Villa Bagatelle
Technical Report

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Villa Bagatelle

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Technical Report

Department of Civil Engineering
Technical University of Denmark
2012

Villa Bagatelle

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Introduction

This report investigates options to renovate the listed building, considering both requirements due to the historical details of the building, and the desire to reduce the overall environmental impact of the building. Reducing energy demand not only reduces energy bills but also reduces the building's impact on the global environment, which has an effect on the building. In this report the current energy demand is analysed as well as the thermal comfort. Options to improve the building's fabric and infiltration are investigated.

The primary goal of this case study is to investigate passive ventilation options to provide a comfortable thermal environment for the building's occupants and comply with current building regulations. There is a strong desire from the client to avoid mechanical ventilation, as this will require ducting through the internal space. However, passive ventilation may be less energy efficient if no heat exchange is used. The report investigates the actual building, villa Bagatelle, located on the Jægersborgs alle 147, Gentofte, Denmark.

Background

Villa Bagatelle is an old residential building from 1920, which is now used as a day-care centre for children between 0.6 and 3 years.
The building is a 2-story building with unheated basement and unheated attic space. The building is heated by district heating with a heated area of 279 m^2 and a total area of 571m^2. The building is naturally ventilated, except for the bathrooms, which have mechanical extracts.

The owner of the building, Gentofte Municipality, has been granted permission from the Building Authority to use the building as a day-care centre, if the owner can demonstrate that the current building's ventilation complies with current Building Regulation BR10. The owner of the building has a strong desire to avoid mechanical ventilation that requires ducting through the internal space.

As the building is a working space, the owner of the building is also interested in investigating the current building's thermal comfort in comparison with the comfort requirements for the building's function and find the options for improvement.

The owner of the building is also interested in investigation of the building's current energy usage and suggestions for improvements that will comply with ventilation and thermal comfort requirements.

From the climate change prospective the suggested improvements should be as passive as possible to reduce the overall environmental impact of the building and to be easy to operate and maintain with the minimal running cost. The suggested improvements should also be robust to future climate possibilities.

Priority list

To investigate possible improvements to the building, a meeting with architect Christian Olsen (Gentofte municipality) was held to discuss a priority list and the possible options for improvements that do not change the building's historical character. Later, the priority list was also discussed with the project team: Henning Bakke Jensen (architect and project manager), Anne Thomsen (architect) Jeppe Zachariassen (operation manager) and Ulirk Nielsen (energy advisor) all from Gentofte Municipality.

During these meetings it was suggested that the main priority for the building is to provide a comfortable environment in a manner that respects the historical architectural details of the building as well as reducing energy consumption. As the building owner has a strong desire to avoid ducting in the rooms, sustainable passive ventilation options were considered. Applying sustainable ventilation solutions that require minimal maintenance and running cost will have an economical as well as environmental benefit.

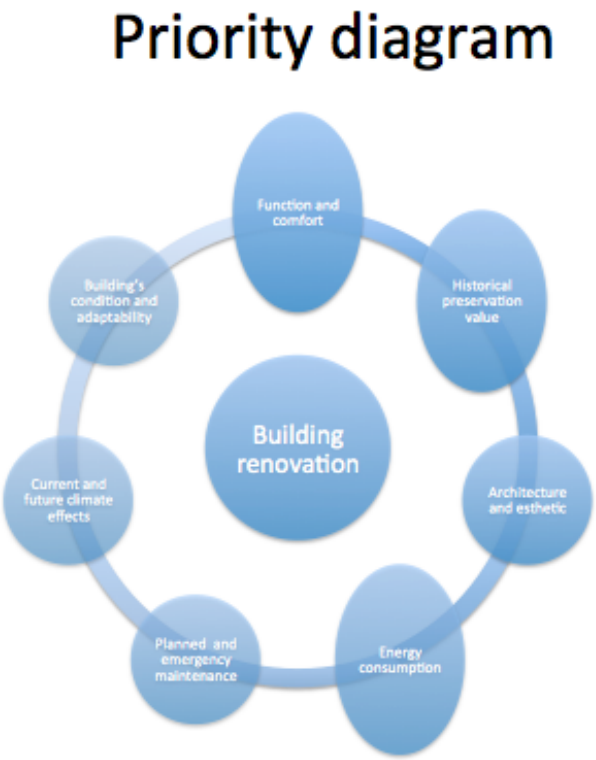


Figure 1 Priority diagram

The following passive options for improvement were considered:

1. Improving the building's envelop:

- Facades –
    - External insulation of the facades with no more than 50mm was considered. However, external insulation increases the risk of vapour condensation on the exterior of the structure. Later, it was confirmed that the cavities of the external facades on the ground

floor and 1st floor have been recently (2009) insulated with 170mm and 130mm of cavity insulation respectively.
    - Internal insulation is not advisable due to the risk of vapour condensation on the interior walls, which can lead to fungus growth.
- Basement – the ground floor construction above the unheated basement is not insulated. By insulating the basement ceiling, the heat loss to the basement can be reduced. However, the owner of the building has plans to convert the basement into occupied and heated space and is therefore concerned about the reduction of the basement height.
- Windows – The original wooden paned windows have secondary glazing placed 120mm from the external windows frames (4x120x4). The U-value of such construction is 2.8W/m^{2}K. It was proposed to add a 3rd layer of K-coated glazing on the secondary gazing frame and improve the U-value to 0.8 W/m^{2}K.

2. Natural ventilation:
It is easy to provide fresh air to the building when the ambient air temperature is close to required internal temperatures. For example, automatic controlled windows on both floors can serve as supply and outlet.

However, in a cold climate like Denmark's, heating is required at least ½ of the year, or when the outside temperature is lower than 17°C. To provide the required fresh air to the occupied rooms during the heating period, the following strategies were considered:

Option 1 – use the existing 2 chimneys, currently not used for heating, as an inlet and outlet for passive natural ventilation without heat recovery
Option 2- the same as Option 1, with the addition of a metal pipe in the exhaust air chimney as a passive heat exchanger
Option 3 – The fresh air will be supplied to the building via a few carefully chosen, automatically controlled top windows on both floors. The windows open only to provide the air change needed to meet ventilation requirements.

