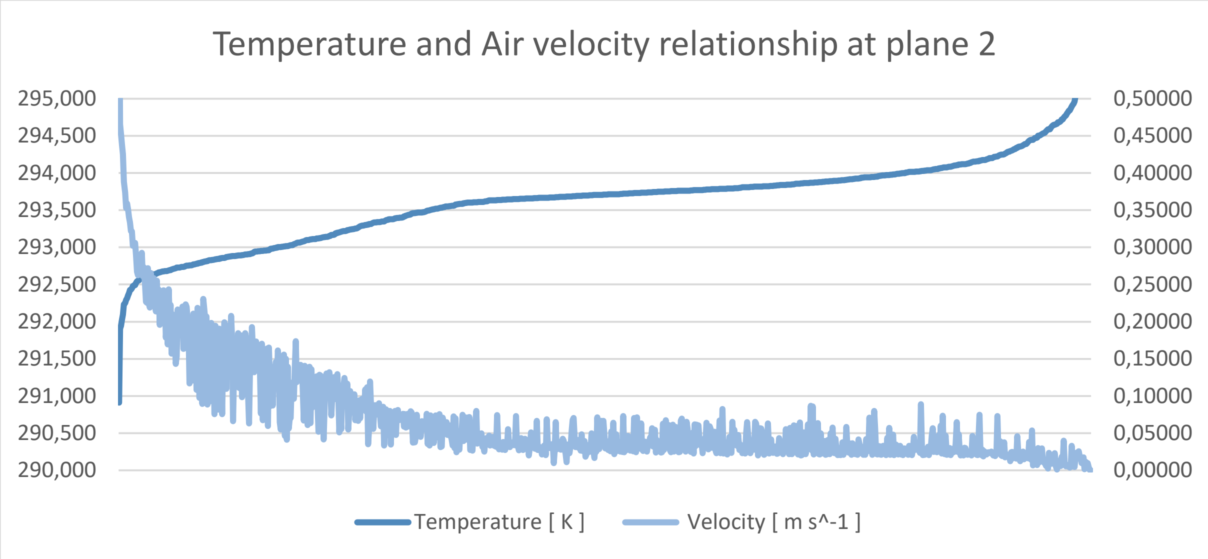


Figure 38: Relation between Temperature and Air velocity at plane 2 (Room.setup.0)

Both figures are similar, showing the relationship between temperature and air velocity, displaying how the temperature decrease when the velocity increase. Clearly because of the low (cold) air temperature outside, anticipated through the window.

7.4. Furniture setup:

To evaluate the impact furniture has on the indoor environment, three room scenarios where selected, in addition to a scenario with no movable furniture (empty room). Each one of these scenarios is examined side by side with figures and tables in the previews chapter. Starting with plane 1 (located 1,15m above floor) and plane 2 (crossing though window and heater);

Table 37: Average temperature and air velocity at plane 1

Plane.1	**Temperature [K]**	**Velocity [m/s]**
Room setup 0	*293.947*	*0.03625*
Room setup 1	*293.995*	*0.03551*
Room setup 2	*294.042*	*0.03763*
Room setup 3	*294.057*	*0.03622*

Table 38: Average temperature and air velocity at plane 2

Plane.2	**Temperature [K]**	**Velocity [m/s]**
Room setup 0	*293.896*	*0.06310*
Room setup 1	*294.049*	*0.06031*
Room setup 2	*293.944*	*0.06812*
Room setup 3	*294.189*	*0.06482*

Table 37 and Table 38 show that the empty room scenario (Room.setup.0) has the lowest average temperature across both planes (plane 1 and plane 2), even though it doesn’t have the highest velocity on average. In general, the average data are very similar (marginal change) and doesn’t describe the whole picture. Examining Figure 39 to Figure 42 or the volume conditions would give a better description of the furniture influence.

Table 39 and Table 40 describes the volume conditions of the living room for all four scenarios:

Table 39: Percentage of the temperature falling between 20-22 [℃]

	Volume [m^3]	Temperature between 20-22 ℃	In percent [%]
Room.Setup.0	*25,797*	*23,362m^3*	*90,56 %*
Room.Setup.1	*24,494*	*21,980m^3*	*89,74 %*
Room.Setup.2	*24,494*	*22,153m^3*	*90,44 %*
Room.Setup.3	*24,494*	*22,139m^3*	*90,39 %*

Almost 90% of the total room volume is between 20 and 22 ℃, which is considered to be a typical room temperature.

Table 40: Percentage of the velocity found below 0,01 [m/s] and 0,02 [m/s].

	Volume [m^3]	Below 0,01m/s	[%]	Below 0,02m/s	[%]
Room.Setup.0	*25,797*	*1,729 m^3*	*6,70 %*	*4,228 m^3*	*16,39*
Room.Setup.1	*24,494*	*2,315 m^3*	*9,45 %*	*4,765 m^3*	*19,45*
Room.Setup.2	*24,494*	*1,884 m^3*	*7,69 %*	*4,035 m^3*	*16,48*
Room.Setup.3	*24,494*	*2,351 m^3*	*9,60 %*	*5,218 m^3*	*21,31*

Room.setup.2 stands out as favorite/healthier alterative, with only 7,69 % of the total volume below 0,01 m/s and 16,48% below 0,02 m/. Compared to Room.setup.3 with a total volume of 2 351 [m^3] (9,6 % of the total volume) below 0,01 m/s and 21,31 % below 0,02 this is not an ideal percentage, only compared to the other two furniture settings. This could of lead to more dust/ bad air quality and unhealthy environment in general.

There are some differences between the room scenarios according to the CFD simulations, but nothing drastic. Here are some points that could explained why:

- The living room selected for this project was relatively small, which makes it difficult to drastically change the furniture setup.
- Low air velocity: Especially on the day of measuring it the in the living room, reducing the effect a window opening has on such apartment.

7.5. Occupant activity:

In context of the building and equipment design, it is always difficult to establish exact knowledge about how and the equipment will be used by the occupants. An important element to know is how users preferred devices and furniture setting will influence the room environment in terms of surface temperatures and air flow patterns. Microsoft Kinect managed to track occupants' activity successfully (with high accuracy), achieving a better understanding of the users' lifestyle. Tracing all 25 nodes simultaneously, with information about node location and time.

The obtained results show that most of the occupants' movement was influenced by the sofa and TV placement, all three different furniture settings have that in common. This observation is interesting and can prove that furniture placement influence occupants' activity, naturally influence the environment surrounding them.

Chapter 6 provided figures (charts) of node 1 (spine base) and 4 (head), for the three tested room scenarios. Figure 51- Figure 53 display temperature, Figure 54- Figure 56 display air velocity. By examining these figures (charts), a difference of 0-0,5 ℃ in temperature is recorded between these two nodes, and approximately 0,02 m/s in air velocity. Room scenario 2 having less change between node 1 and 4, compared to the two other scenarios.

The user (person living in the selected apartment) when asked about his assessment of the different furniture settings tested, Room.scenario.2 gave easy access to the rooms furniture, better mobility and more space for activity, as he also ended up leaving the furniture as described in that scenario instead of the original setup he had before (which is Room.setup.1). This can be noticeable in the results below:

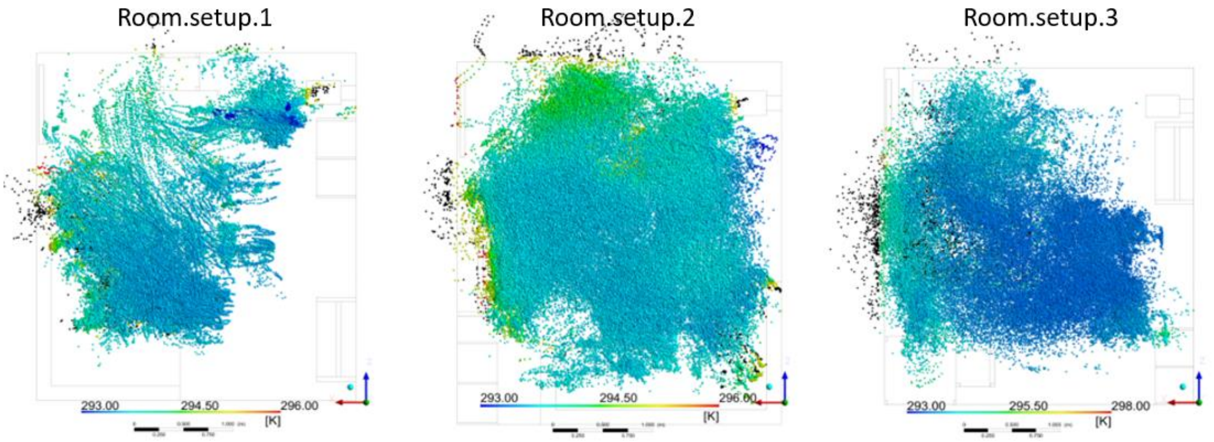


Figure 58: Activity captured by the Kinect device

Room setup 1 and 3 didn't capture as much activity as room setup 2 did across the entire room. Actually, the desk area was completely isolated in room setup 3.

8. Conclusion:

Occupant behaviour impacts building structure by movement or actions, witch by default determines the buildings indoor environment quality (IEQ) and energy consumption. Due to the inconsistency of the occupant movement and actions in most cases makes it hard point out one particular factor, making the prediction very complex. On the other hand, buildings energy use and indoor environment can affect the occupant both physical and mental health.

In this thesis, emphasis is placed on how furniture location would have an effect on the occupant and their environment, in residential buildings. Preforming a number of measurements and numerical CFD simulations using ANSYS, it's been possible to reach an accuracy of 88-100%. According to the set boundary conditions and the solution method, described in chapter 6.

ANSYS and Microsoft Kinect are capable of providing helpful data regarding the room environment, occupant behaviour and potential discomfort zones. Processed data show that the furniture setting didn't affect the indoor environment drastically, but had a noticeable impact on the occupant pattern. Some room scenarios where more convenient than others; namely Room.setup.2 covering 83,52% of its total air volume velocities above 0,02 m/s, which is 4-5% higher than other room scenarios with furniture.

ANSYS prediction of what could be a convenient furniture setup is also confirmed by the user of this apartment. As he ended up with leaving the furniture placed as described in Room.scenario.2. instead of the original setup (Room.setup.1). According to him this gave a feeling of better mobility, easy access to the rooms furniture and increased his space for activity in general.

9. Improvements and proposal for further work:

There could be a room for improvement in both the measuring method and the numerical CFD simulation. Improving the measuring method by:

- Increasing the number of tests measured, to gain a better description of the rooms condition.
- Measure the temperature and air velocity of other locations in the selected room.

When talking about the numerical CFD simulation, it could be improved by:

- Different meshing method (keep the mesh quality in mind).
- Consider different (k-epsilon) turbulent flow methods, like the RNG or Realizable.
- Run the simulation at second order discretization rather than the default first order discretization (Which possibly improves the results quality/ precision).

Proposal for further work in the future would be:

- Develop a realistic heater model, possibly change heater placement to gain a better understating of how it influences the environment surrounding occupants.
- Work on bigger rooms or office buildings with larger space for furniture.

ANSYS numerical CFD simulation seems promising and could play a big role in the future of indoor environment studies and understanding occupant behaviour.

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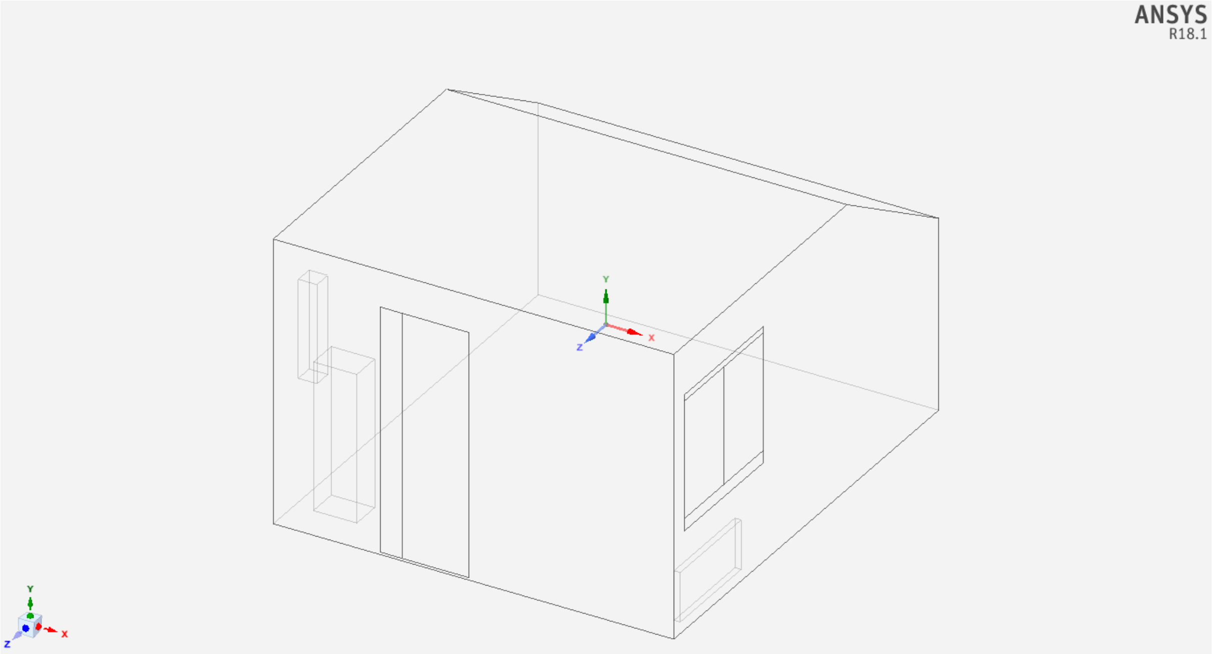
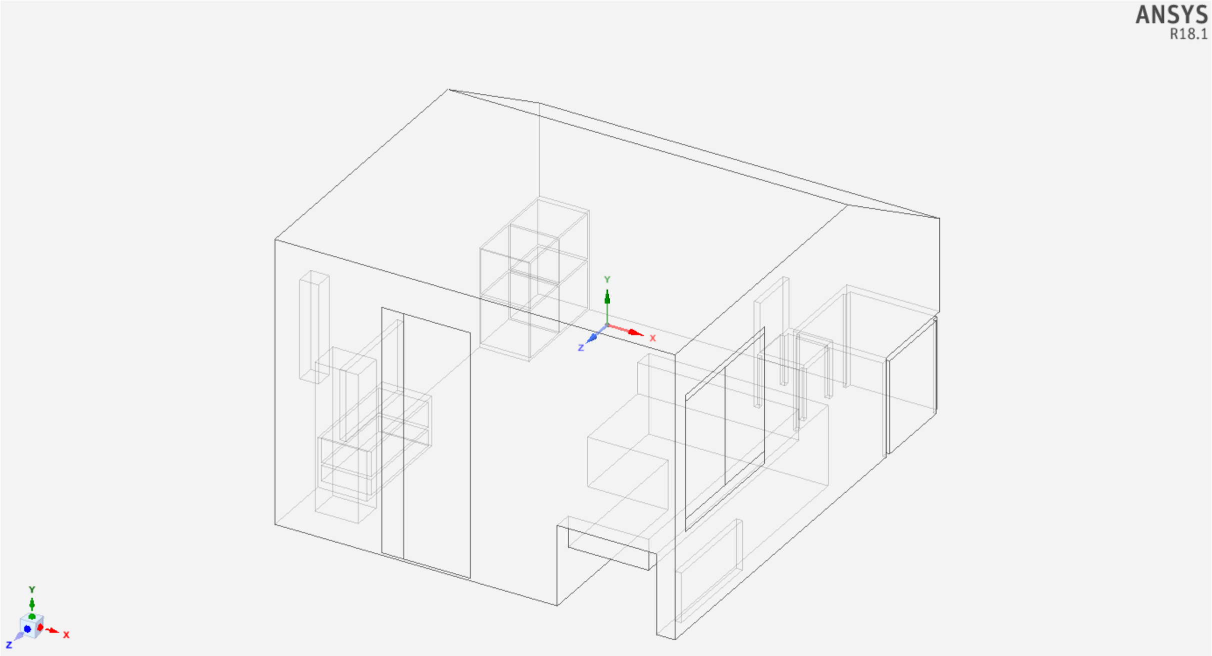
Appendix:

Room description: Room dimensions, including furniture, door, window and heater placement

Room.setup.0

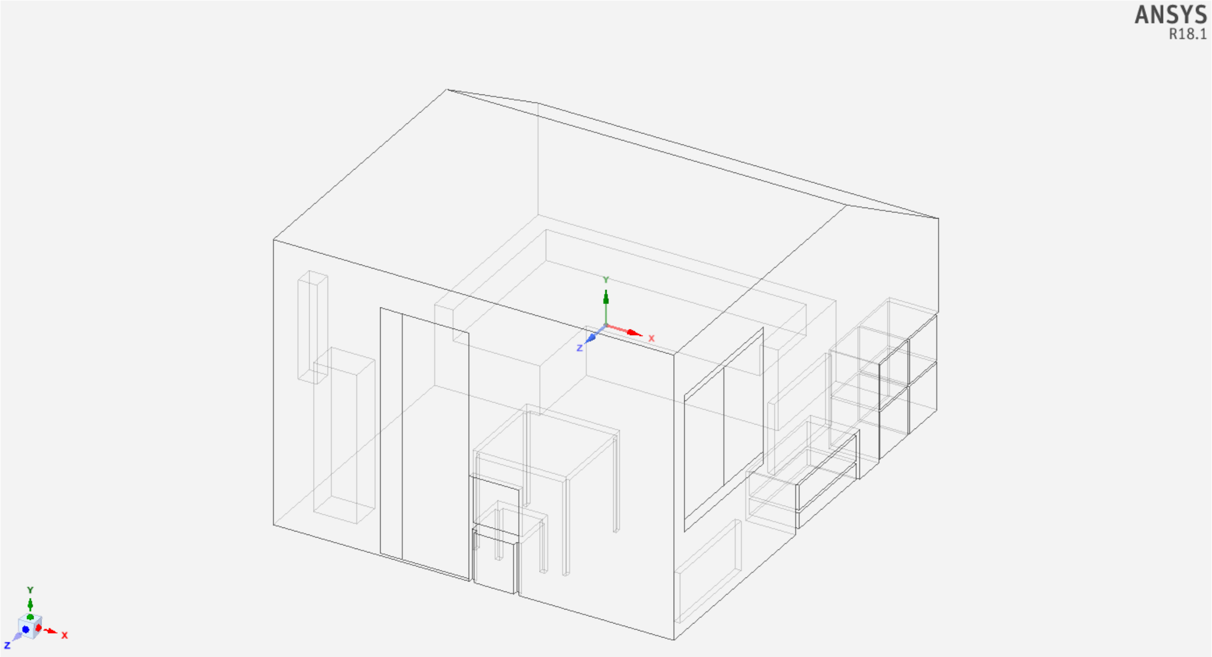


Room.setup.1

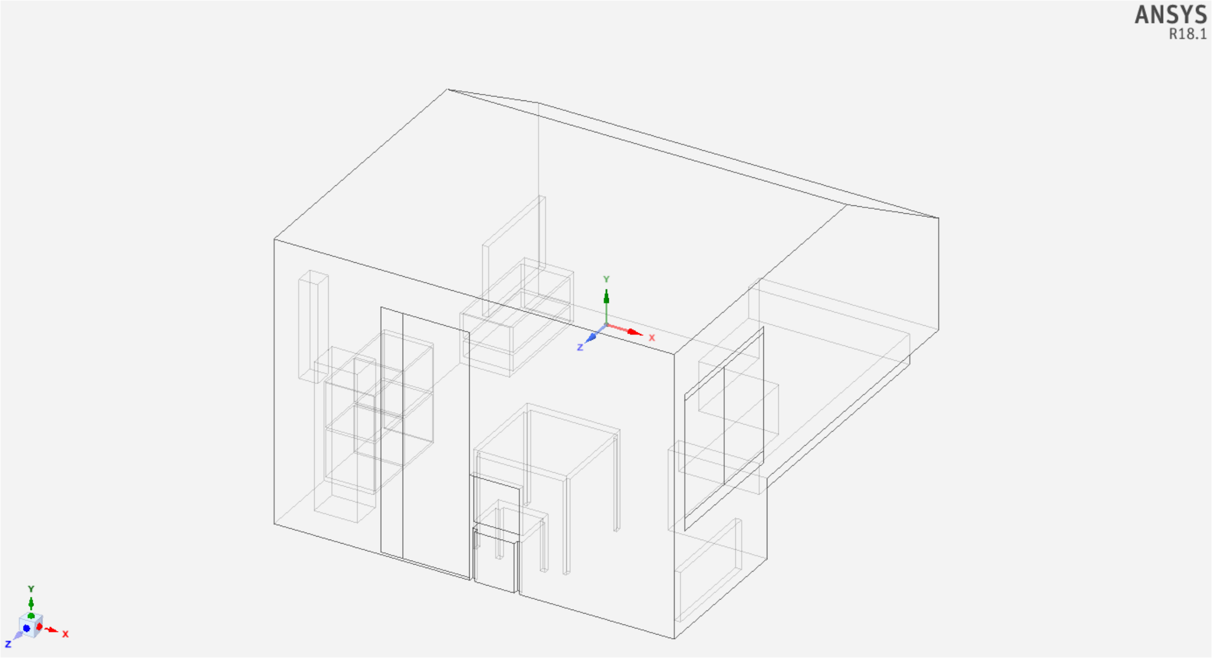


Room description:

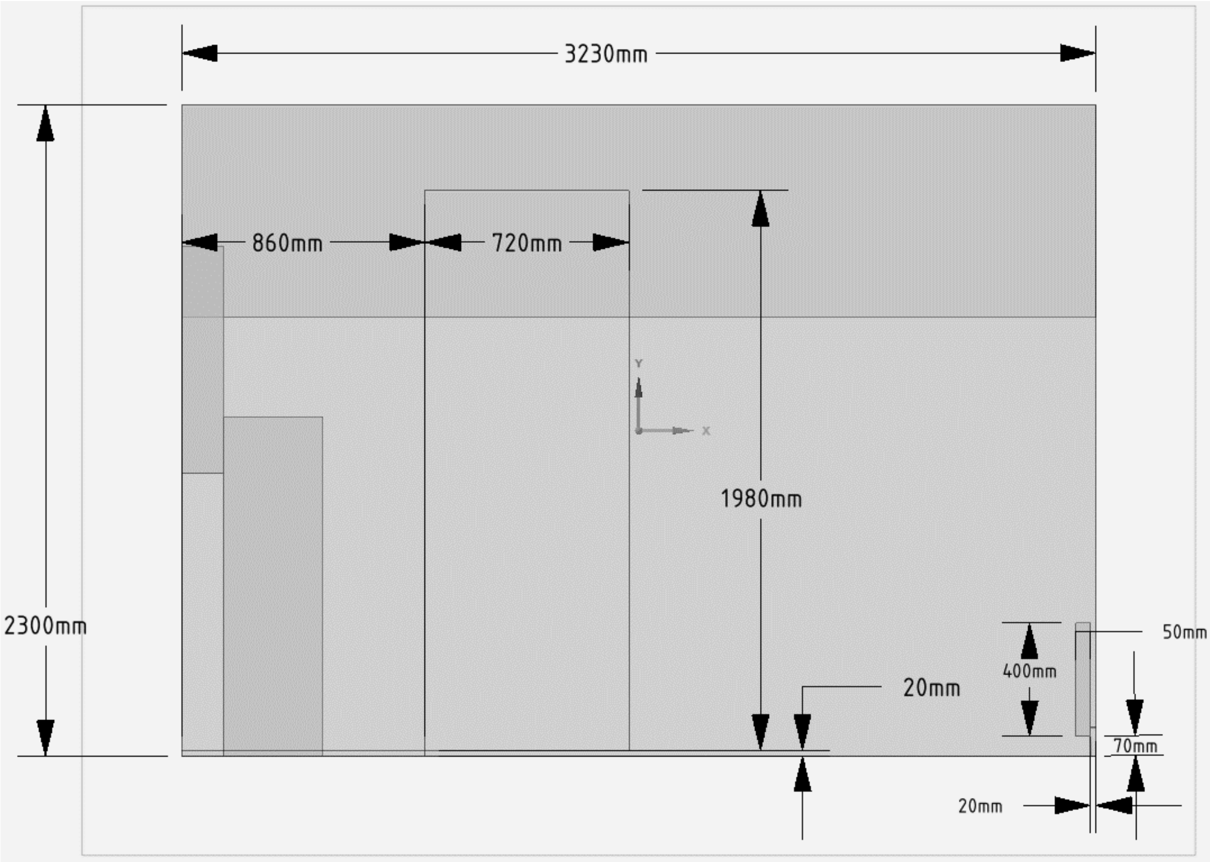
Room.setup.2

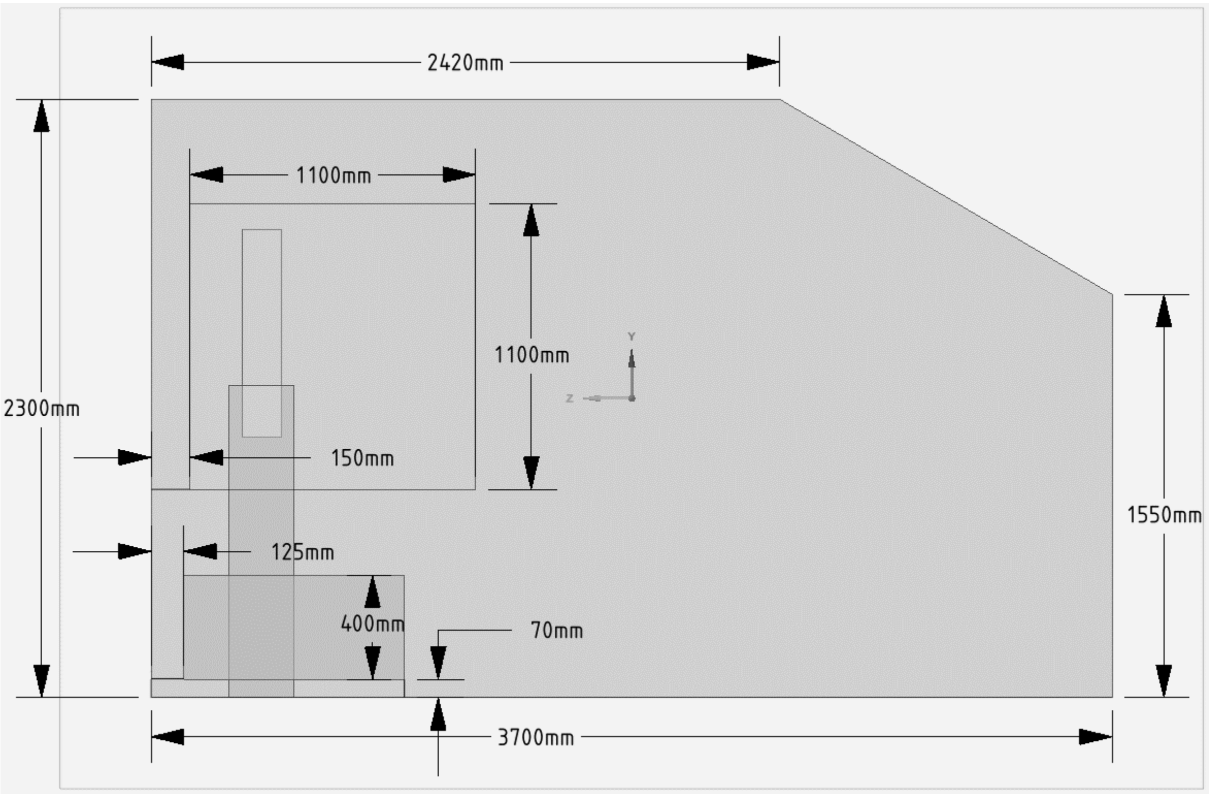


Room.setup.3

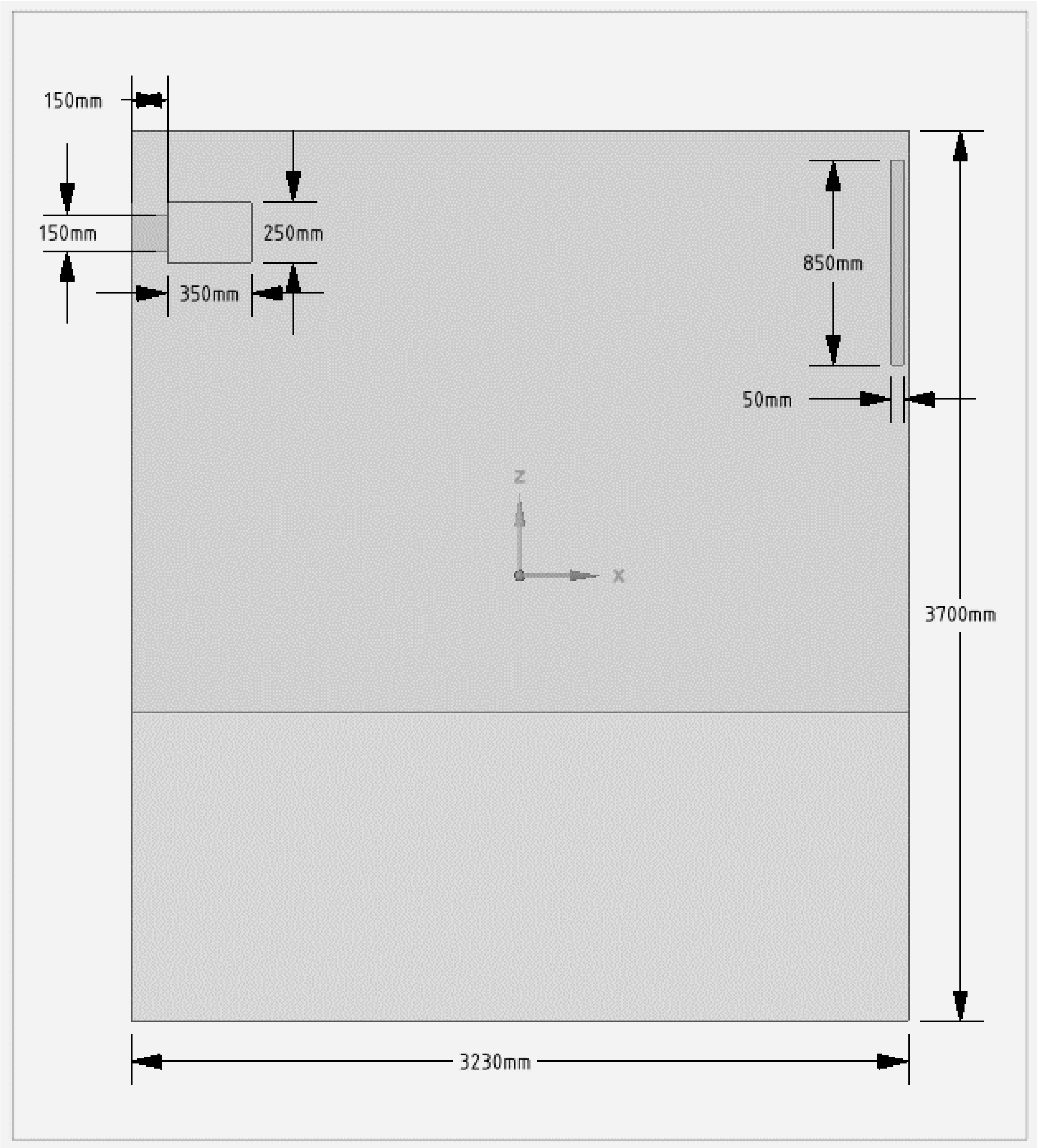


Sketch of Room.setup.0



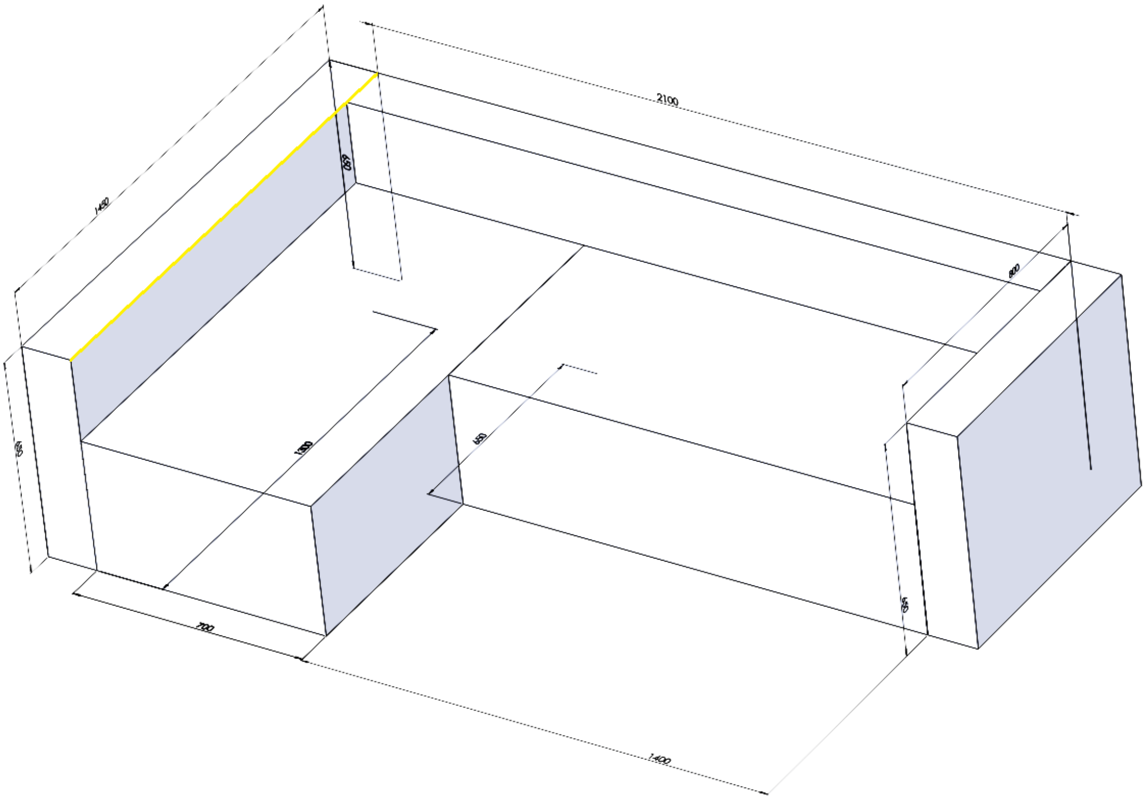


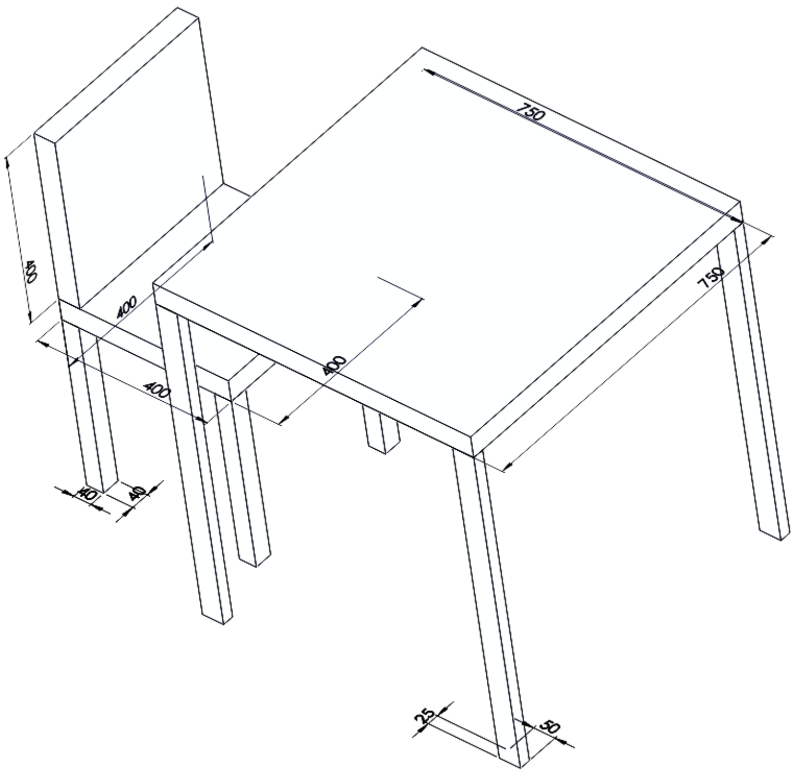
Sketch of Room.setup.0



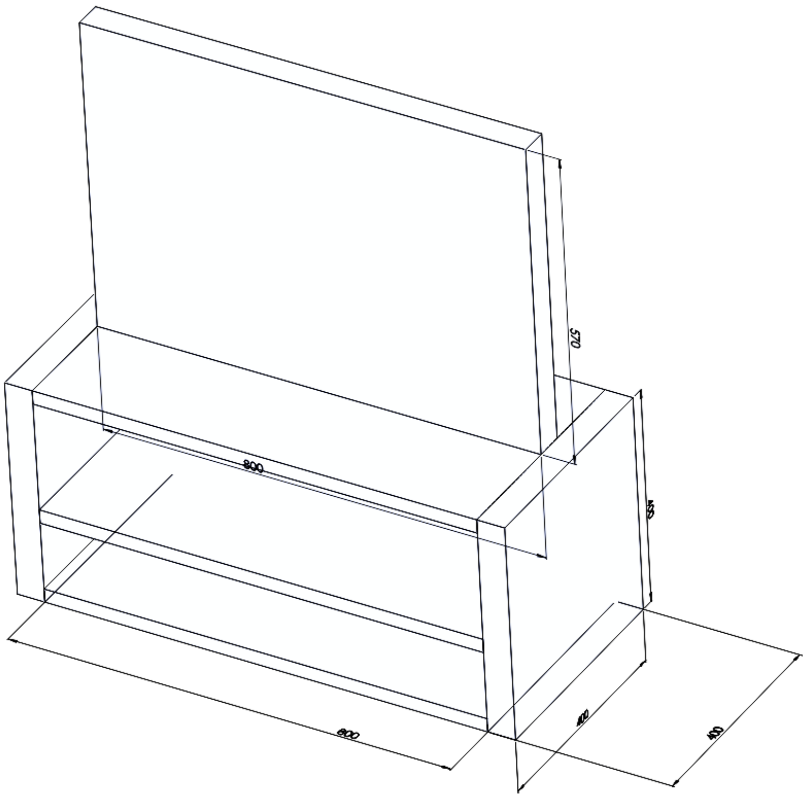
Furniture size in mm:

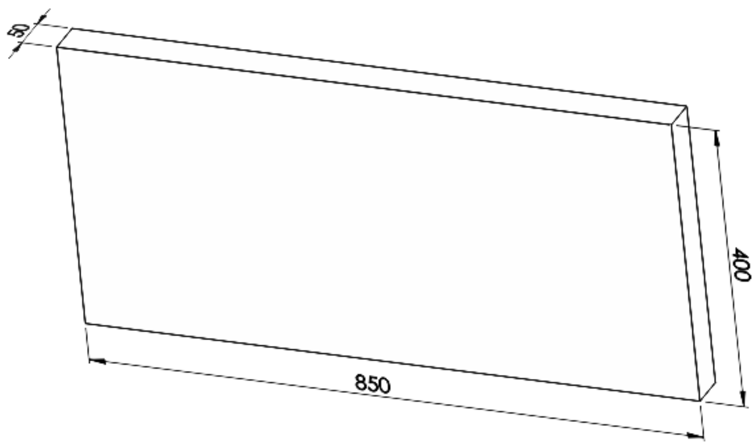
Furniture:



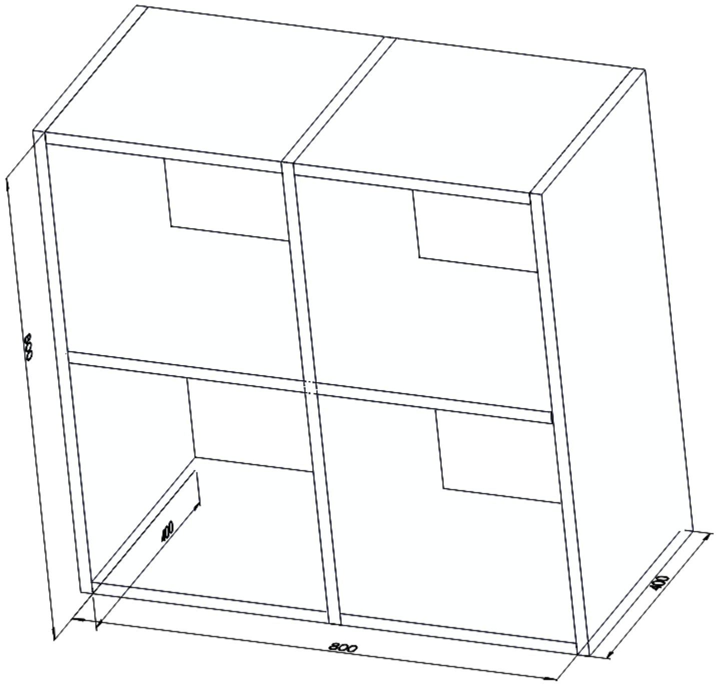


Furniture:

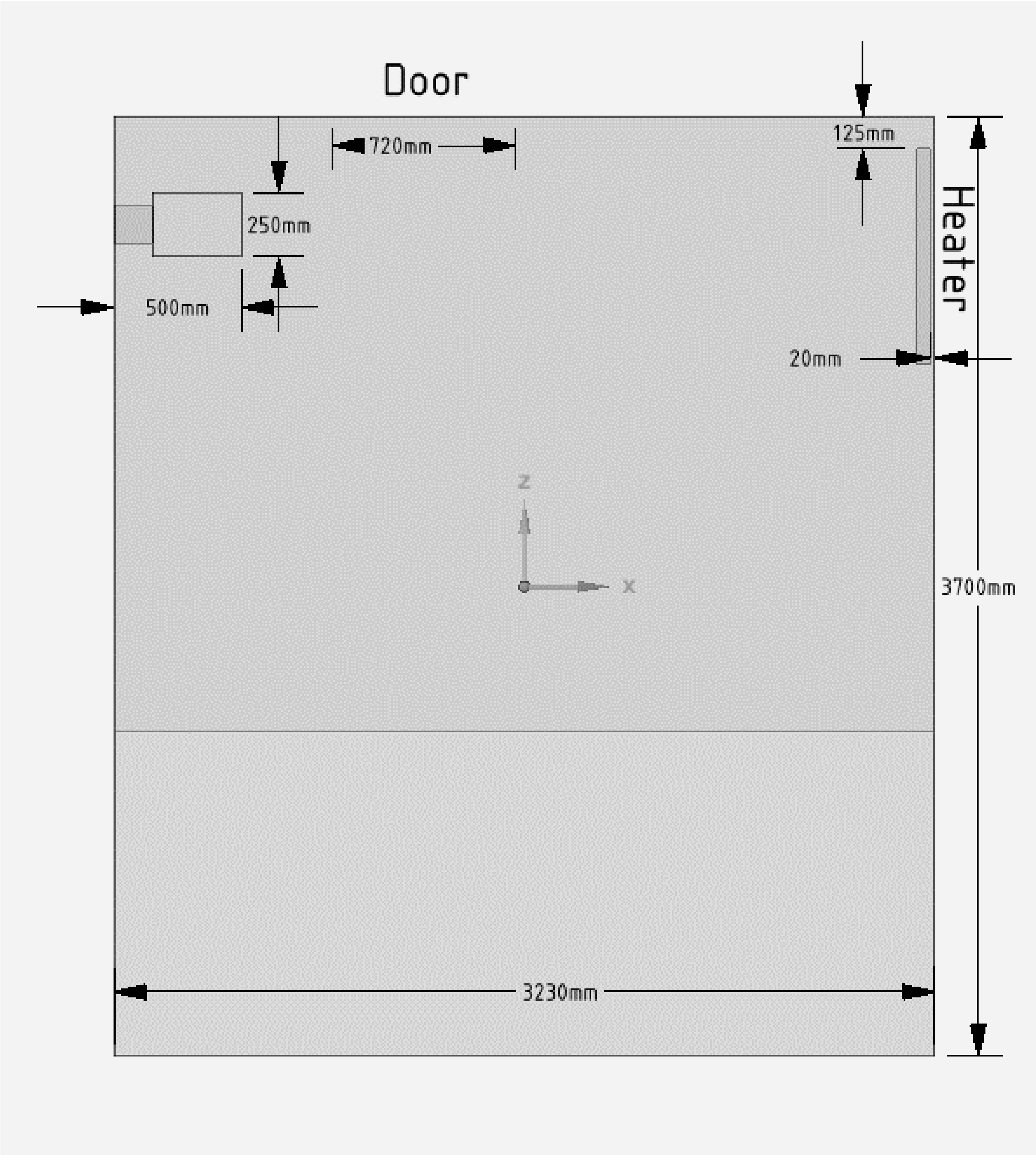




Furniture:

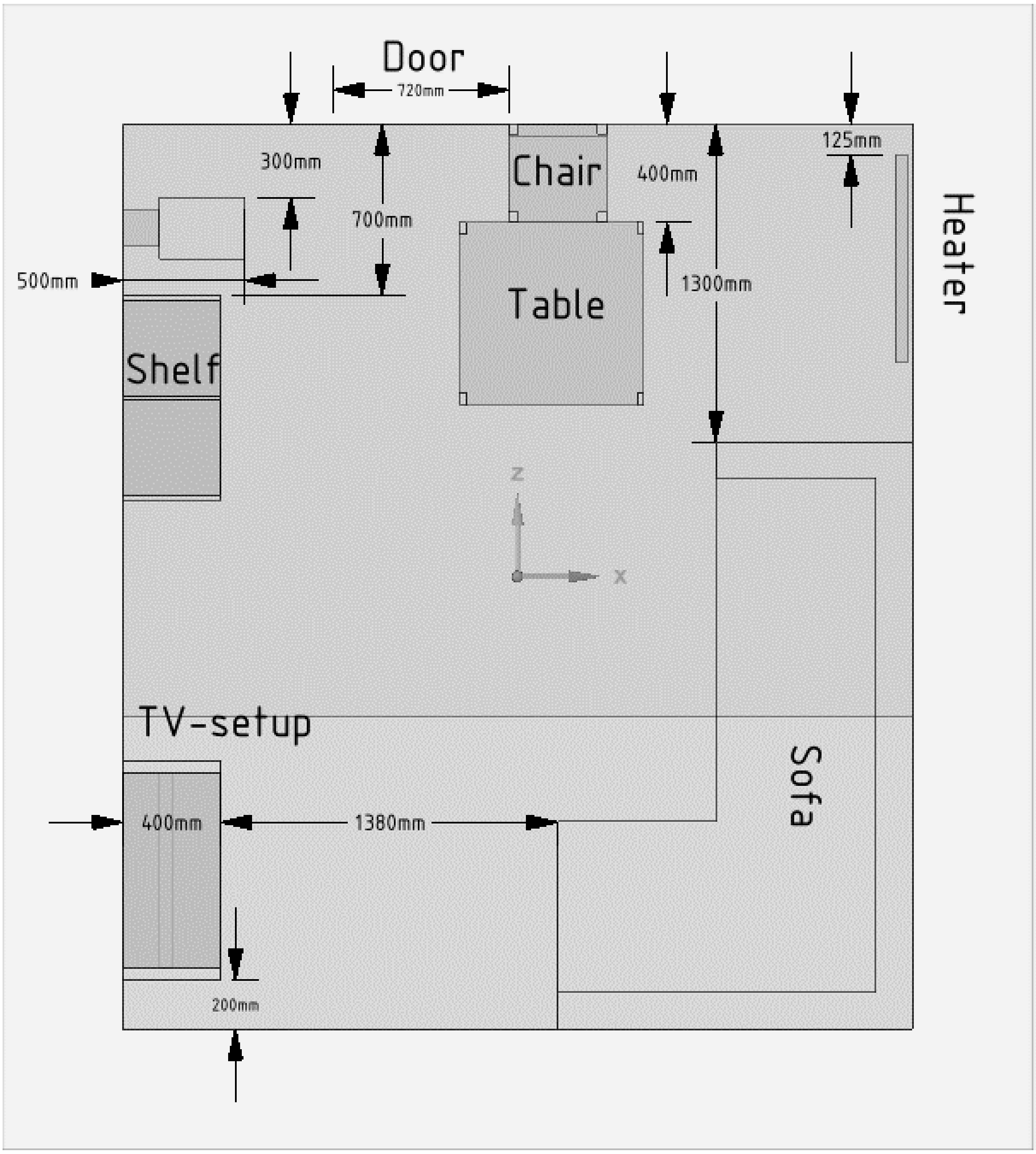


Room.setup0 in 2D view:



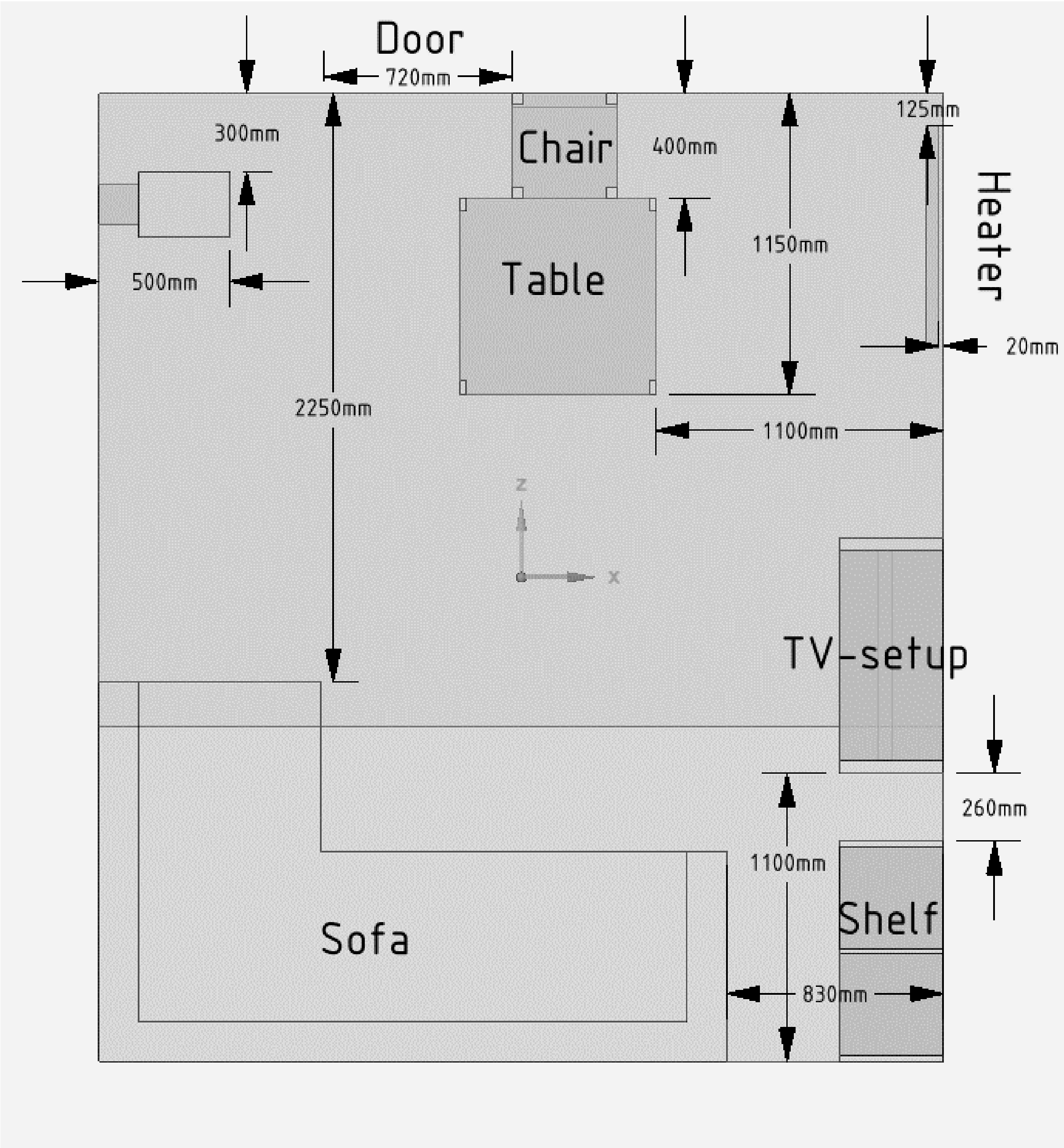
Room.setup1 in 2D view:

Showing the distance, between fixed objects and room walls.



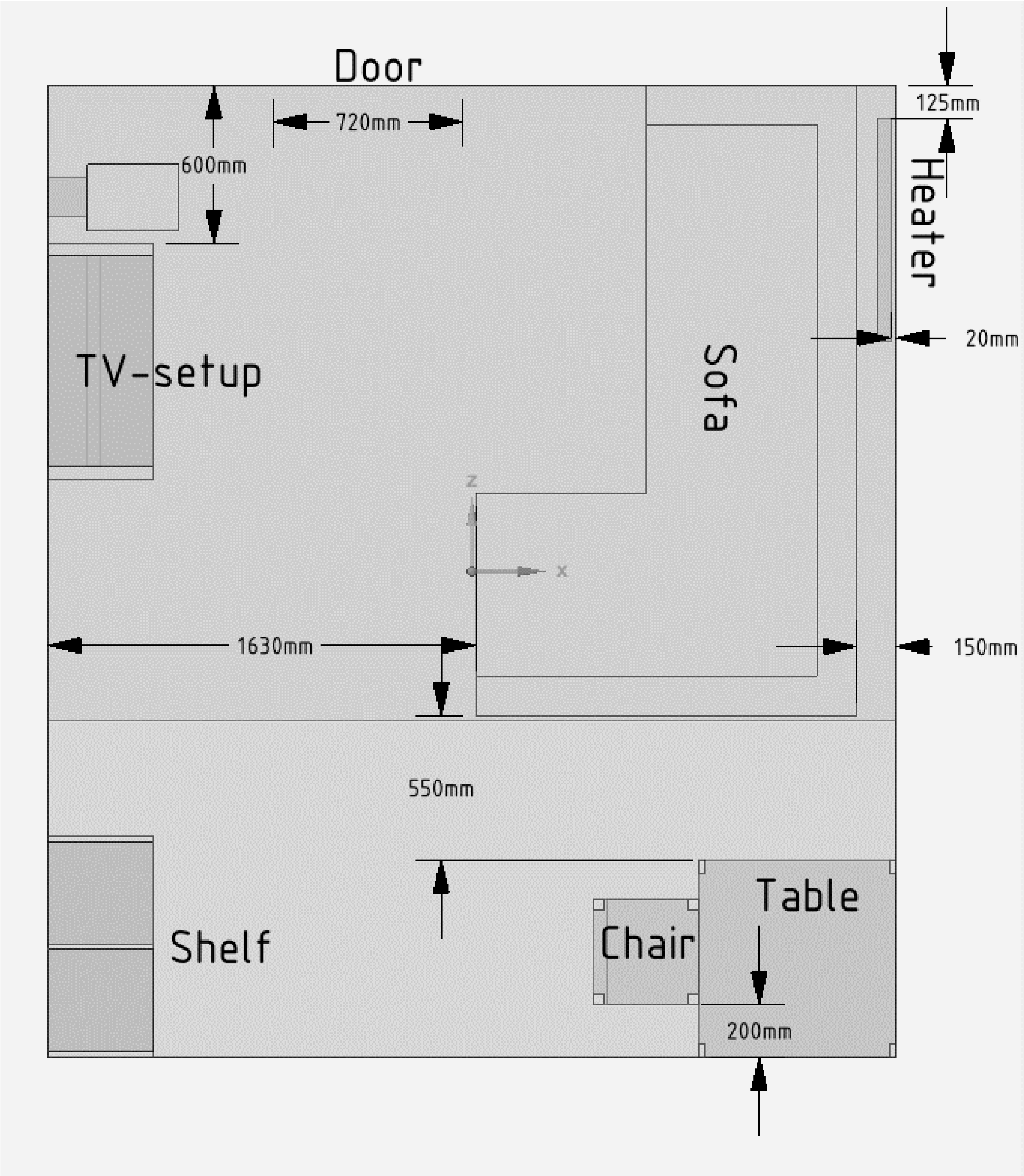
Room.setup2 in 2D view:

Showing furniture placement



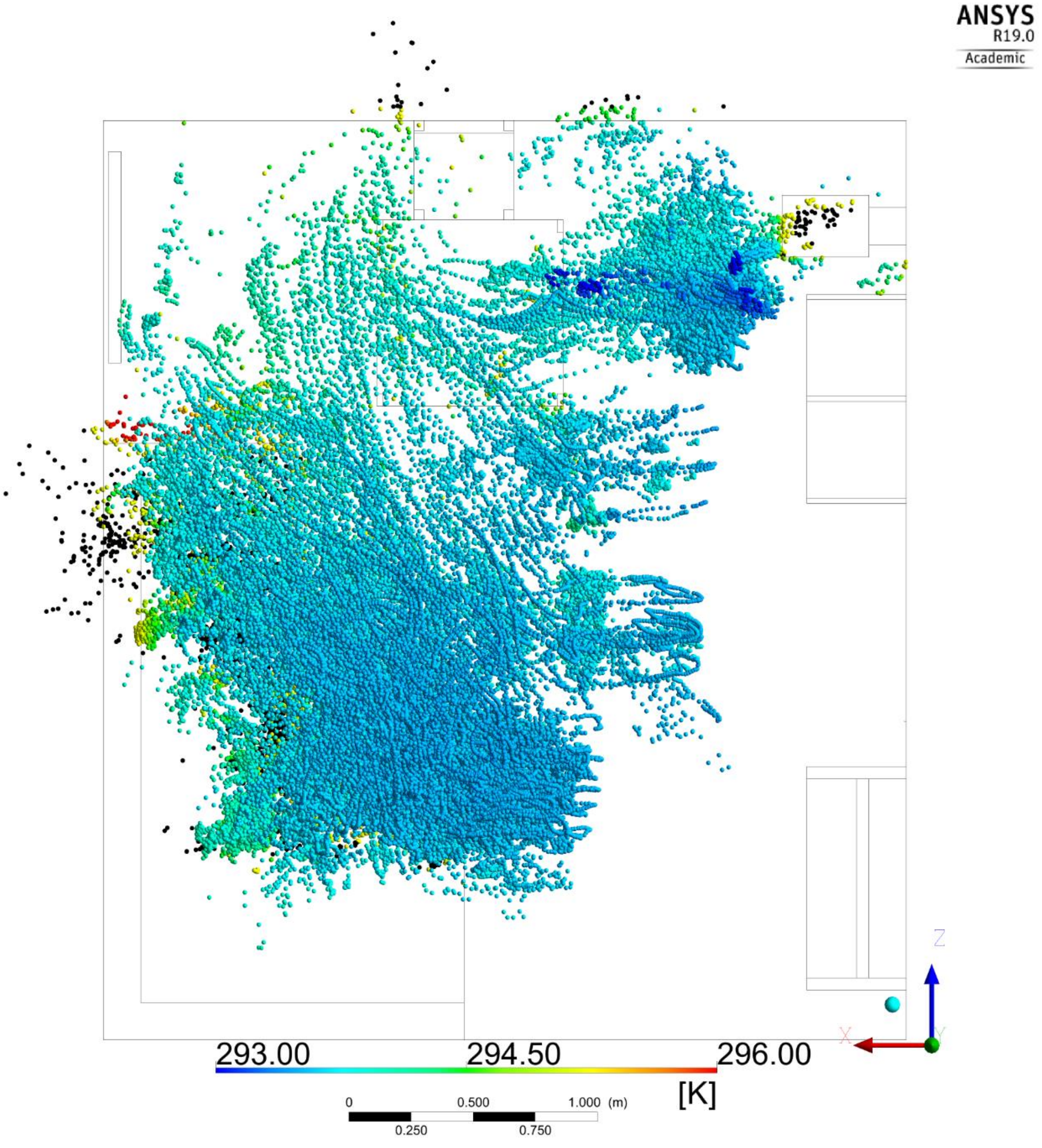
Room.setup.3 in 2D view:

Showing all furniture placement



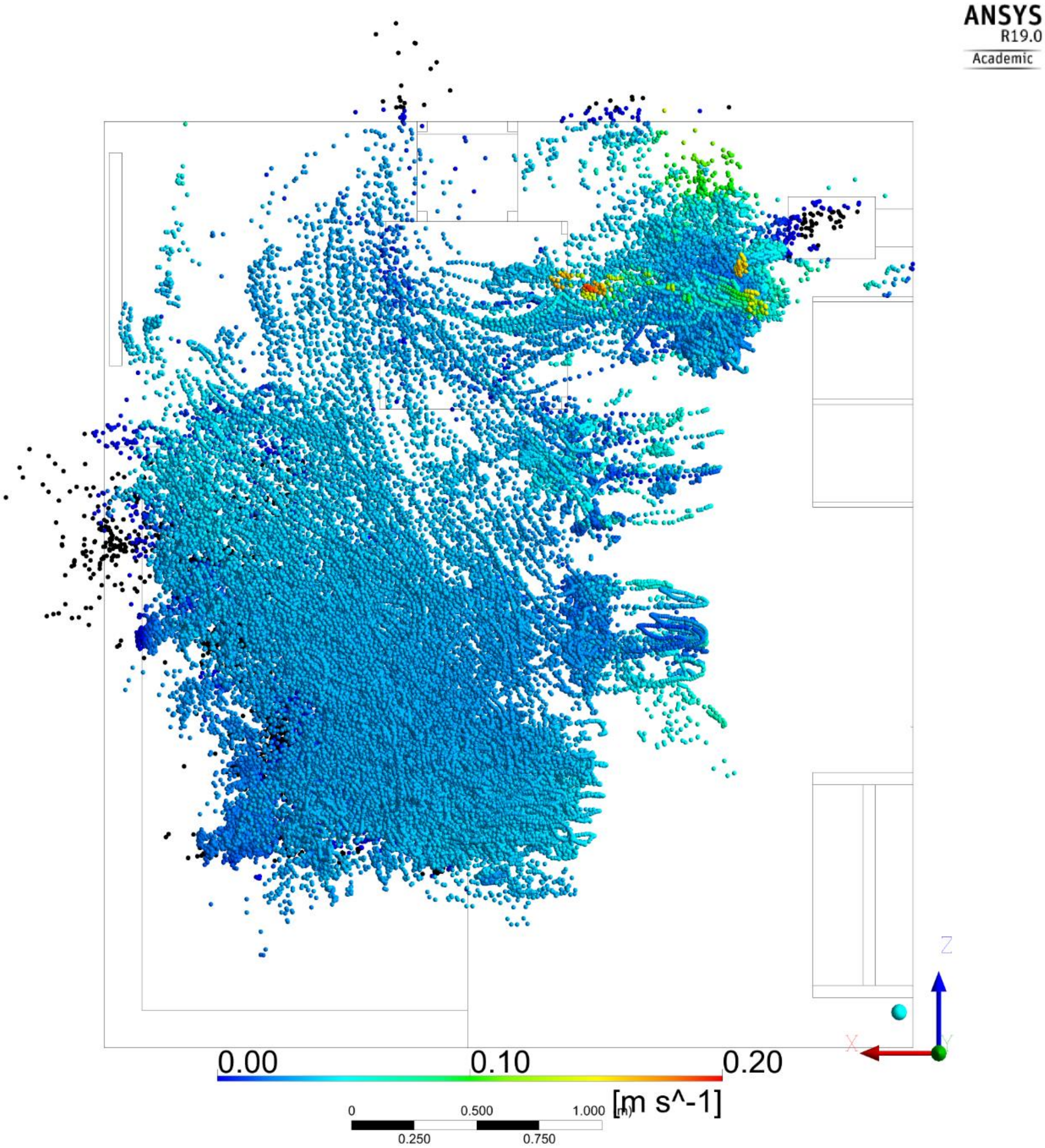
Processed data from Microsoft Kinect:

Room.setup.1. temperature. All 25 nodes



Processed data from Microsoft Kinect:

Room.setup.1. velocity. All 25 nodes



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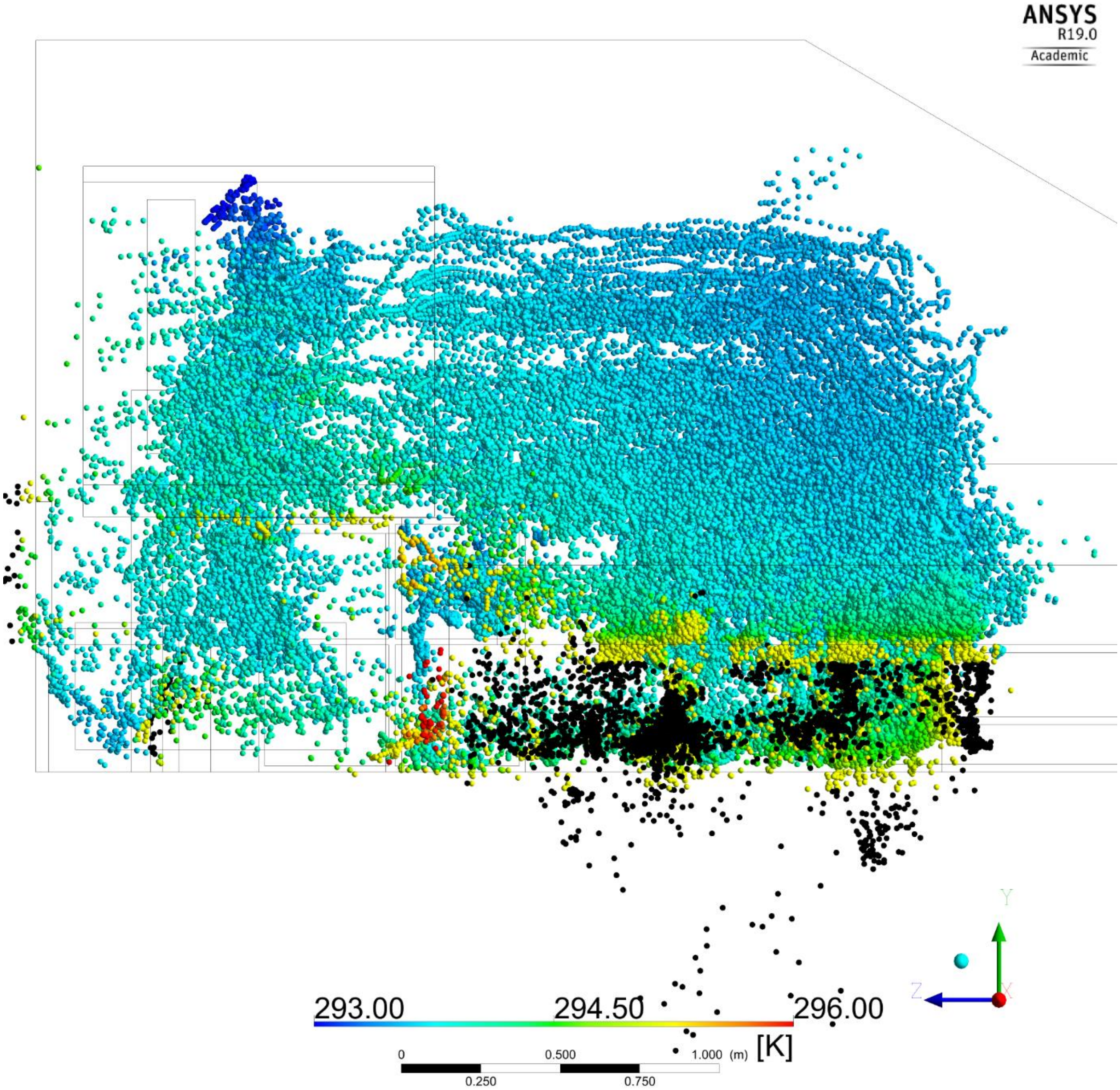
Room.setup.1. temperature. All 25 nodes



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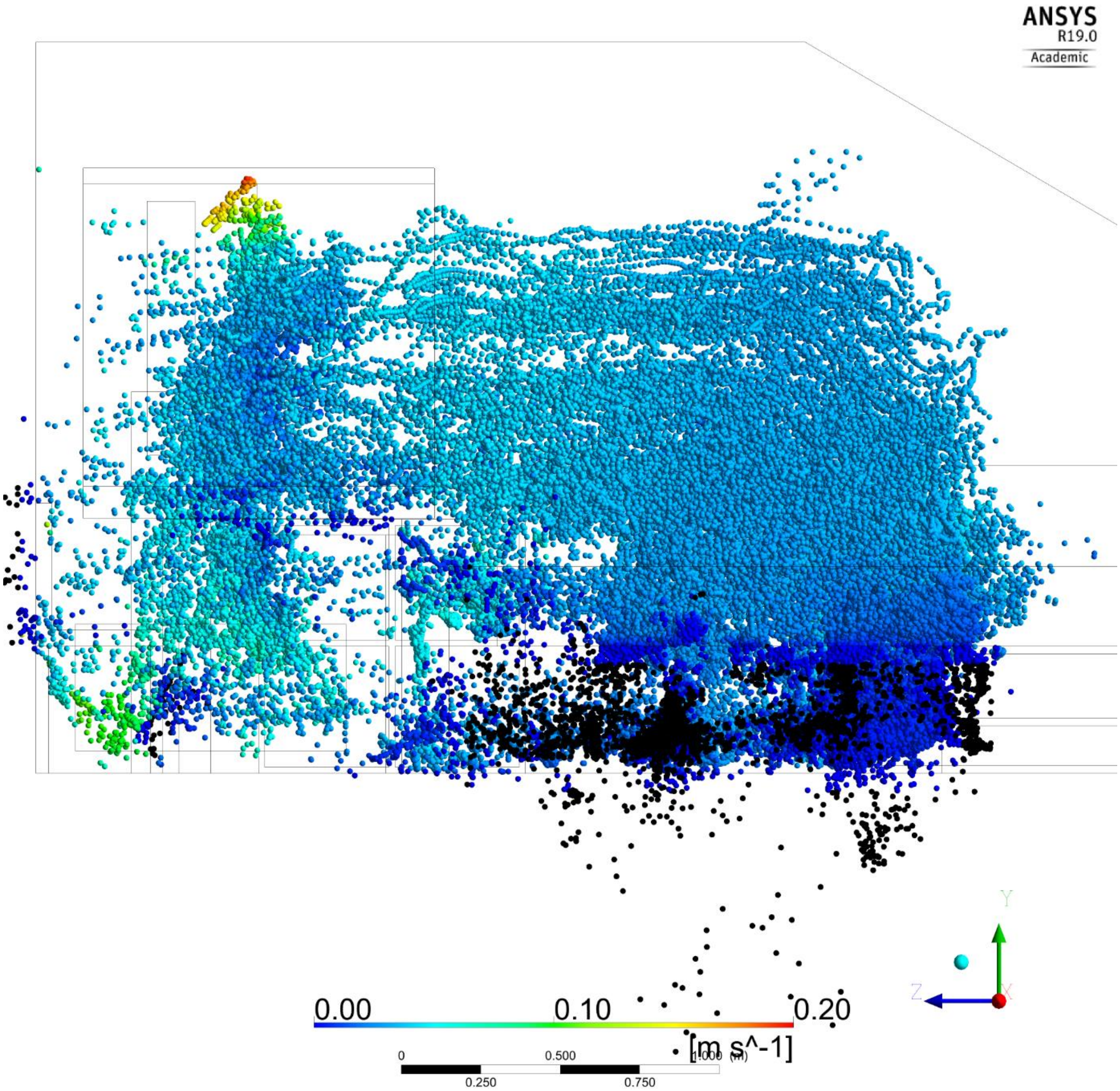
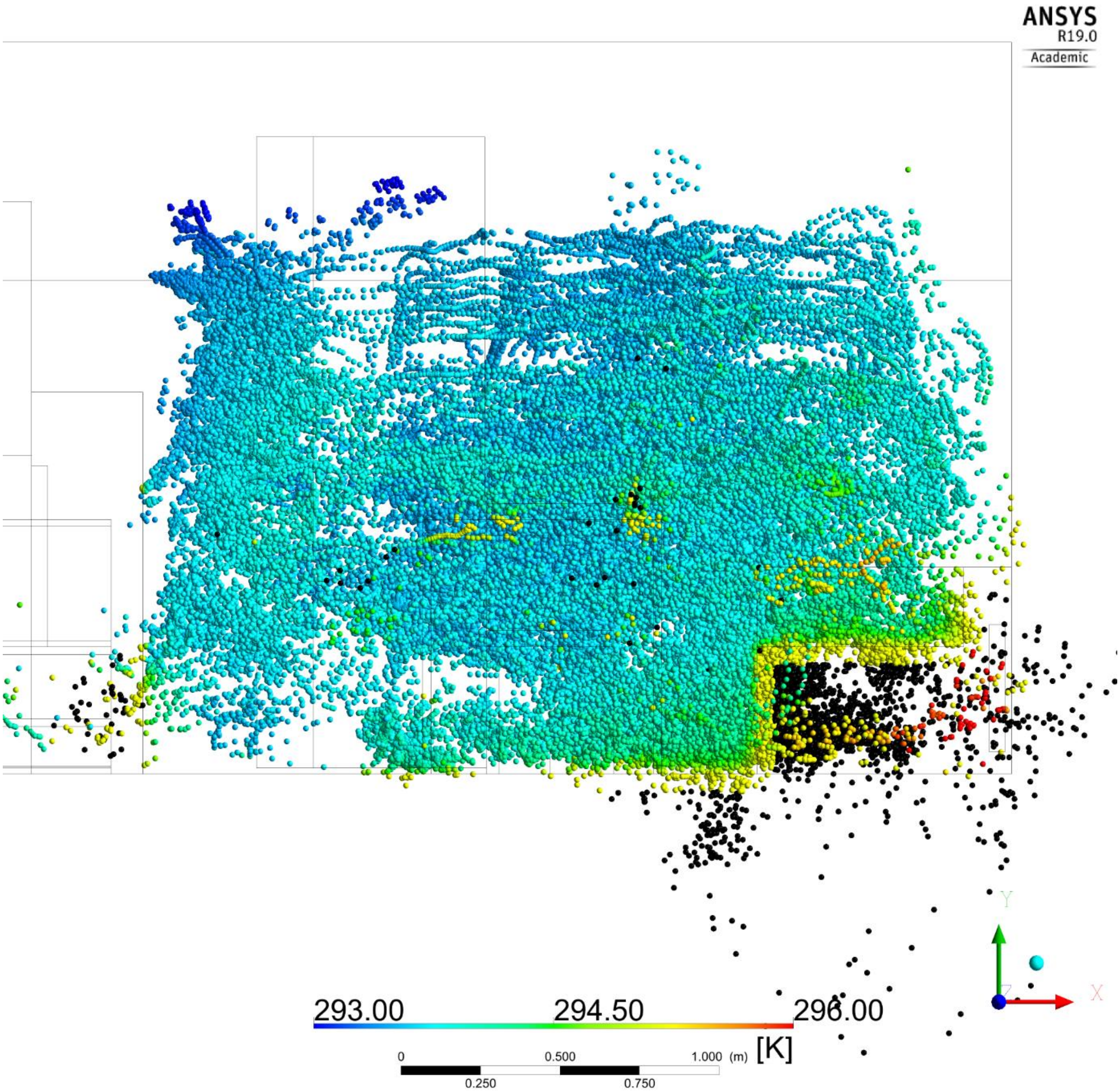
Room.setup.1. velocity. All 25 nodes



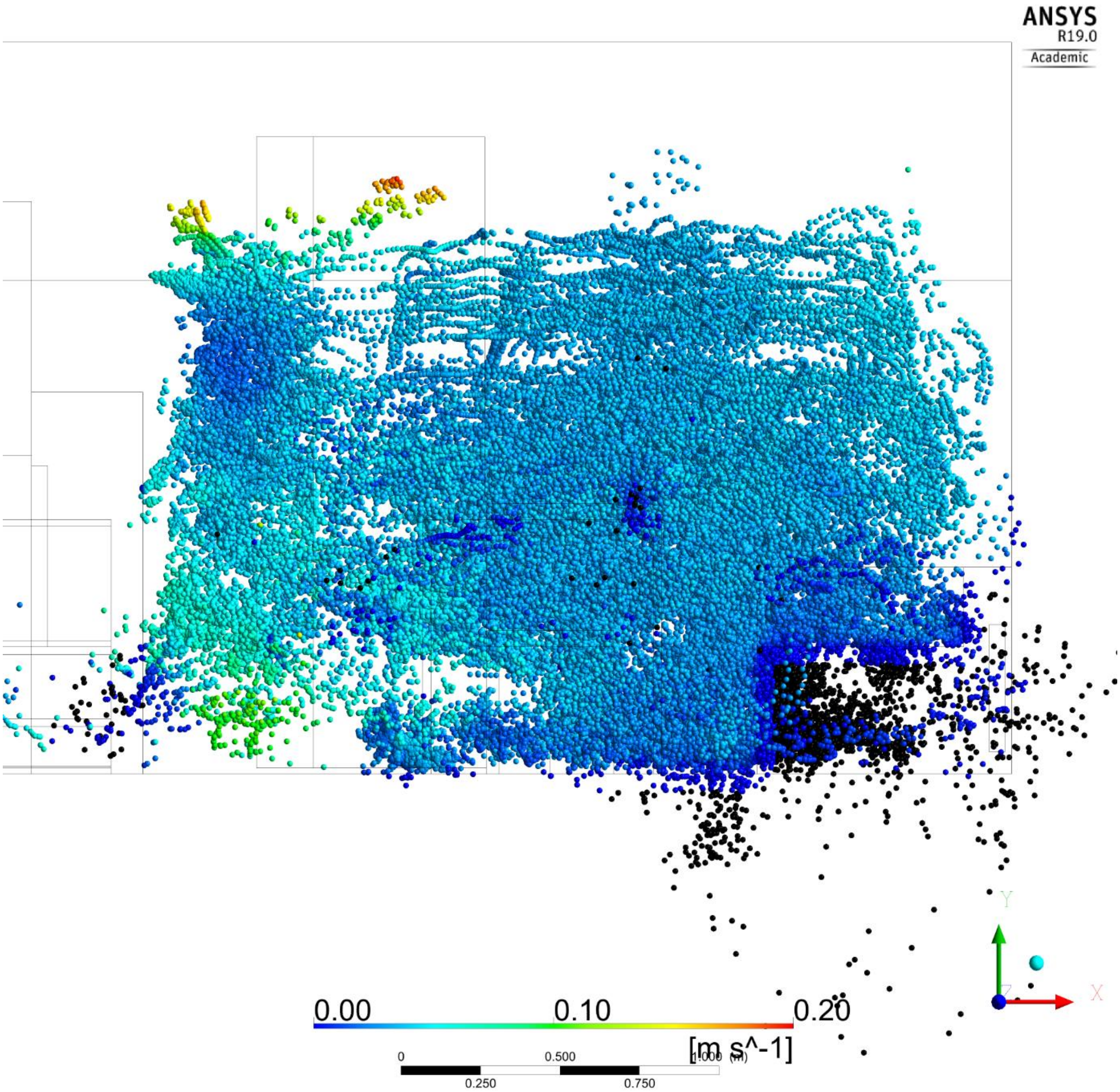
Processed data from Microsoft Kinect:

Room.setup.1. temperature. All 25 nodes



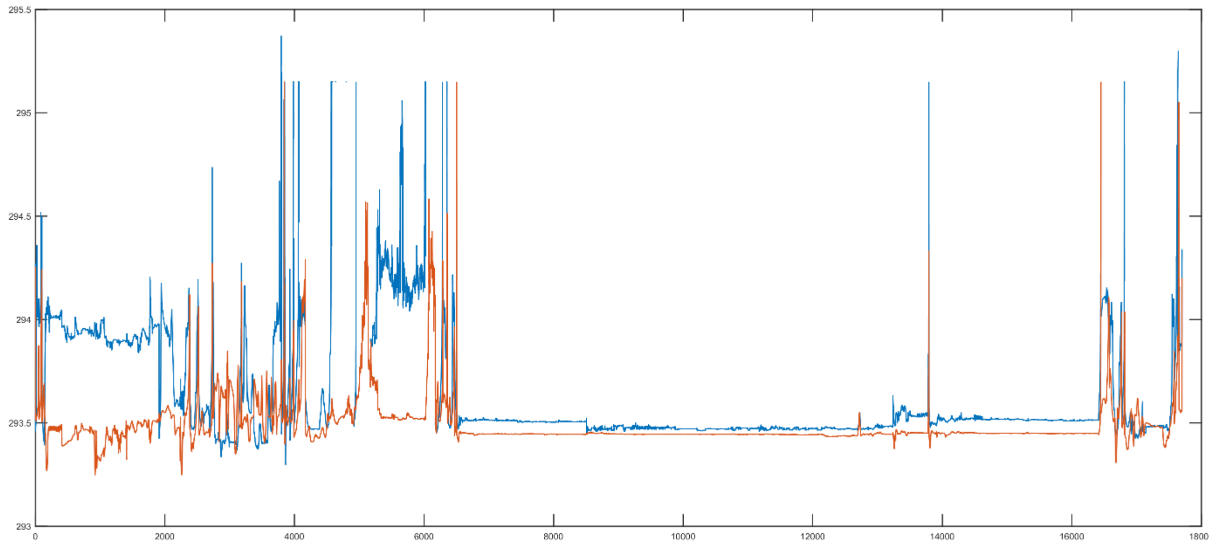
Processed data from Microsoft Kinect:

Room.setup.1. velocity. All 25 nodes

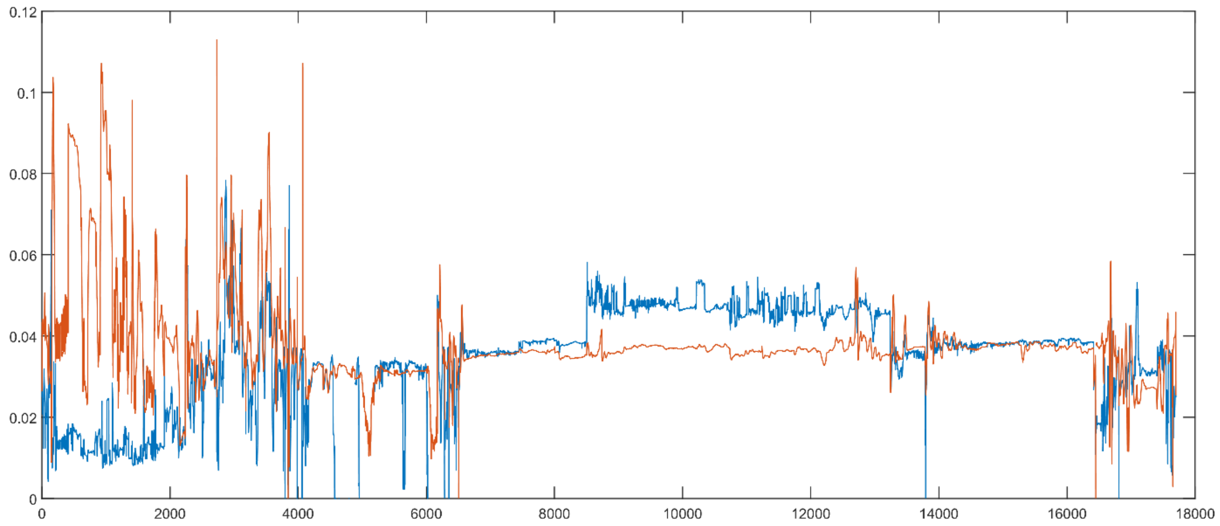


Processed data from Microsoft Kinect:

Room.setup.1. temp. node 1 and 4

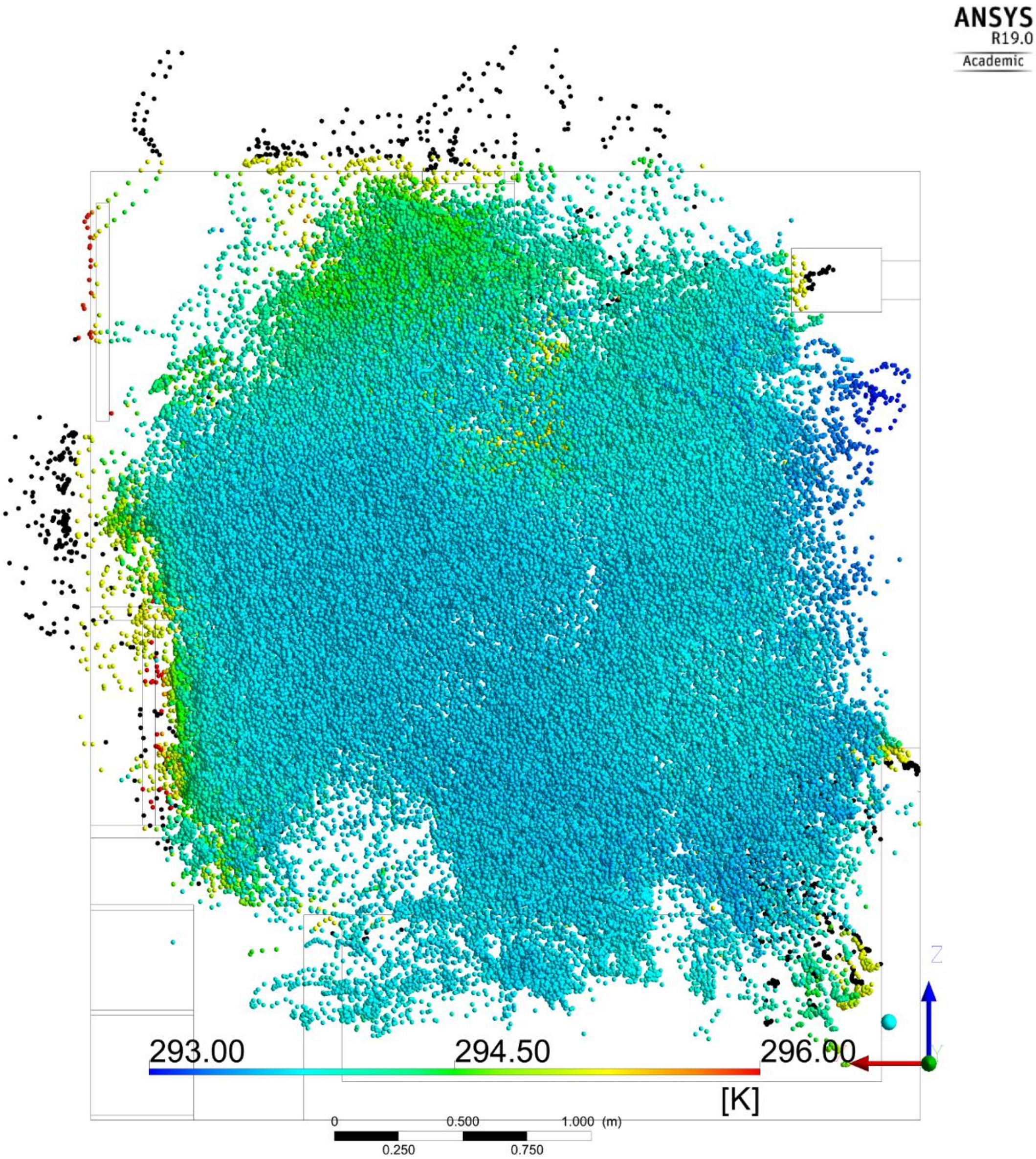


Room.setup.1. velocity. node 1 and 4



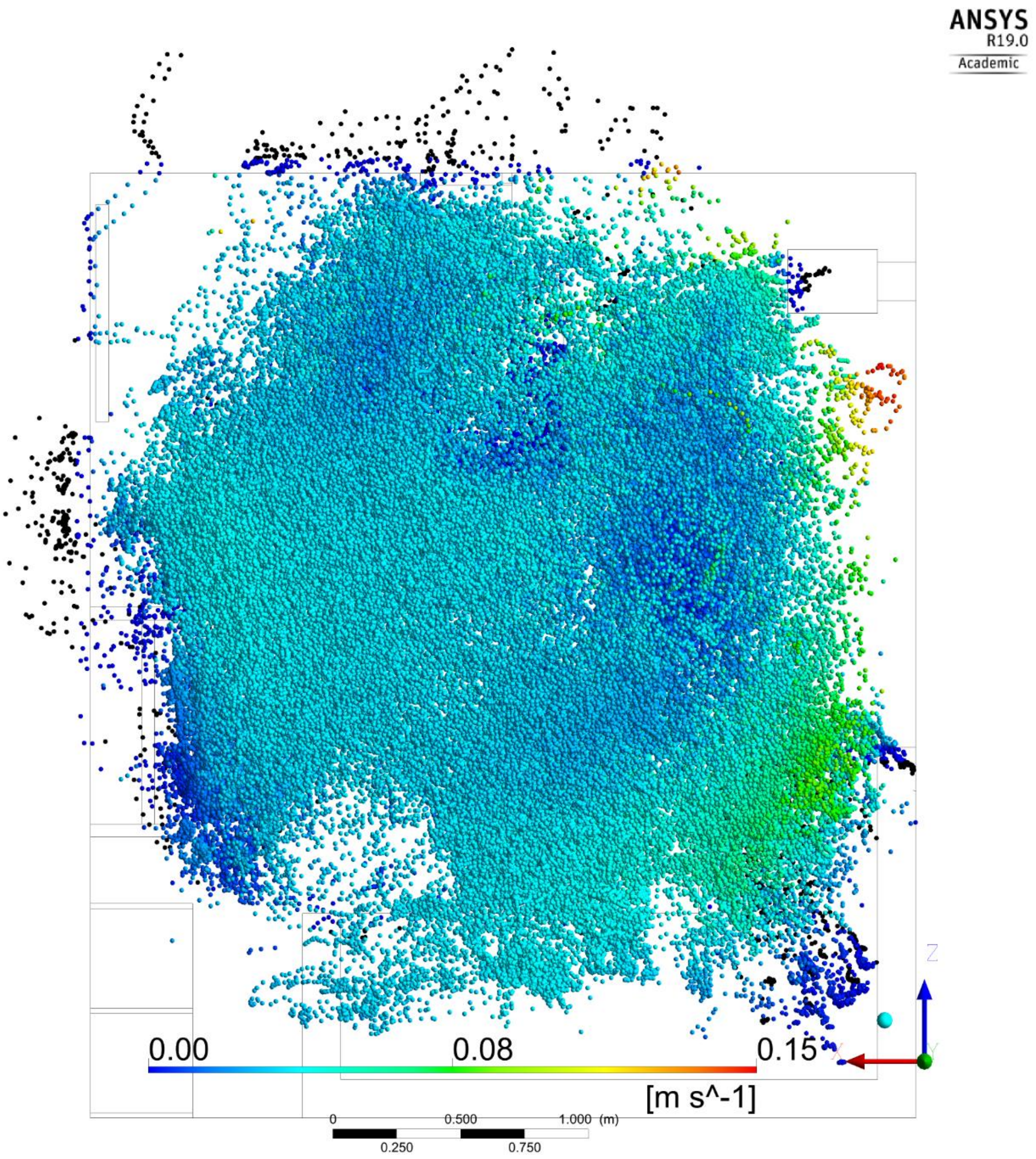
Processed data from Microsoft Kinect:

Room.setup.2. temperature. All 25 nodes



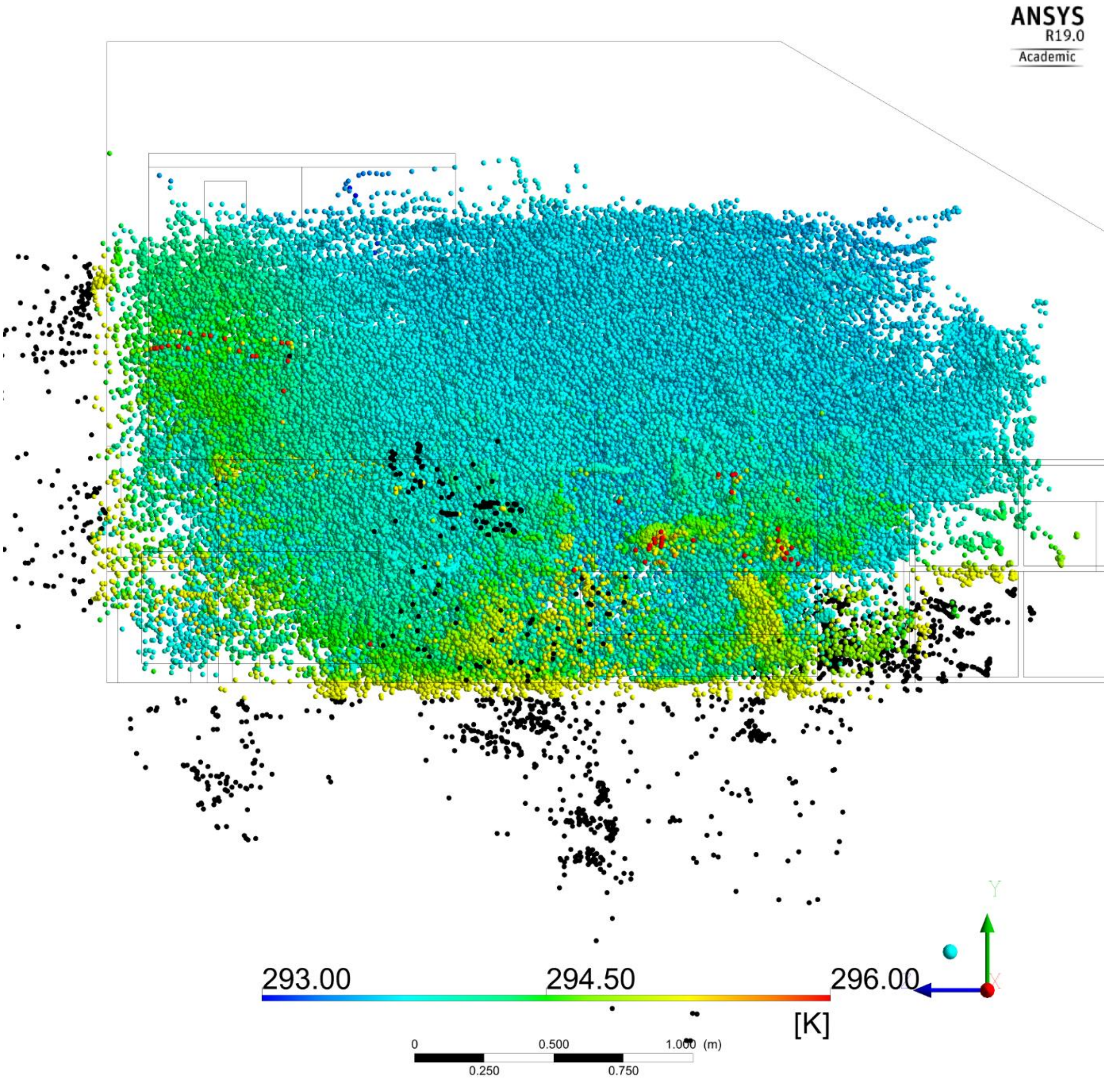
Processed data from Microsoft Kinect:

Room.setup.2. velocity. All 25 nodes



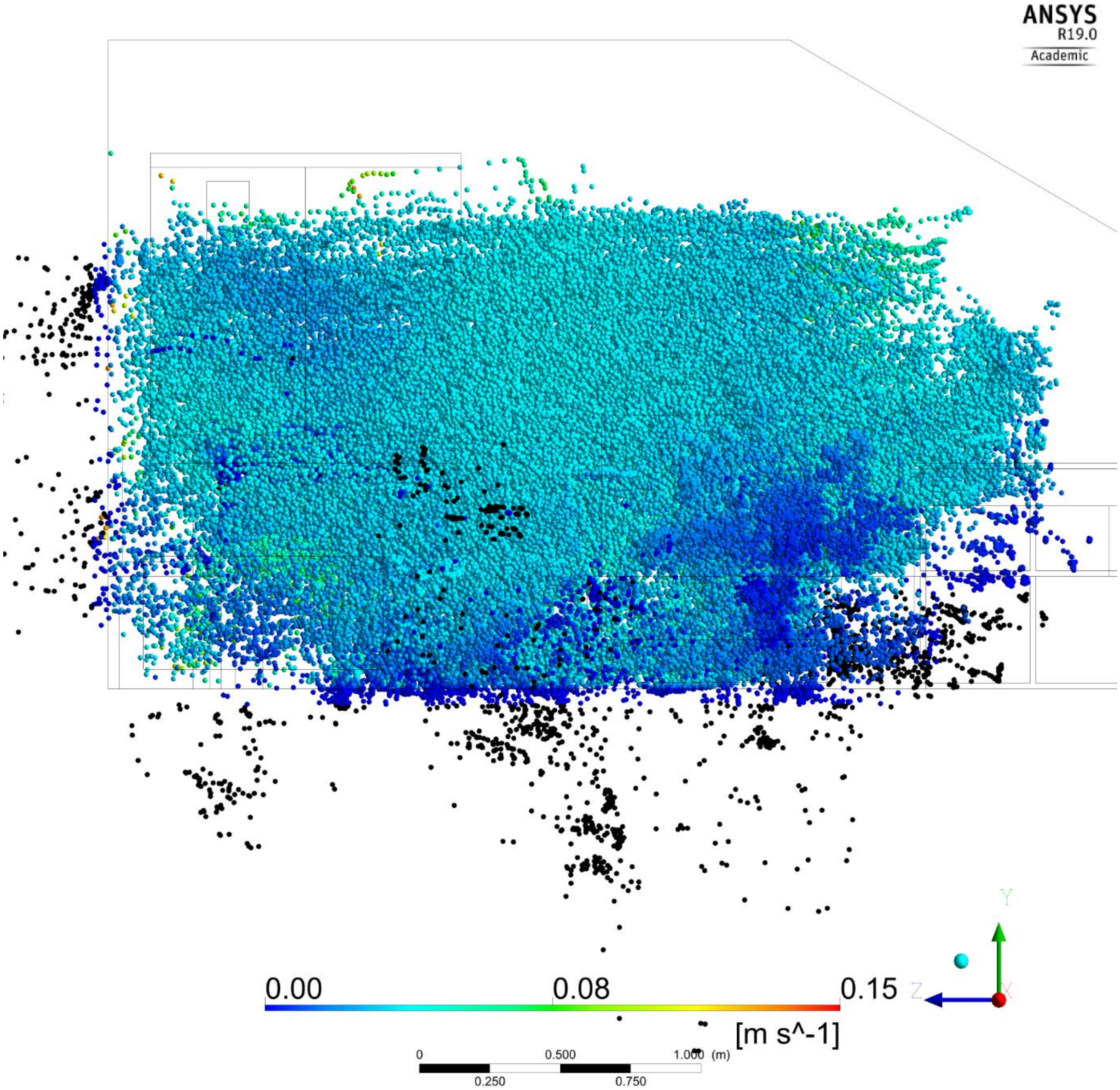
Processed data from Microsoft Kinect:

Room.setup.2. temperature. All 25 nodes



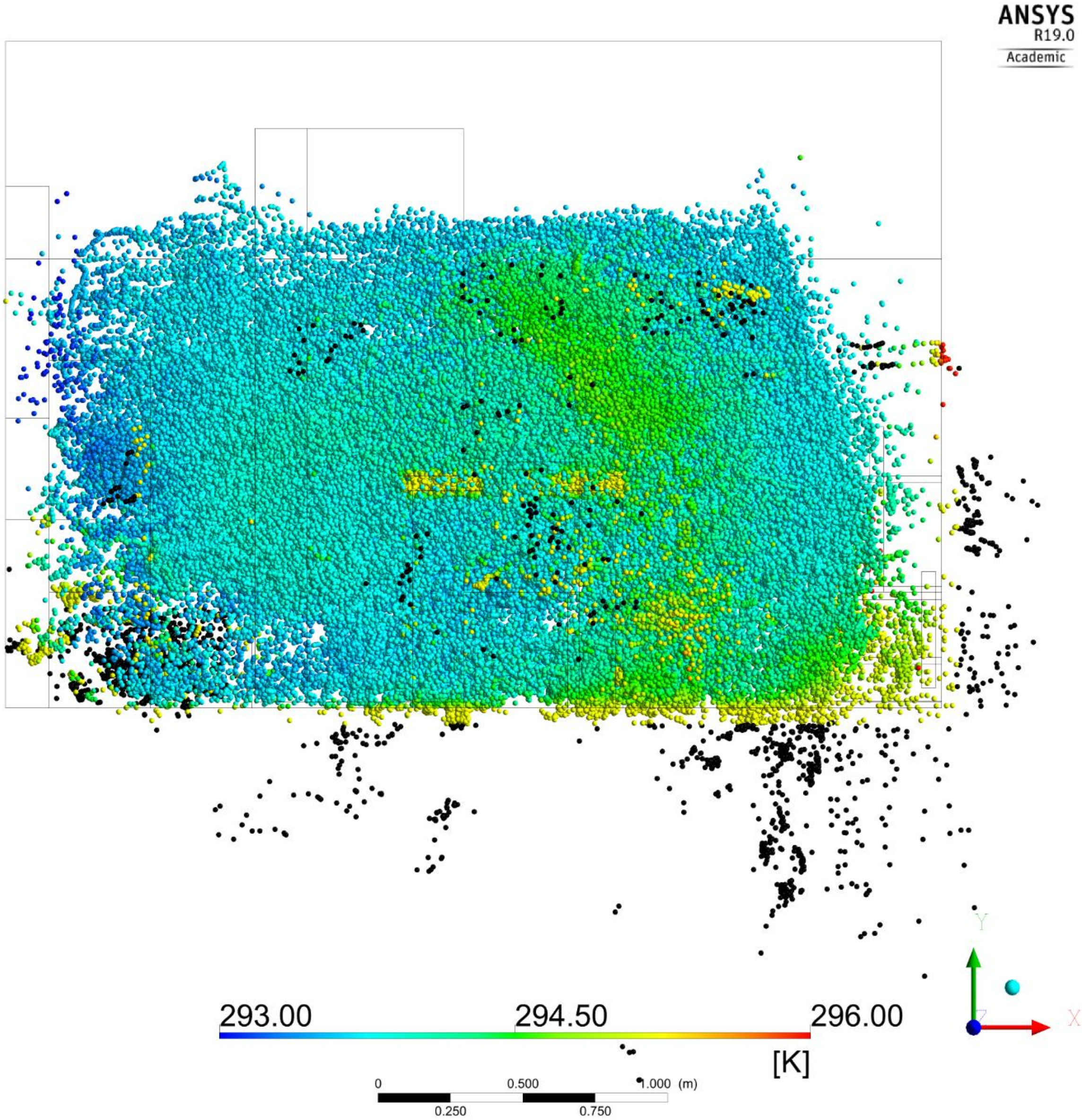
Processed data from Microsoft Kinect:

Room.setup.2. velocity. All 25 nodes



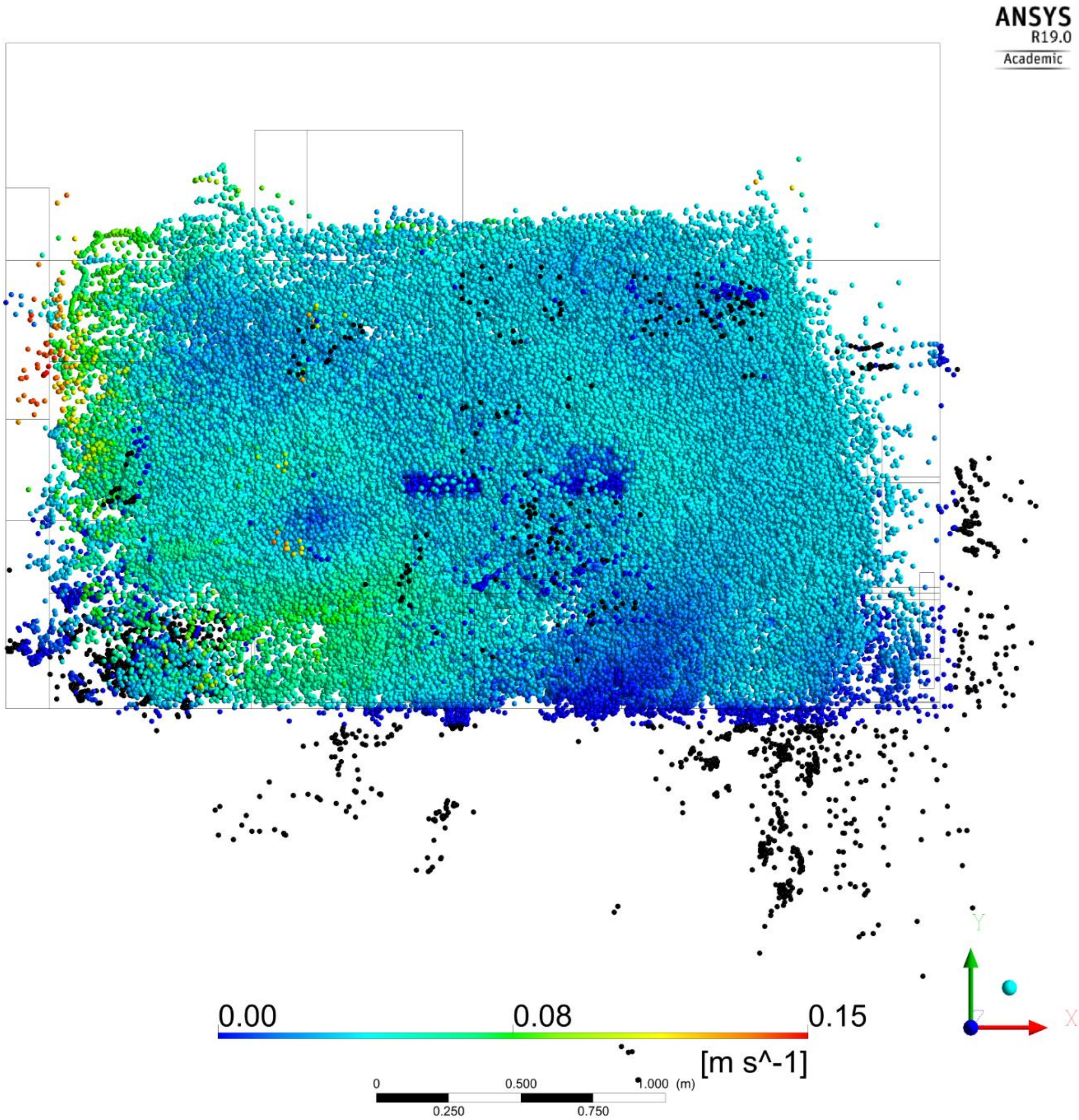
Processed data from Microsoft Kinect:

Room.setup.2. temp. All 25 nodes



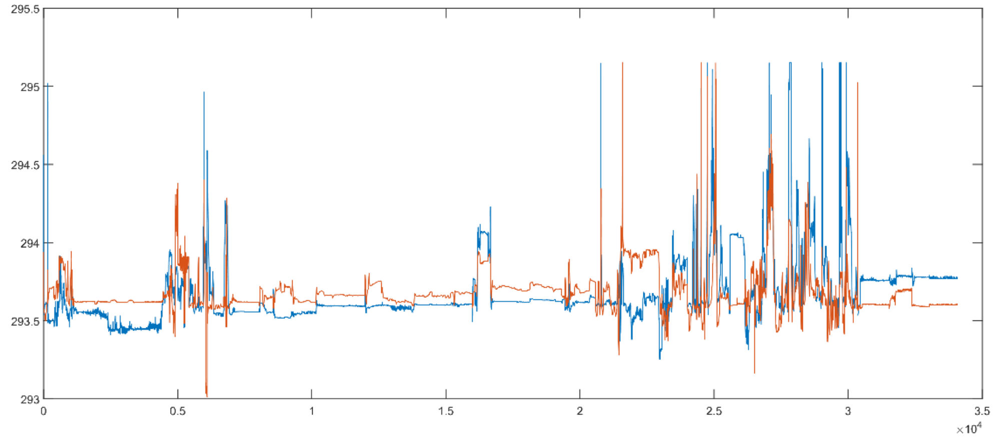
Processed data from Microsoft Kinect:

Room.setup.2. velocity. All 25 nodes

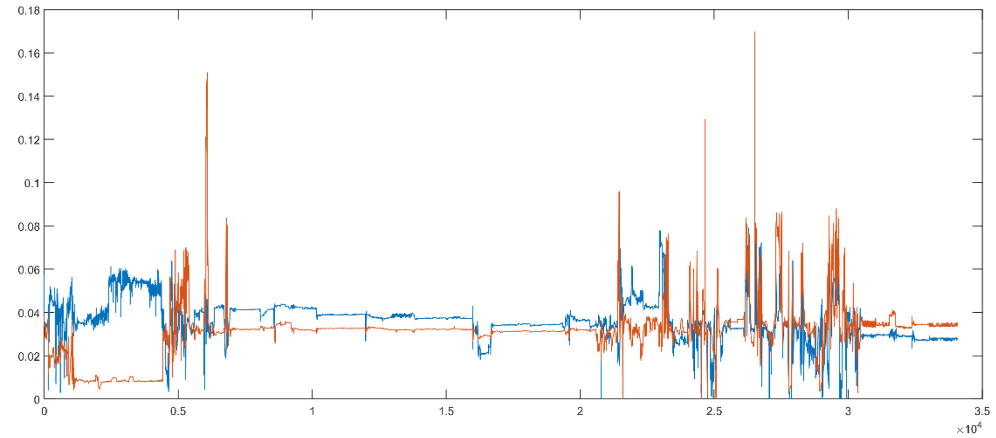


Processed data from Microsoft Kinect:

Room.setup.2. temp. node 1 and 4

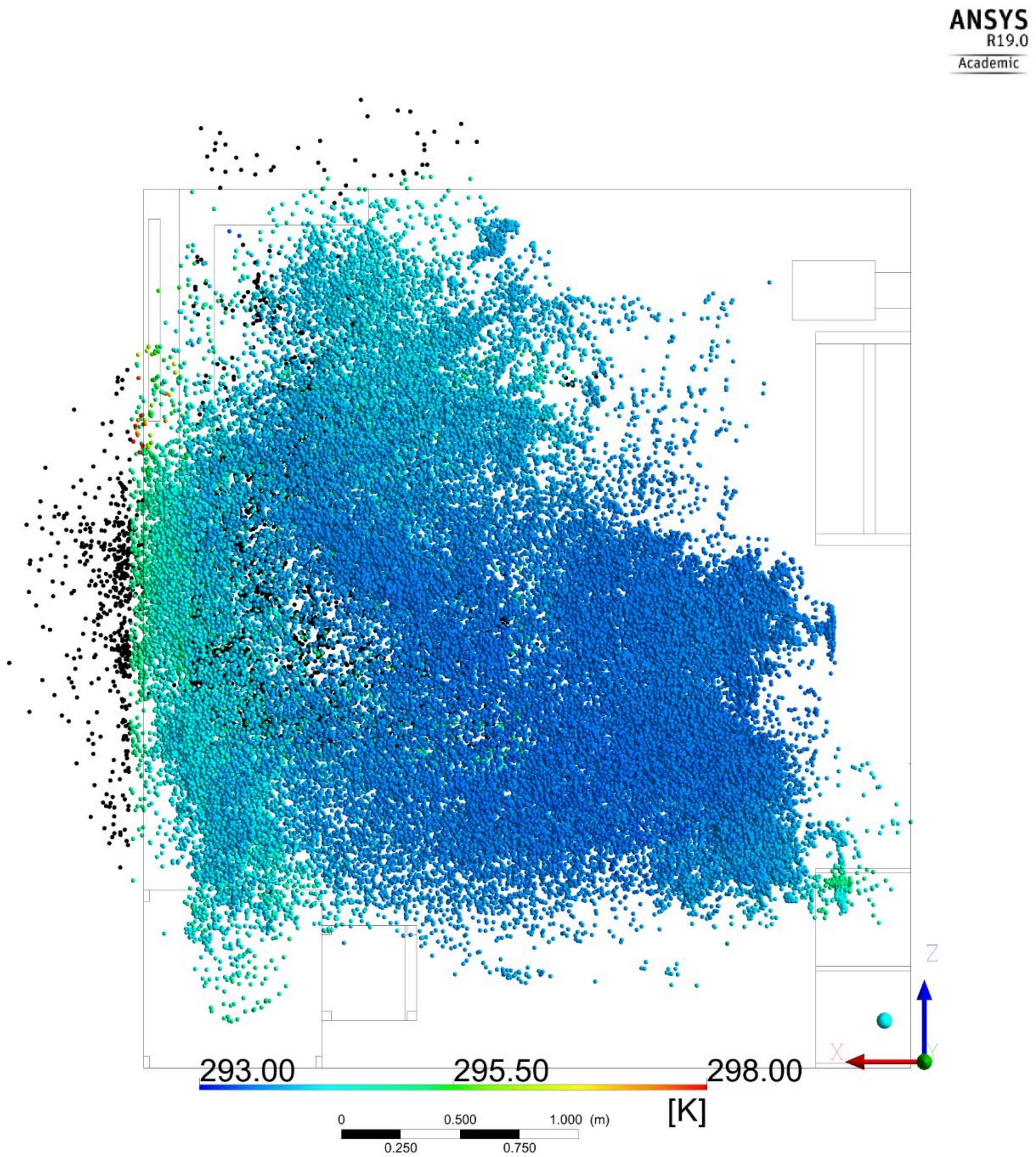


Room.setup.2. velocity. node 1 and 4



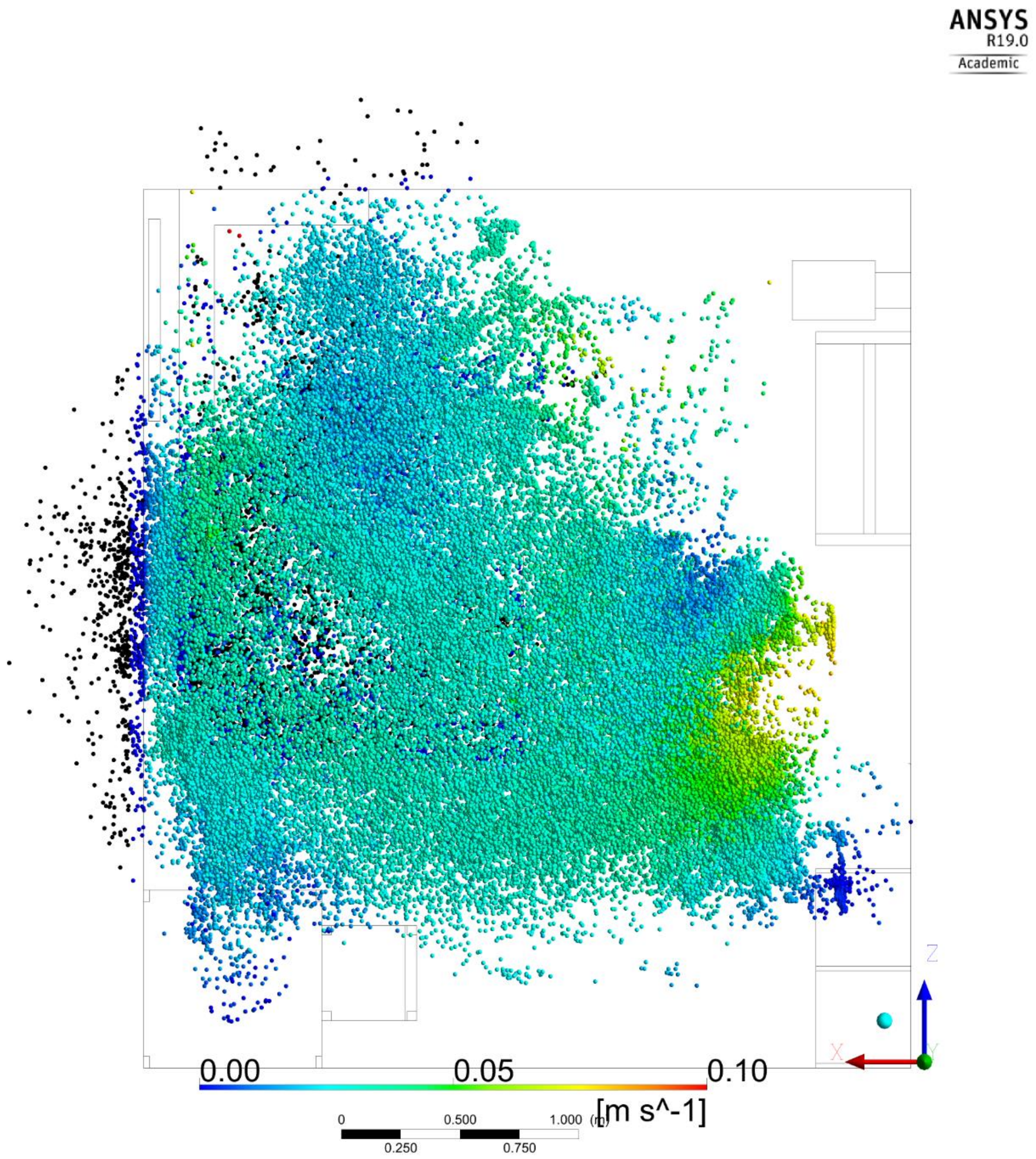
Processed data from Microsoft Kinect:

Room.setup.3. Temperature. All 25 nodes



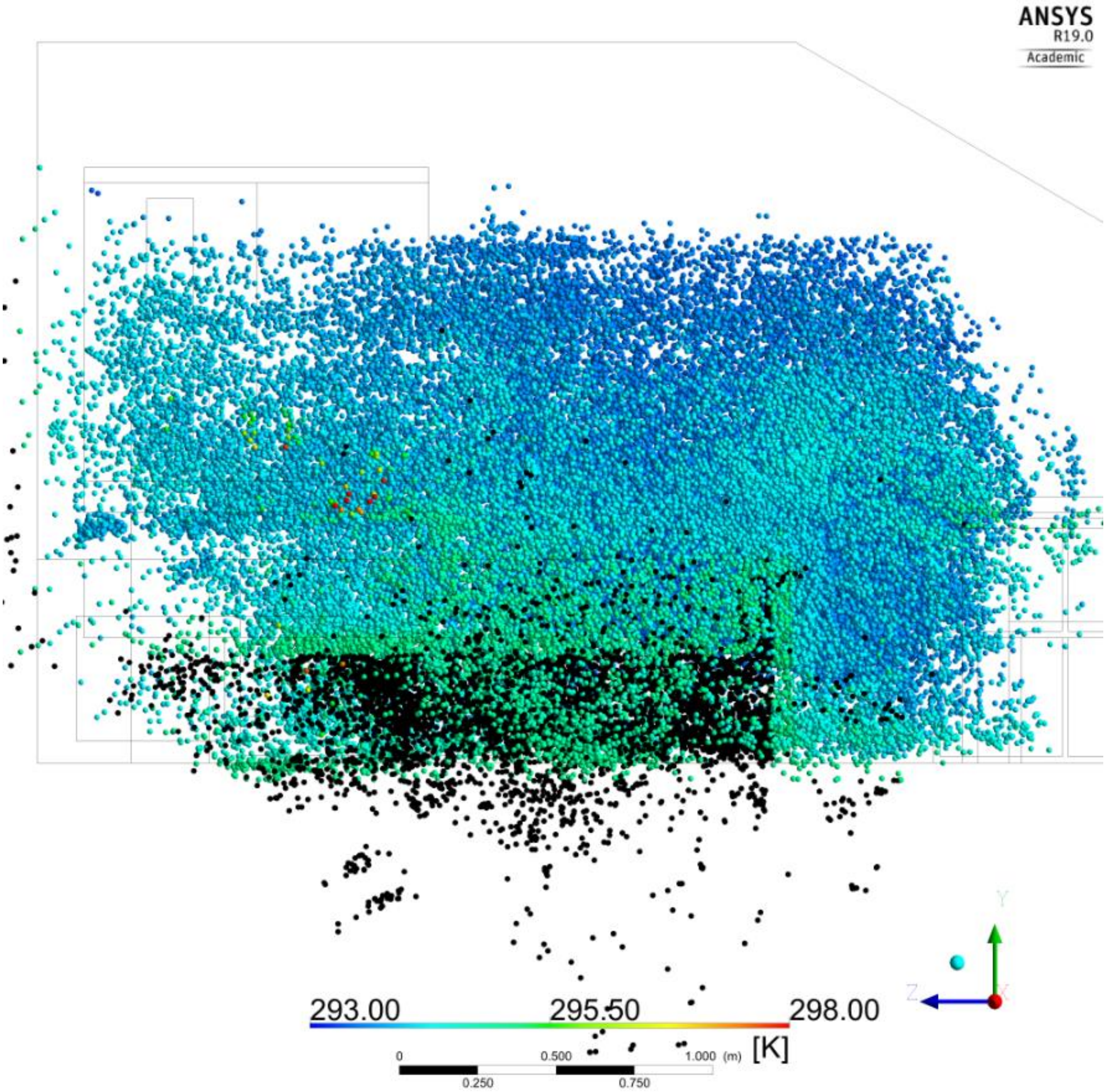
Processed data from Microsoft Kinect:

Room.setup.3. velocity. All 25 nodes



Processed data from Microsoft Kinect:

Room.setup.3. temperature. All 25 nodes



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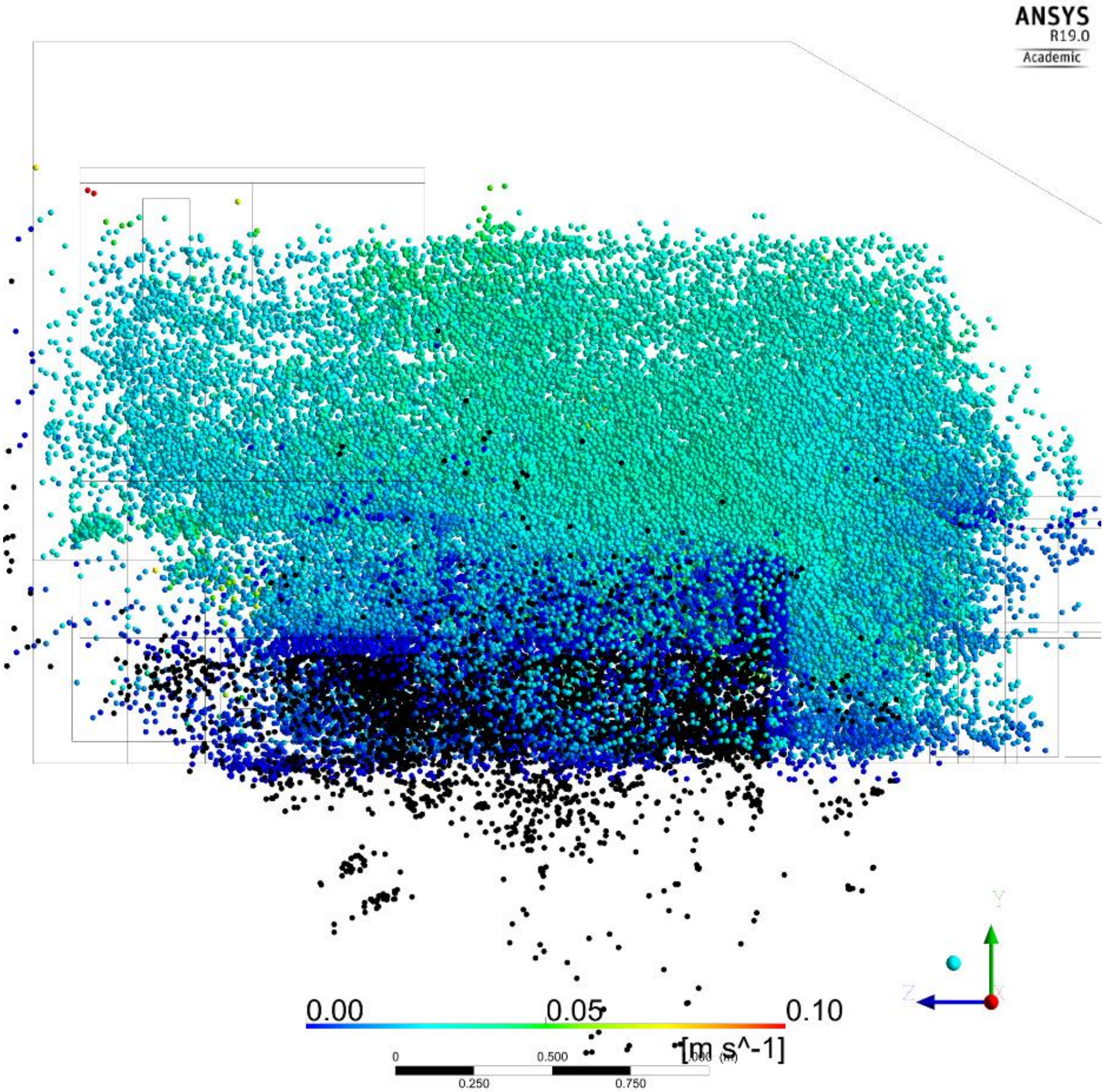
Room.setup.3. velocity. All 25 nodes



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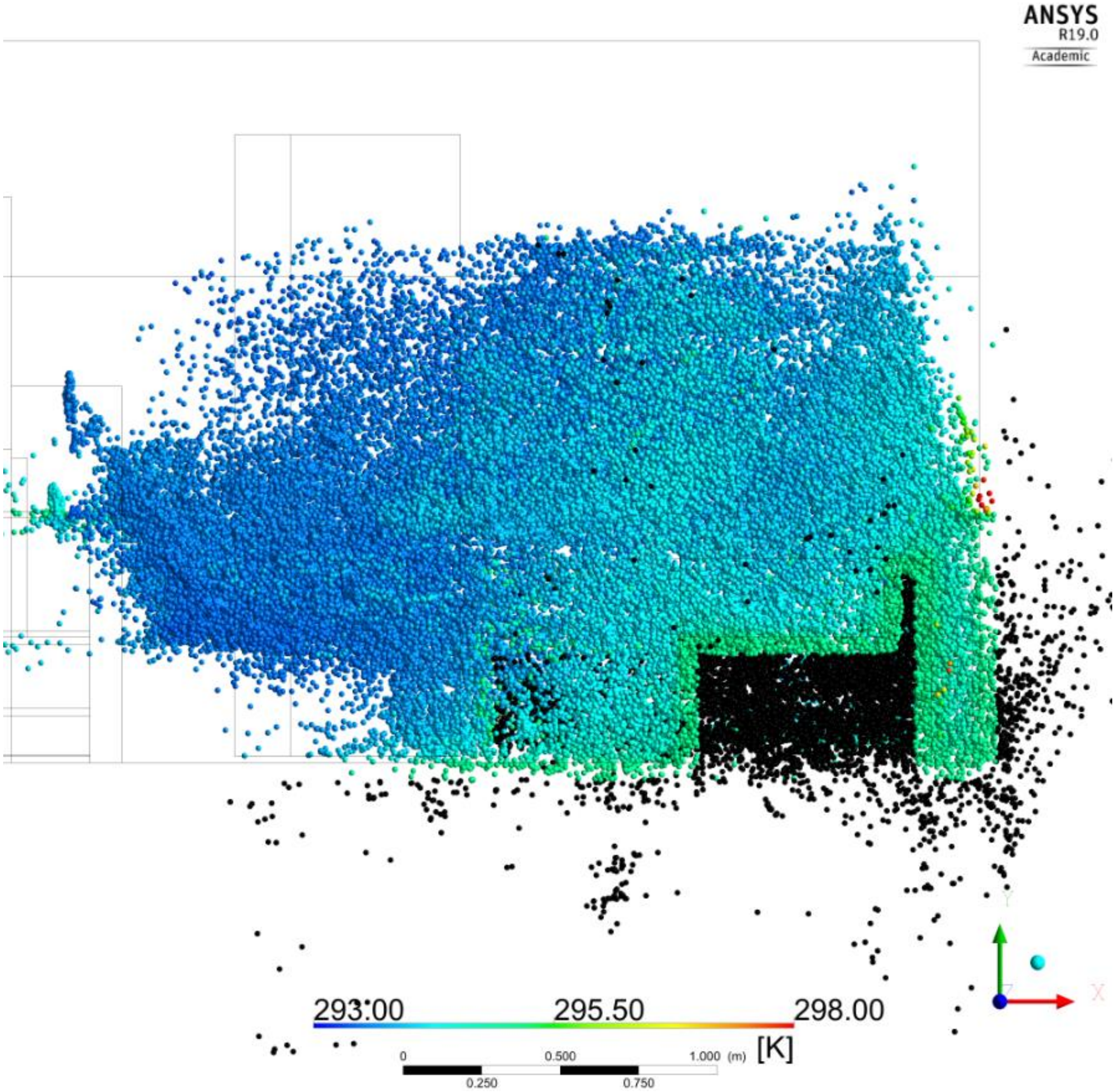
Room.setup.3. temperature. All 25 nodes



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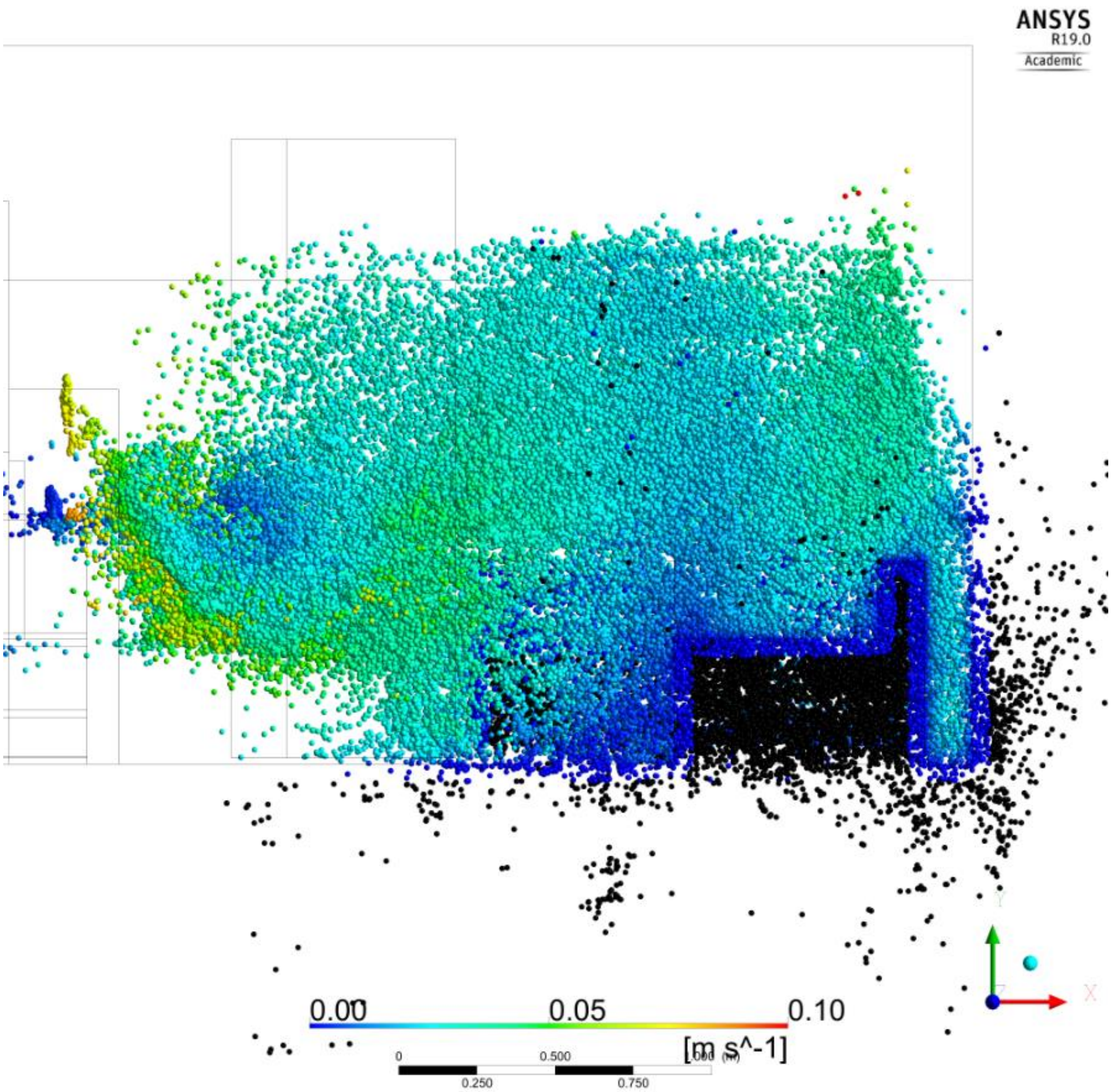
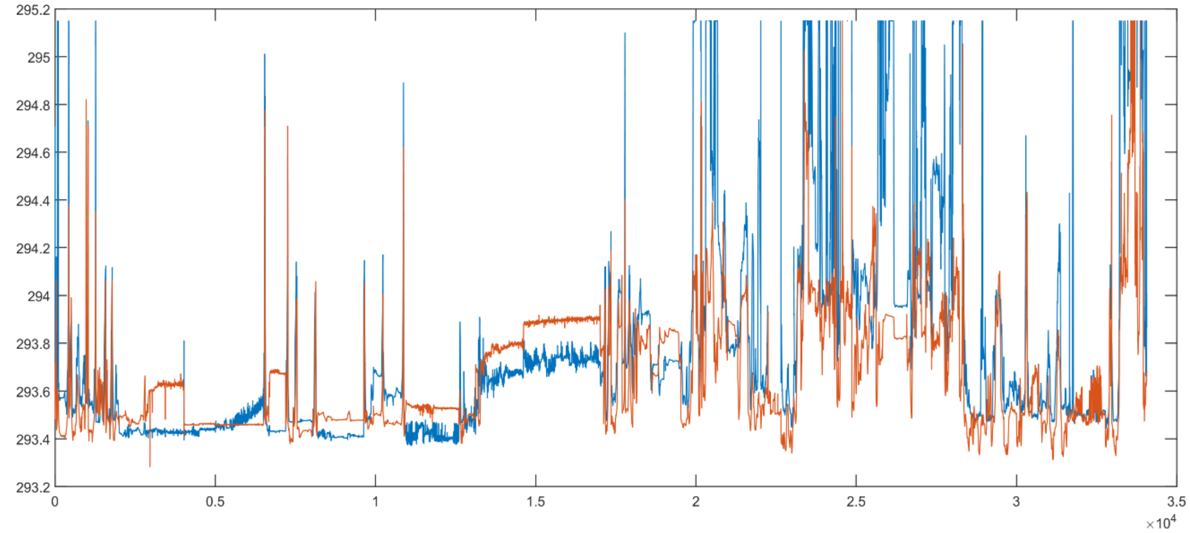
Room.setup.3. velocity. All 25 nodes

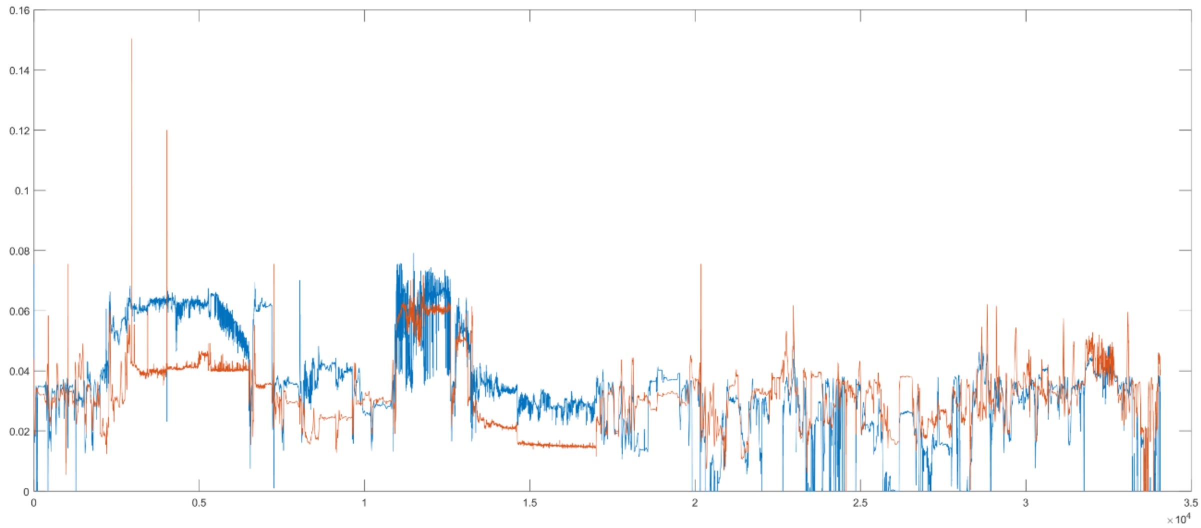


Processed data from Microsoft Kinect:

Room.setup.3. temperature. Node 1 and 4



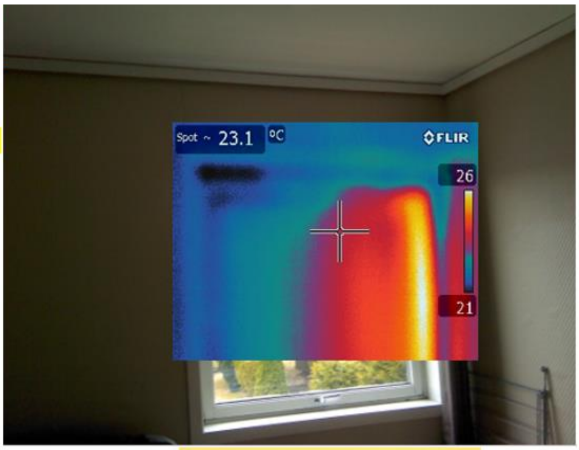
Room.setup.3. Velocity. Node 1 and 4



Processed data from thermal camera (BC)

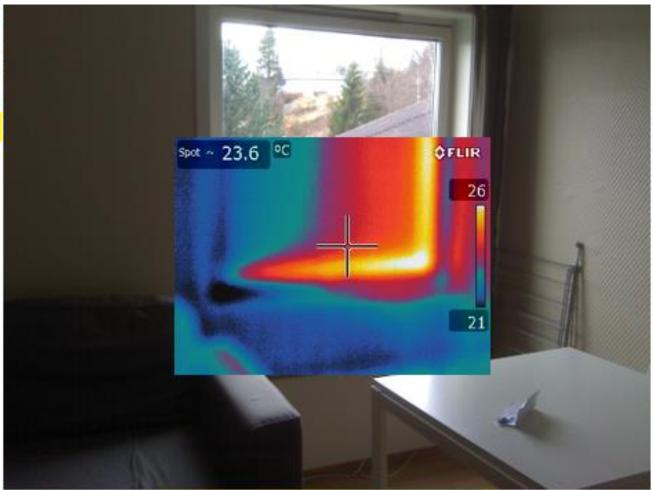
Window 1: The window frame has a lower temperature than the rest of the window (glass). the window opening is from the upper frame.