Current building's conditions

Energy usage

The building's energy performance has been calculated based on the building's annual usage obtained from Gentofte municipality for the period 2010-2012 (Appendix 1). In 2011 the building was not in use due to refurbishment, and therefore 2010 is used as a reference year. The heating is provided by district heating with an annual consumption of 83,000kWh in 2010. The hot water in villa Bagatelle is provided by district heating, with an annual consumption of water usage of 195 m^3 in 2010. The electricity usage was 10,082kWh.
To calculate the proportion of provided district heating warm water usage, the following assumption was made:

1m3 of district heating= 44 kWh
The total amount of district heating to provide 83,000kWh requires 83,000/44=1,886m3 of district heating.

I assume that the 30% of the total water consumption is supplied by district heating. The amount of heating that is due to warm water is
195x44x30% = 2,574kWh.

Although the building has a floor area of 571m^2, the building's attic and basement are not used and therefore are not included. The energy performance calculation is based on the building's conditioned area of 279m^2, which consists of the ground floor and 1st floor.

The energy rating of the building is
(83000x1.0+10082x3.31)/279=417kWh/m2, which corresponds to an energy performance class "G".

Infiltration

To determine the current infiltration a Blow Door test was carried out (Appendix 2). The current infiltration rate was measured at 7.88 ach or 6.42 l/s/m^2 under 50 Pa pressure, and 1.68ach under 4Pa (normal conditions).

Ventilation

Currently the building has no mechanical ventilation, except for the extractors in the bathrooms.

Required air changes per hour

Ground floor		1.4 ach
3*25+5*6+0.35*84.86=104.6 l/s	376.7m3/h	
1st Floor		
3*15+5*5+0.35*75.07=71.3l/s	256.6m3/h	1.1 ach

The current infiltration of 1.68ach is higher than the required ventilation of 1.4ach. The high infiltration makes it difficult to heat the building, increases cold draughts and heat loss, and reduces thermal comfort for the occupants.

Thermal comfort

The building's temperature and relative humidity have been measured during the period between 30.01.12 and 24.02.12. (Appendix 3). The graphs below show the internal temperatures and relative humidity in the kitchen and in the day-care room on the 1st floor for a week from Monday the 6th to Sunday the 12th of February. The kitchen is located on the north part of the building and the day-care room is in the south. The loggers were placed approximately 30-40 cm from the windows. The door between the kitchen and day-care rooms is often open during the occupied hours.

The internal temperatures are shown together with the measured relative humidity, which increases with the occupancy. In the kitchen on the 1st floor the average temperature is around 17°C and varies between 16-19°C. The internal temperature fluctuates with the outside temperature.

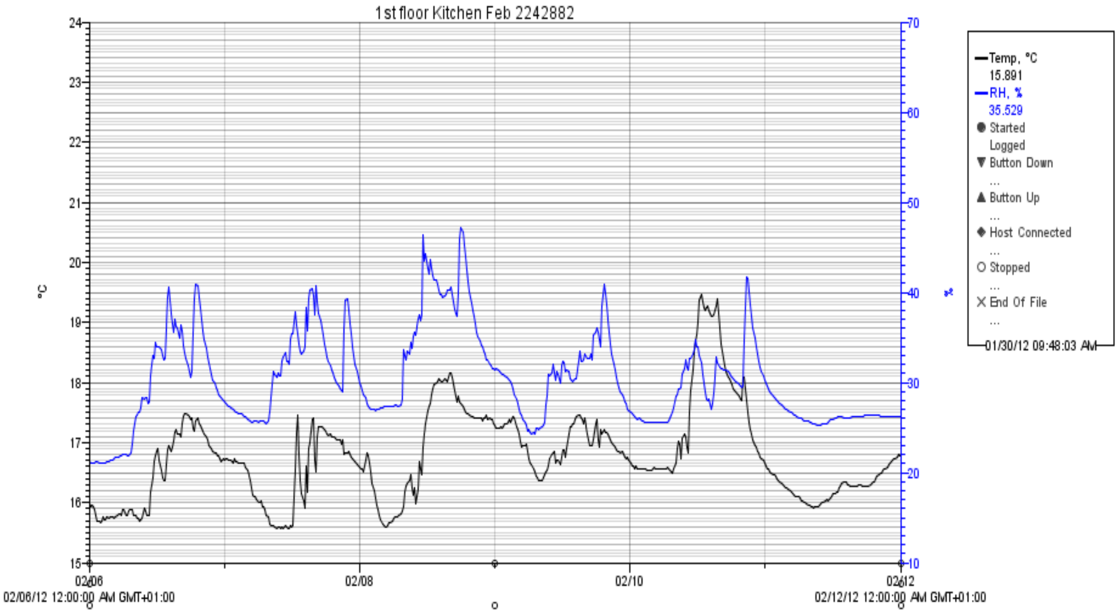


Figure 2 Temperature and relative humidity in kitchen 1st floor during the period 06/2-12/2

The temperature in the day-care 1st floor is between 16 -22°C with the highest temperatures occurring during times when the external temperature or the number of occupants is highest. This is the room where the occupants spend most of their time. The average temperature is 19.5°C, which is lower than the temperature accepted as comfortable, which is between 21-23°C.

The high frequency noise present in the curves is indicative of down draughts from infiltration and heat conduction through the glazing.