Window	Average temperature values [C]	Kelvin [K]
Top	18,9	293,05
left	22,47	296,62
right	24,66	298,81
TOTAL	*22,6*	*296,75*



Window 2: Second photo of the window

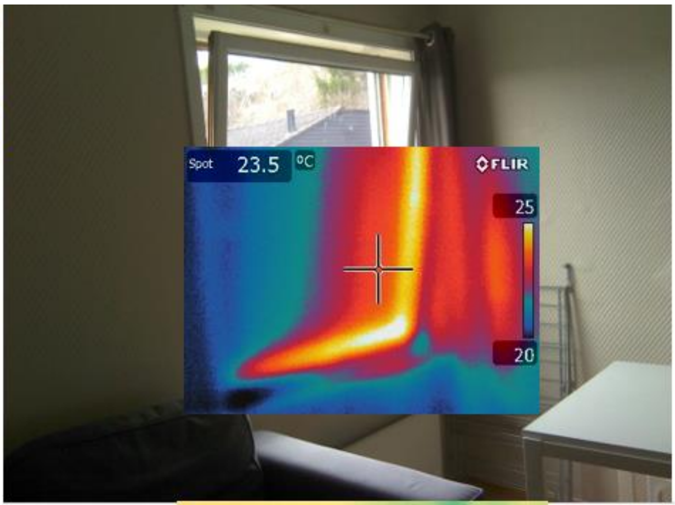
Window	Average temp.values	Kelvin [K]
Left	21,86	296,01
Right	23,43	297,58
Bottom	24,14	298,29
TOTAL	*22,35*	*296,5*

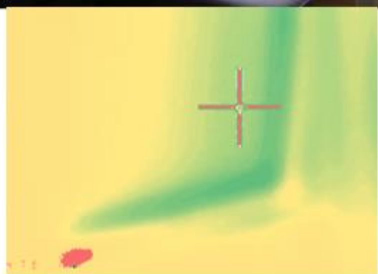


Processed data from thermal camera (BC)

Window 3: Third window photo

Window	Average temp.values	Kelvin [K]
Left	21,05	295,2
Right	22,84	296,99
Bottom	23,94	298,09
TOTAL	*21,81*	*295,96*





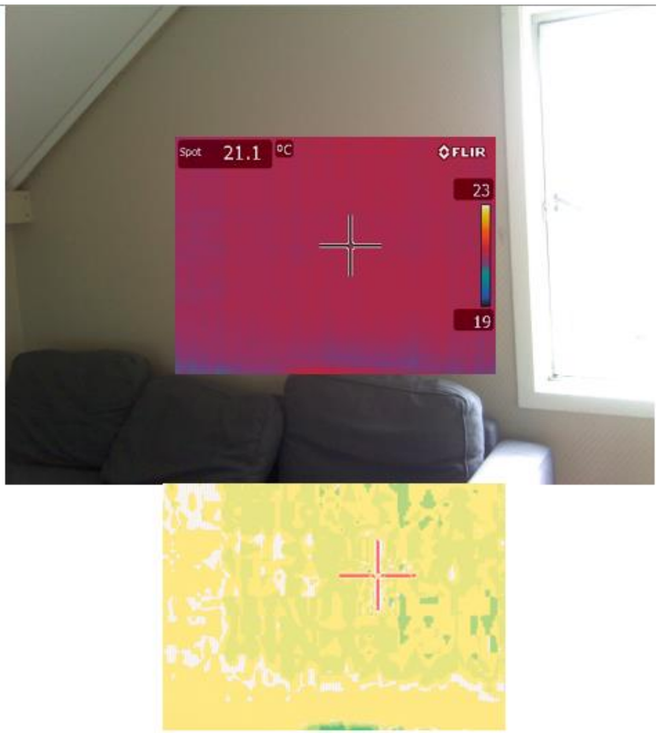
The average value of temp for all window surfaces (zones), considering all three photos taken:

	Celsius [°C]	Kelvin [K]
Left:	21,79333	295,9433
Right	23,64333	297,7933
Top:	18,9	293,05
Bottom	24,04	298,19

Processed data from thermal camera (BC)

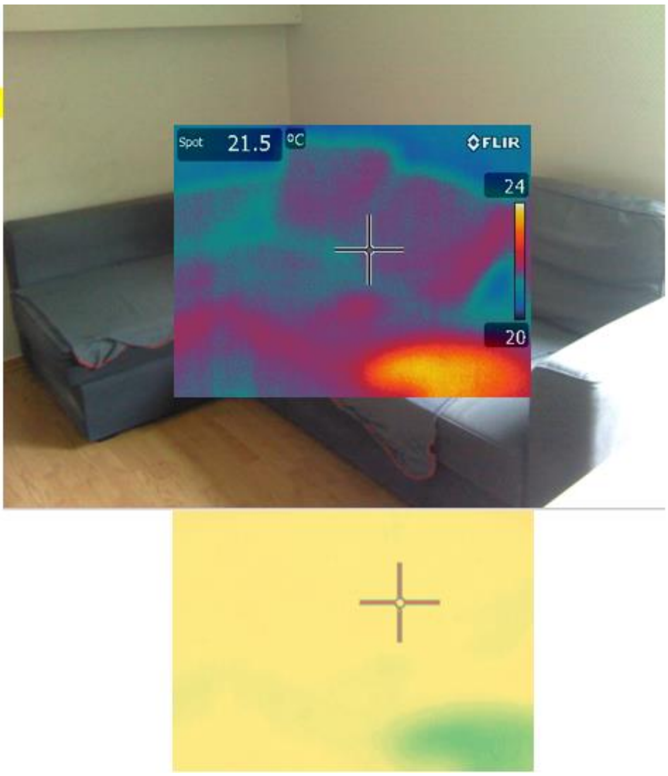
Thermal photo of a wall without any furniture covering it, displaying the average temperate of the wall inside the room.

	Average.temp.values	Kelvin [K]
Wall	20,916	295,066



Note that the Heat on the right side of the sofa is coming from the heater (and should be ignored).

Furniture (Sofa)	**Avr.Temp.Value**	**Kelvin [K]**
Red spot	23,14	297,29
Rest	21,4	295,55
TOTAL	*21,6*	*295,75*



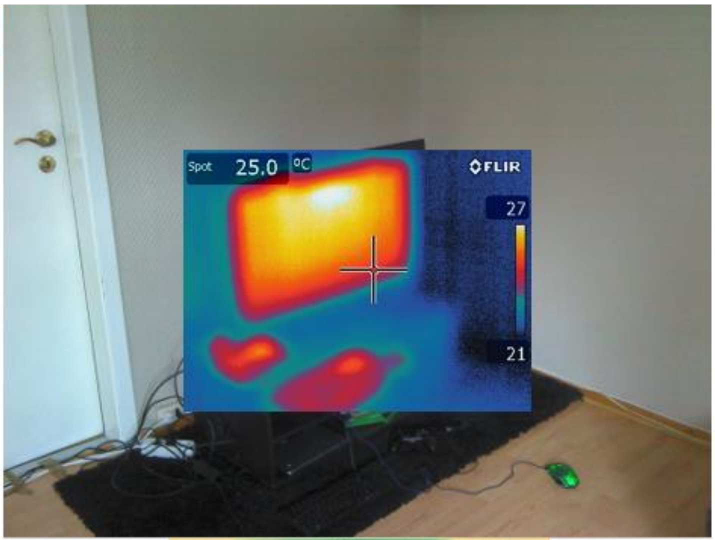
Processed data from thermal camera (BC)

This figure shows three devices with relatively high temperature value;

1. The TV
2. PC (connected to the Kinect device)
3. Kinect charger

Hence only the TV is included in the CFD simulation.

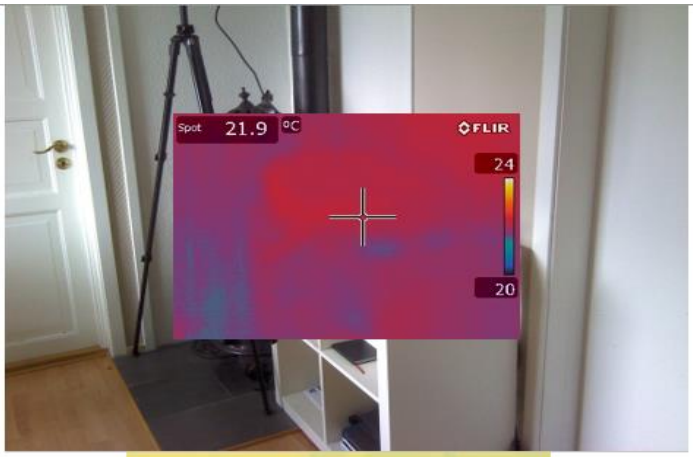
Furniture	avr.temp [C]	Kelvin [K]
TV	26,03	300,18
Wall	21,23	295,38

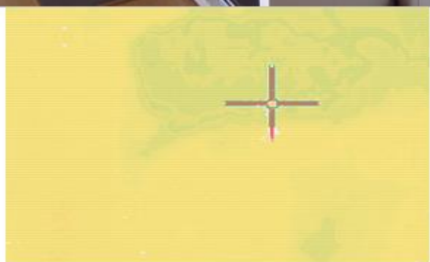


Processed data from thermal camera (BC)

Furniture: Shelf

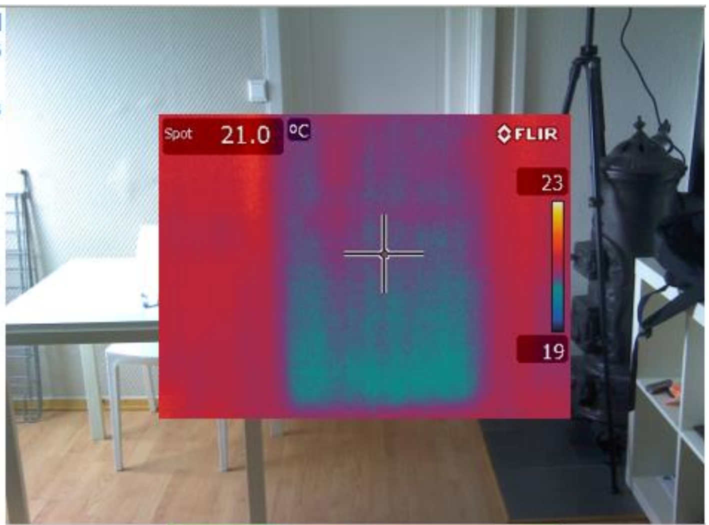
	Avr.temp [C]	Kelvin [K]
Shelf	21,82	295,97





Main door as mentioned in the paperwork.

	Avr.temp [C]	Kelvin [K]
Closed.Door	20,31	294,46
Wall	21,18	295,33



➔ the BC temperature for walls and furniture in the living room is set to be 21 °C (295.15 K), close to the processed data.

Processed data from Ventilation meter

Ventilation Meter Data

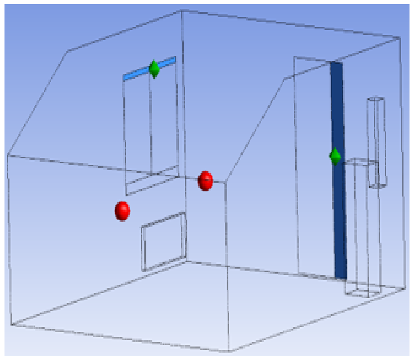
	Action (ON/OFF)	Velocity (m/s)				Temperature °C			
	Case.1	Take.1	Take.2	Take.3	Average	Take.1	Take.2	Take.3	Average
Window opening	ON	0,61	0,78	0,67	0,69	18,83	14,77	15,96	16,52
Door opening	ON	0,13	0,08	0,11	0,11	19,73	19,70	20,90	20,11
Mid.point in the room	-	0,03	0,04	0,02	0,03	19,42	20,70	19,80	19,97
Furthest point	-	0,01	0,02	0,02	0,02	21,40	20,70	20,50	20,87
	Case.2								
Window opening	ON	0,92	0,62	0,59	0,71	19,85	14,92	16,19	16,99
Door opening	OFF	0,16	0,11	0,16	0,14	20,42	21,20	19,91	20,51
Mid.point in the room	-	0,01	0,04	0,03	0,03	19,70	19,33	20,86	19,96
Furthest point	-	0,02	0,03	0,03	0,03	21,19	21,30	19,78	20,76
	Case.3								
Window opening	OFF	0,37	0,20	0,25	0,27	17,52	17,80	19,72	18,35
Door opening	ON	0,08	0,06	0,09	0,08	20,11	20,46	19,37	19,98
Mid.point in the room	-	0,02	0,02	0,04	0,03	19,20	21,55	19,64	20,13
Furthest point	-	0,03	0,00	0,00	0,01	21,32	20,74	20,50	20,85
	Case.4								
Window opening	OFF	0,32	0,15	0,21	0,23	19,23	18,44	17,12	18,26
Door opening	OFF	0,04	0,07	0,02	0,04	20,40	20,63	21,11	20,71
Mid.point in the room	-	0,01	0,03	0,00	0,01	19,87	21,04	20,20	20,37
Furthest point	-	0,00	0,00	0,02	0,01	22,14	21,74	20,68	21,52

	Velocity (m/s)	Temp. °C	Temp. K
Inlet	0,70	16,75	290,90
Door opening:	0,09250	294,46	
Mid.point	0,02833	294,12	
Point.f	0,02167	294,96	

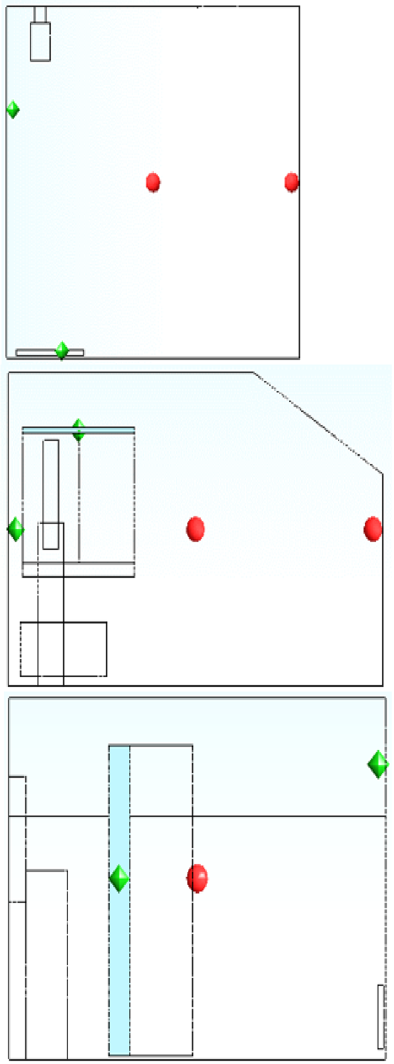
The velocity and temp is measured 3 times at each point.
Each action is 3 minutes apart.
The meter is held still for 30 sec at each position.
ON = Open
OFF= Closed

The main important measurmnets are in case 1, where the Window and Door are both open.
The other 3 measurments where done to have a better idea on what is effecting the rooms indoor air quality. (extra measurmnets)

By observing the data, there is no significan change between the door on/off action, its mostly the window opening that determens the velocity and temp inside the room.
The Total Average Value Of Inlet Velocity is 0,7 m/s and Temp 290,9 K



Top view, and side view of all 4 points tested.



Comparing data (real measurements and simulated values)

Comparing data (real measurements and simulated values)

Measured DATA			
	Velocity [m s^-1]	Temp [K]	C°
Window	0,700	290,90	16,75
Door opening:	0,093	294,46	20,31
Mid.point	0,028	294,12	19,97
Point.f	0,022	294,96	20,81

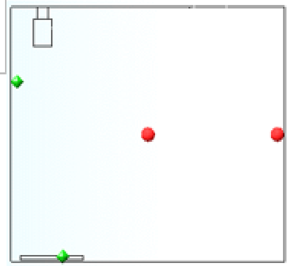
Real measurements is refering to the values collected from the living room using the tools mentioned in the report (which is also considerd the basis from the BC!).
Consist of the temp and velocity of 4 points insdie the living room + 6 other points/surfaces taken with the Thermal Camera.

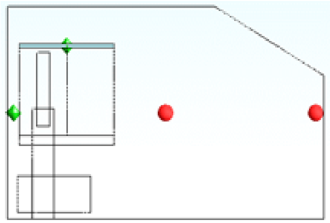
While Simulated values refers to the data gathered from ANSYS CFD Results.

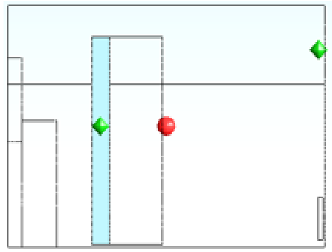
Some of thepossible errs could be from:
1. The velocity of the inlet in real life is not "constant" as it is in the simulation.
2. There could be some mainor errors when holding and measuring the velocity manuallty for each point to be presist!
3. the presition of the equipment in low velocity areas *

Room.Setup.0	**Velocity [m/s]**	**Temp [K]**	**°C**
Window Opening	0,700	290,90	16,75
Door Opening	0,086	294,04	19,89
Mid.Point	0,026	293,44	19,29
Point.X	0,024	293,85	19,70
Room.Setup.1			
Window Opening	0,700	290,90	16,75
Door opening	0,087	294,15	20,00
Mid.point	0,026	293,52	19,37
Point.X	0,028	293,83	19,68
Room.Setup.2			
Window Opening	0,700	290,90	16,75
Door opening	0,083	294,19	20,04
Mid.point	0,027	293,58	19,43
Point.X	0,026	293,94	19,79
Room.Setup.3			
Window Opening	0,700	290,90	16,75
Door Opening	0,088	293,99	19,84
Mid.Point	0,030	293,47	19,32
Point.X	0,023	293,90	19,75

	Velocity.accuracy	**Temp.accuracy**
Window	100,00 %	100,00 %
Door	93,34 %	97,93 %
Mid.point	92,02 %	96,57 %
Point.X	88,57 %	94,67 %
Window	100,00 %	100,00 %
Door	93,96 %	98,49 %
Mid.point	92,77 %	96,99 %
Point.X	72,00 %	94,58 %
Window	100,00 %	100,00 %
Door	89,87 %	98,65 %
Mid.point	96,79 %	97,29 %
Point.X	80,78 %	95,10 %
Window	100,00 %	100,00 %
Door	95,51 %	97,70 %
Mid.point	92,41 %	96,73 %
Point.X	93,08 %	94,93 %







Comparing Room Setups:

Comparing Room Setups

Room.Setup.0	Velocity [m s^-1]	Temp [K]	C°
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Door Opening	0,086	294,04	19,89
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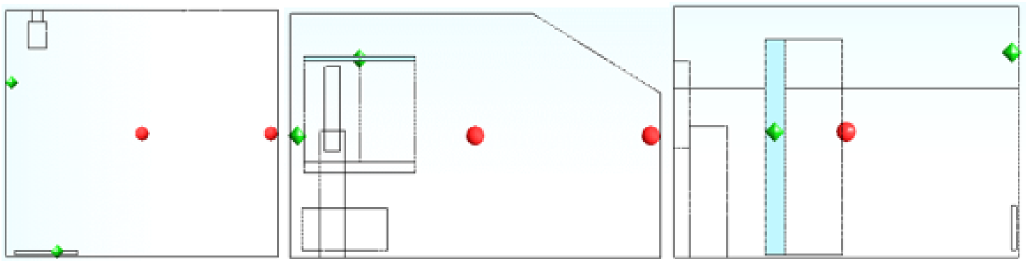

Room Dimentions	Total Size [m]
Width [X]	3,23
Height [Y]	2,3 & 1,55
Length [Z]	3,7

	Volume [m^3]	Between.20-22	in %	With and avr. Temp and vel. Temp	Vel
Room.Setup.0	25,797	23,362	90,56 %	19,58	0,035
Room.Setup.1	24,494	21,980	89,74 %	19,66	0,036
Room.Setup.2	24,494	22,153	90,44 %	19,71	0,038
Room.Setup.3	24,494	22,139	90,39 %	19,66	0,036

	Volume [m^3]	Below: 0,01 m/s	In %	below: 0,02 m/s	%	Below 0,03 m/s	%	Below 0,04	%
Room.Setup.0	25,797	1,729	6,70 %	4,228	16,39 %	12,856	50 %	17,635	68,36 %
Room.Setup.1	24,494	2,315	9,45 %	4,765	19,45 %	10,907	45 %	16,919	69,07 %
Room.Setup.2	24,494	1,884	7,69 %	4,035	16,48 %	9,271	38 %	16,005	65,34 %
Room.Setup.3	24,494	2,351	9,60 %	5,218	21,31 %	10,127	41 %	16,343	66,73 %