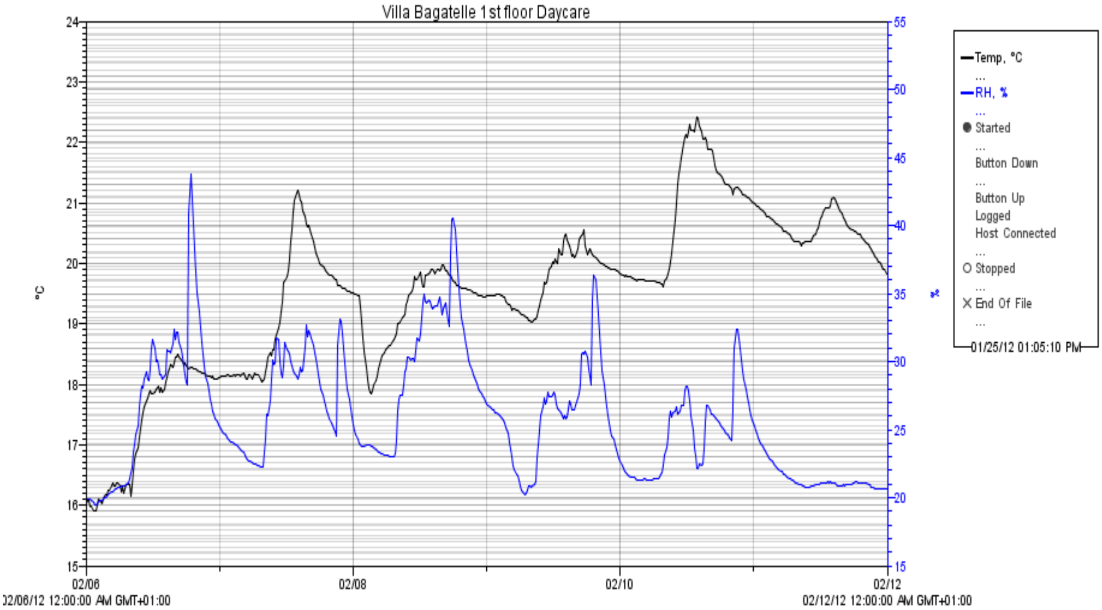


Figure 3 Temperature and relative humidity in day-care room 1st floor during the period 06/2-12/2

The outside temperature, which was measured on site during the same period, shows variations between -10 and 1°C.

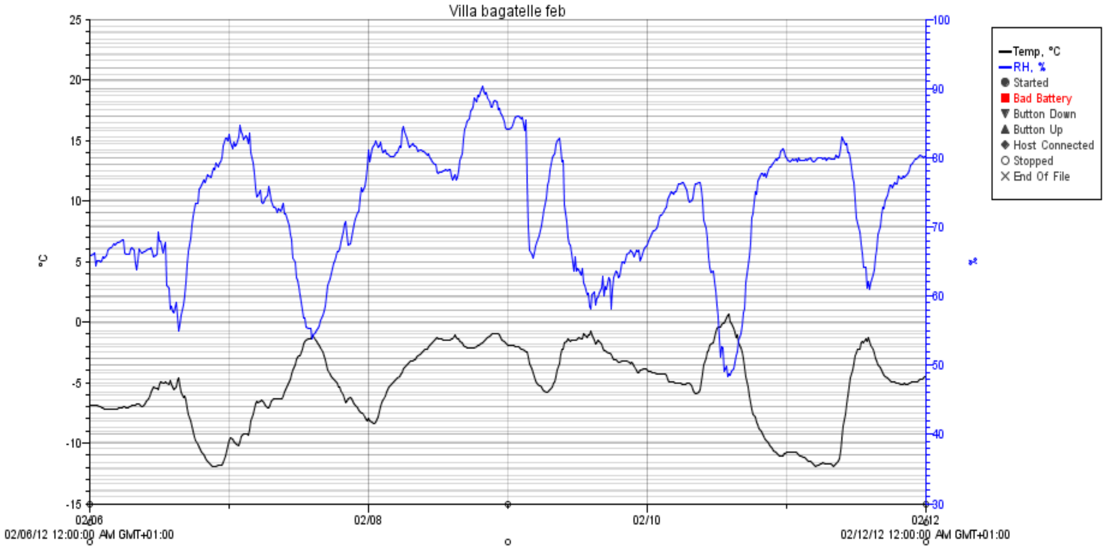


Figure 4 Temperature and relative humidity (RH) outside during the period 06/2-12/2

The measurements show that the internal tempertures fluctuate with the external conditions, indicating that the building is difficult to heat and to maintain comfortable temperatures during cold periods. The temperature fluctuation can also be due to the high infiltration rate of 1.68 ach. Also note that the infiltration rate can increase to 7ach under conditions where there is a large temperature difference between the interior and exterior and high winds. In these conditions, the pressure difference can been close to 50Pa, which increases infiltration to almost 7ach.

Description of experiments

A 3D model was created in the dynamic simulation program, TAS.
The model was created based on the drawings received from Gentofte Municipality, the description of the materials, as well as a visit to the site.
The building's 3D model has been zoned and exported to a TAS tbd file where the constructions, internal conditions, occupied hours, as well as weather data has been assigned.

	Area of the room m2	Lighting fittings	Lightings heat gains W/m2	Occupant latent heat W/m2	Occupant sensible heat W/m2
Ground floor		8.88		6.81	4.09
Day-care 1	24.00	240	10.00		
Day-care 2	37.08	240	6.47		
Day-care 3	23.60	240	10.17		
1st floor		12.93		6.19	4.61
Day-care 1	59.93	600	10.01		
Day-care 2	15.15	240	15.84		

Table 1. Calculation of occupant latent and sensible heat

Assumptions made based on ASHRAE standards

Latent heat for an adult male	75W
Latent heat for a woman 85%	
Latent heat for a child 75%	
Sensible heat	45W

The occupants' latent and sensible heat as well as lighting gains were calculated based on the ASHRAE standards.

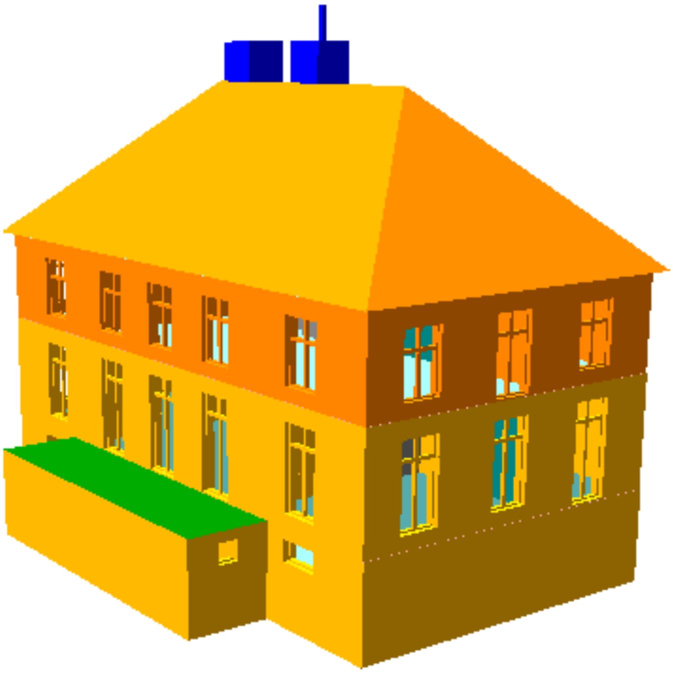
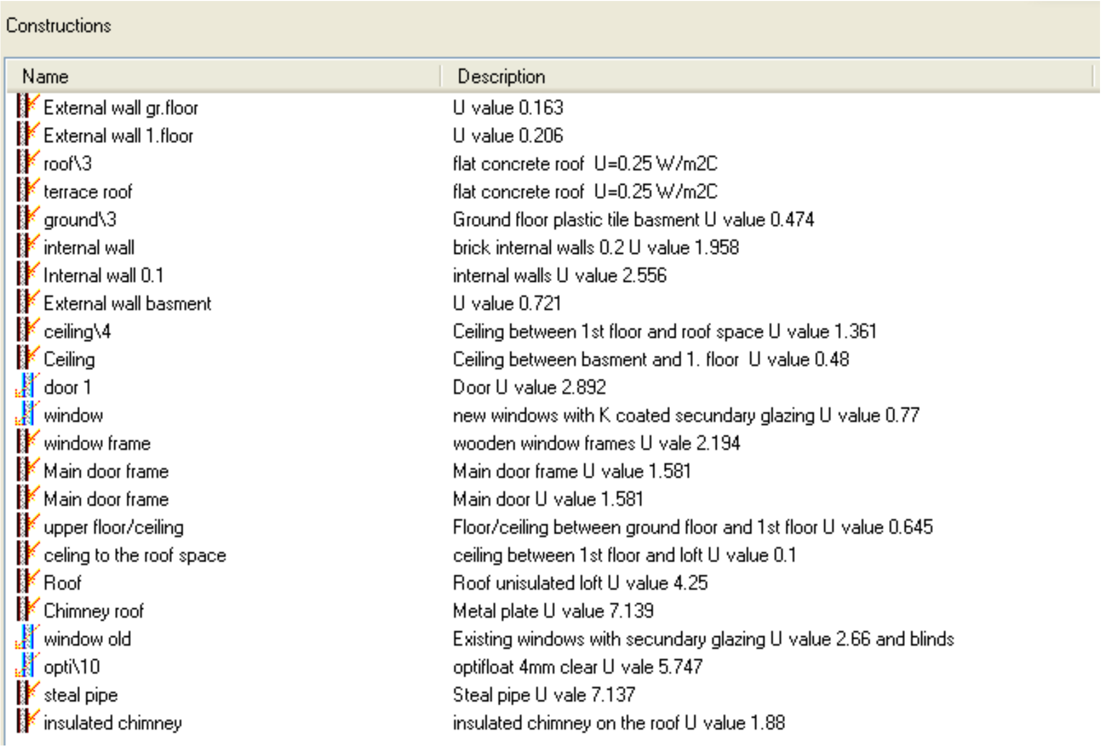


Figure 5 Model of the building created in TAS

Based on information received from Gentofte Municipality, the following materials have been assigned to the building's construction.



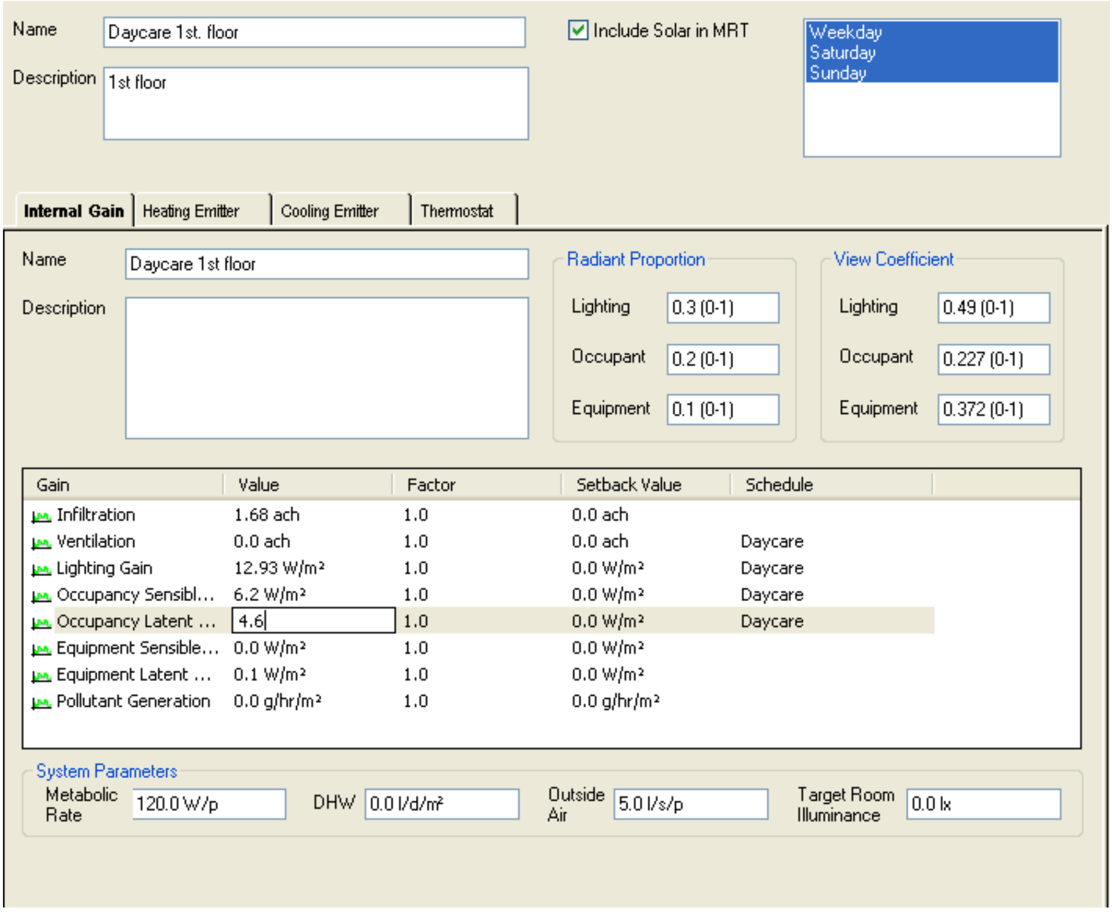
Constructions

Name	Description
External wall gr.floor	U value 0.163
External wall 1.floor	U value 0.206
roof\3	flat concrete roof U=0.25 W/m2C
terrace roof	flat concrete roof U=0.25 W/m2C
ground\3	Ground floor plastic tile basment U value 0.474
internal wall	brick internal walls 0.2 U value 1.958
Internal wall 0.1	internal walls U value 2.556
External wall basment	U value 0.721
ceiling\4	Ceiling between 1st floor and roof space U value 1.361
Ceiling	Ceiling between basment and 1. floor U value 0.48
door 1	Door U value 2.892
window	new windows with K coated secundary glazing U value 0.77
window frame	wooden window frames U vale 2.194
Main door frame	Main door frame U value 1.581
Main door frame	Main door U value 1.581
upper floor/ceiling	Floor/ceiling between ground floor and 1st floor U value 0.645
celing to the roof space	ceiling between 1st floor and loft U value 0.1
Roof	Roof unisulated loft U value 4.25
Chimney roof	Metal plate U value 7.139
window old	Existing windows with secundary glazing U value 2.66 and blinds
opti\10	optifloat 4mm clear U vale 5.747
steal pipe	Steal pipe U vale 7.137
insulated chimney	insulated chimney on the roof U value 1.88

Figure 6 Constructions applied for the TAS model

The weather file for this simulation was taken from an ASHRAE Design Conditions Design Day Data file (DDY) (DNK_Copenhagen.061800_IWEC.ddy), created for the year 1989.

The internal conditions for the occupied areas include calculation of internal gains due to lighting and occupant heat. (Table 1)



Name: Daycare 1st. floor

Description: 1st floor

☑ Include Solar in MRT

Weekday
Saturday
Sunday

Name: Daycare 1st floor

Description:

Radiant Proportion

Lighting	0.3 (0-1)
Occupant	0.2 (0-1)
Equipment	0.1 (0-1)

View Coefficient

Lighting	0.49 (0-1)
Occupant	0.227 (0-1)
Equipment	0.372 (0-1)

Gain	Value	Factor	Setback Value	Schedule
Infiltration	1.68 ach	1.0	0.0 ach	
Ventilation	0.0 ach	1.0	0.0 ach	Daycare
Lighting Gain	12.93 W/m²	1.0	0.0 W/m²	Daycare
Occupancy Sensibl...	6.2 W/m²	1.0	0.0 W/m²	Daycare
Occupancy Latent ...	4.6	1.0	0.0 W/m²	Daycare
Equipment Sensible...	0.0 W/m²	1.0	0.0 W/m²	
Equipment Latent ...	0.1 W/m²	1.0	0.0 W/m²	
Pollutant Generation	0.0 g/hr/m²	1.0	0.0 g/hr/m²	

System Parameters

Metabolic Rate: 120.0 W/p
DHW: 0.0 l/d/m²
Outside Air: 5.0 l/s/p
Target Room Illuminance: 0.0 lx

Figure 7 Internal conditions applied for the model

The infiltration was measured by an infiltration test that was carried out on the 19.03.12 (Appendix 2.1). The test showed that the actual infiltration is 1.68ach at (4Pa normal conditions) which is higher than the required ventilation of 1.4 ach. At the moment there is no ventilation in the building except for extractor fans in the bathrooms.

To verify the model's accuracy, the building was simulated with the actual infiltration of 1.68 in all occupied space and no infiltration in the unheated and unoccupied spaces such as roof, chimneys, basement and back stairs, as these spaces were excluded from the infiltration test.

The building has been simulated with heating without night- or weekend sinking. The temperature in the occupied rooms such as day-care rooms 1st and ground floor has been kept constant within the range 20-23° C. The temperature in other heated rooms, circulation, bathrooms and kitchens has been kept between 19-23°C.

The following simulations are intended to (i) verify the accuracy of the model, and then determine (ii) the heat loss due to the building fabric, (iii) the energy required to heat the replaced air due to ventilation (with no heat recovery), (and iv) the heat loss due to infiltration.

I then considered a scenario in which the infiltration is reduced to 0.07 and examined the energy requirements for a passive ventilation system with no heat recovery.

Experiment 0: Verification of the model

Experiment 0 simulates the actual conditions in the building, i.e.

- Measured infiltration of 1.68 ach at a wind speed of 3m/s and a function of the environmental wind speed
- No ventilation
- Actual heating gains, such as solar, occupants, heating features and lighting.
- Temperatures for heated spaces are set between 20-23 in the occupied areas and 19-23 in other rooms
- Internal blinds have been applied to all windows, as all windows have curtains or blinds, which can be manually drawn by the occupants in the building.

The simulation is based on hourly temperature and wind data for the year 1989.

The purpose of the experiment is to compare the simulated energy consumption with the actual measured energy consumption in order to determine the accuracy of the model.

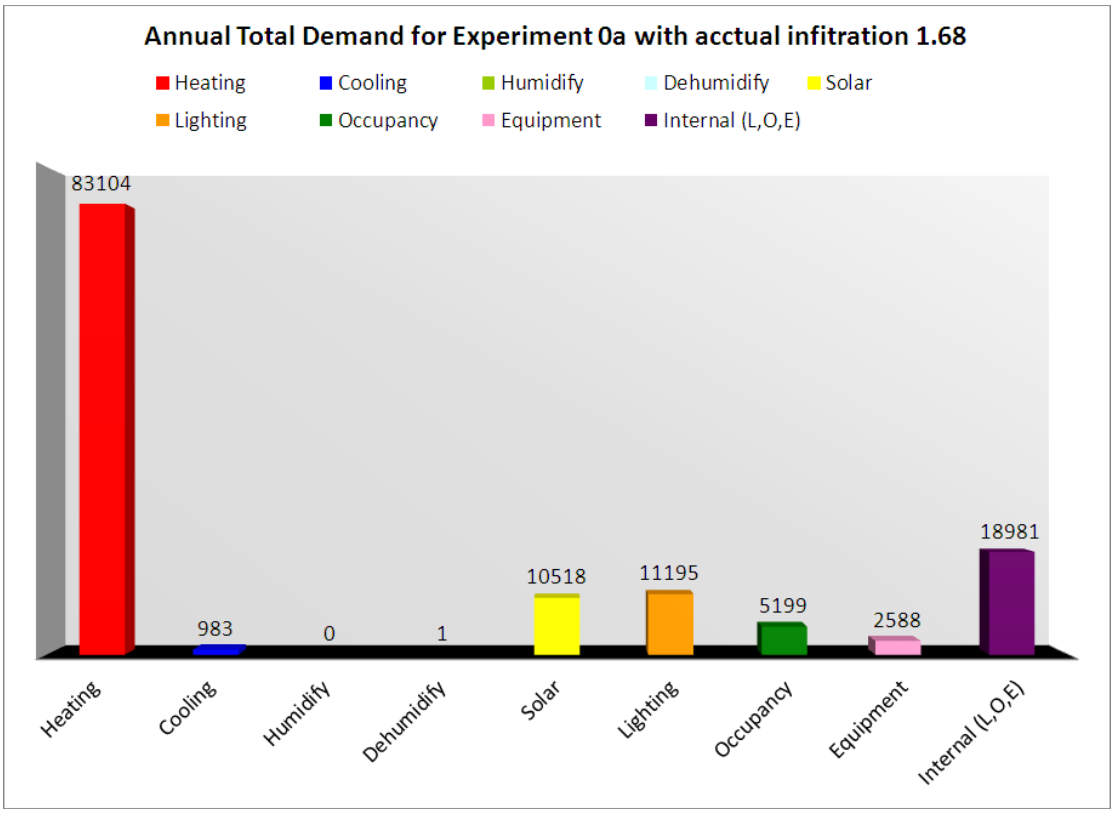


Figure 8 Experiment 0a Current building's annual heating demand with measured infiltration and internal temperatures of 20-23^{o}C

The model predicts an annual heating demand of 83,104KWh.

The actual annual heating usage with degree-day adjustment from the manual reading shows that the heating demand in the building was 83 MWh in 2010.

Although the TAS model demonstrates quite an accurate prediction of annual heating demand, the temperature and humidity readings measured by loggers in the building in February 2012, showed that the average temperatures during measured period were between 19-21C, not 20-23 as simulated. The actual reading included warm water consumption that was calculated to be 2,574kWh. This is approximately half of the additional heating required to raise the room temperature by one degree. Therefore the warm water consumption has been ignored in the next of experiments and only annual heating demand was analysed.

According to the thermal comfort requirements for day-care, the room temperature should be between 21-23C. A simulation with temperatures set to 21-23C, shows that the annual heat demand increases to 88,448kWh. In the following experiments the annual heating demand is compared based on room temperatures set to 21-23C, i.e. with a predicted heating demand of 88,448kWh.

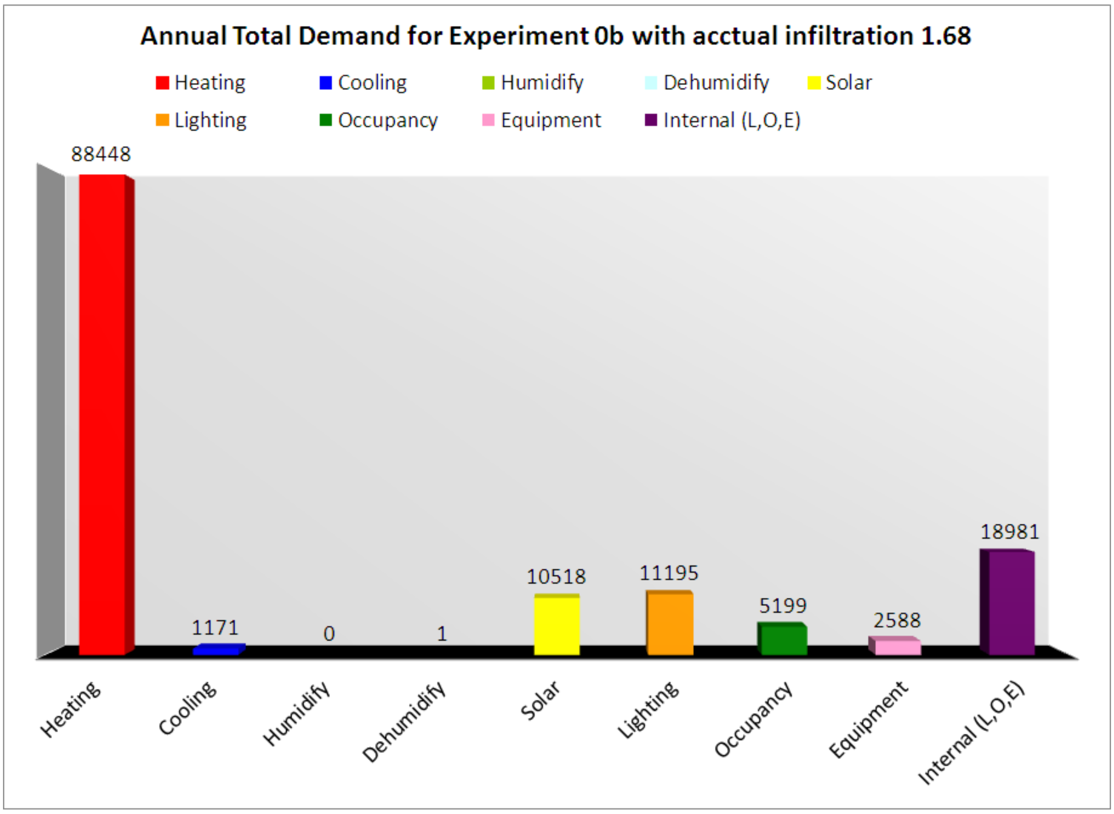


Figure 9 Experiment 0b showing building's current annual heating demand with measured infiltration of 1.68 ach and adjusted internal temperature of 21-23°C

Experiment 1: Heat loss due to building fabric

Experiment 1 investigates how much heat energy is lost through the building fabric.

Experiment 1 is the same as Experiment 0, except that infiltration is now set to 0 and room temperatures to 21-23. There is neither infiltration nor ventilation provided to the building. Thus, any heat loss is entirely due to the building fabric.

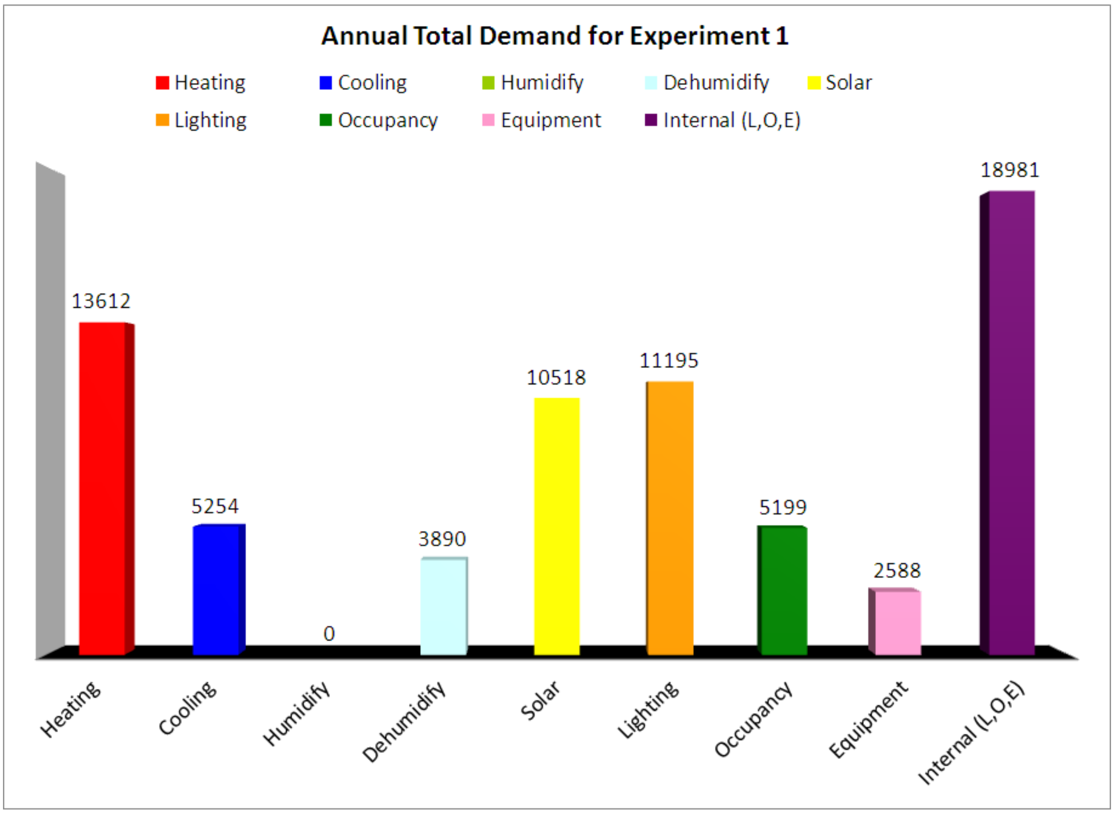


Figure 10 Experiment 1 showing annual heating demand due to building's fabric.

Experiments 1.a -1.c investigates what annual energy savings could be achieved if the building fabric is improved.

In Experiment 1a, the existing windows, with the U-value of 2.7 W/m^{2}K, are improved by adding a secondary K coated Pilington glass to the internal glass frame and keeping the internal blinds. The new glazing has a U-value of 0.77 W/m^{2}K.

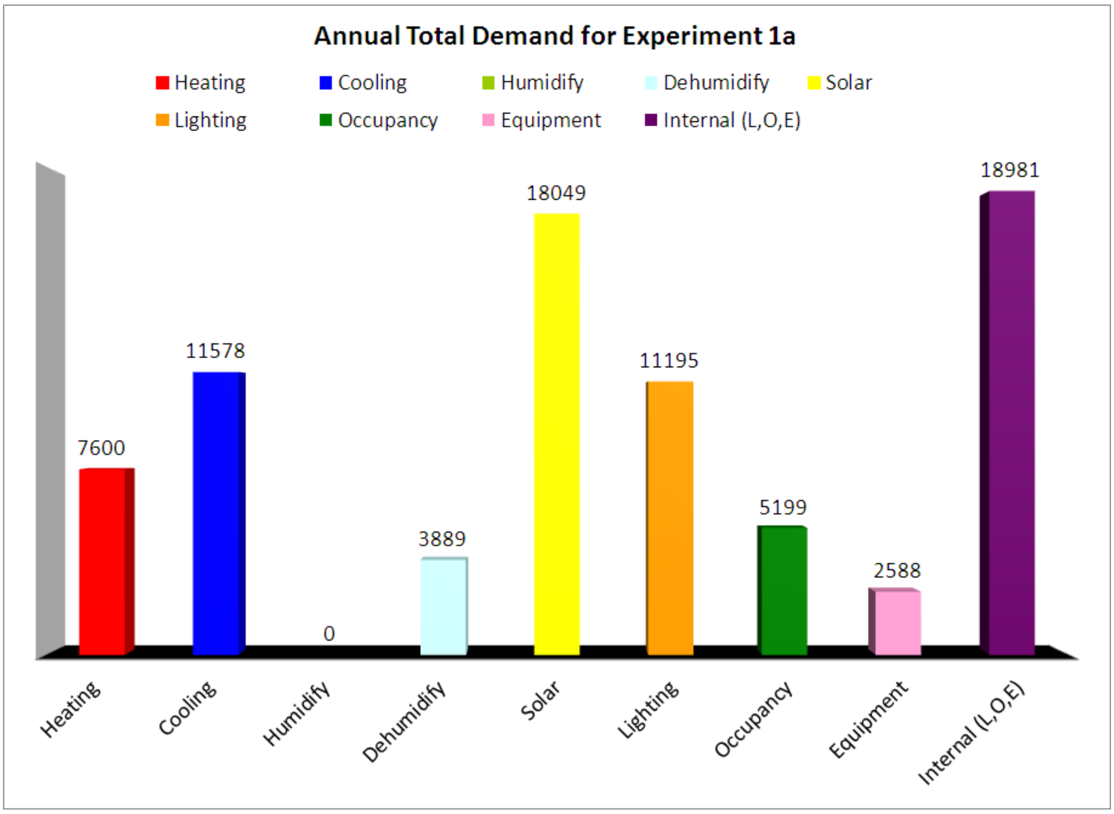


Figure 11 Experiment 1a showing heat loss due to the building's fabric with new windows

Experiment 1.a shows that the new windows could reduce building's heating demand by 13,612 – 7,600 = 6,012kWh. However this reduction is only 7% of total current heating requirement.

In Experiment 1b the existing windows are kept, but the external façade is insulated with 50mm foamed polyurethane (U-value 0.026 W/m^{2}K). So the U-values of:

- External 1st floor façade can be improved from U-value 0.206 W/m^{2}K to U-value of 0.15W/m^{2}K
- External basement façade with U-value of 0.721 W/m^{2}K can be improved to 0.314 W/m^{2}K
- External ground floor façade with U-value of 0.163 W/m^{2}K can be improved to 0.125 W/m^{2}K

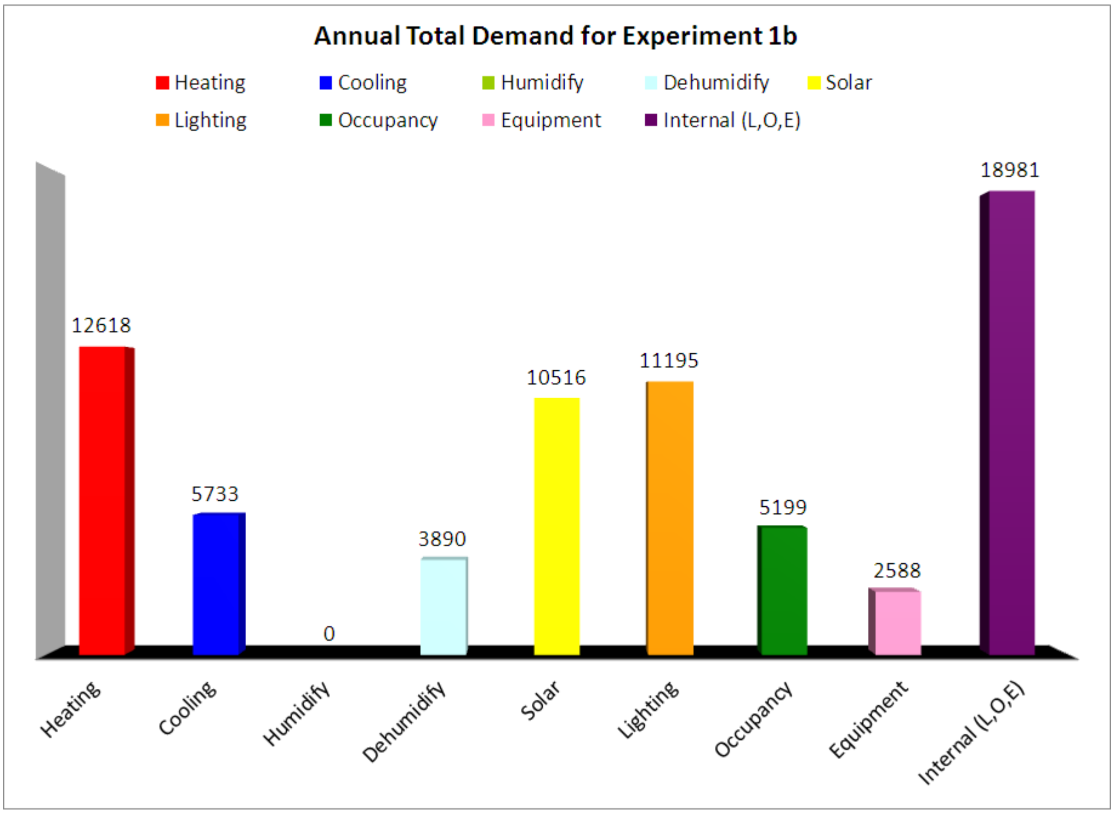


Figure 12 Experiment 1b shows the building's heat loss with improved external walls

Experiment 1b shows that the heat loss can be reduced by 13,612 -12,618 = 994 kWh, which is 1% of the current total heating demand of the actual building.

In Experiment 1c the existing windows and façade construction are kept but the floor/ceiling between the unheated basement space and the occupied ground floor space are insulated with 50mm of foamed polyurethane (U-value 0.026 W/m^{2}K). The U-value of the construction can be improved from the current of 0.645 W/m^{2}K and to 0.271 W/m^{2}K.
The estimated savings from this experiment reduce heating cost by 13,612-9,048=4,564 kWh, which is 5% of the actual heating demand.

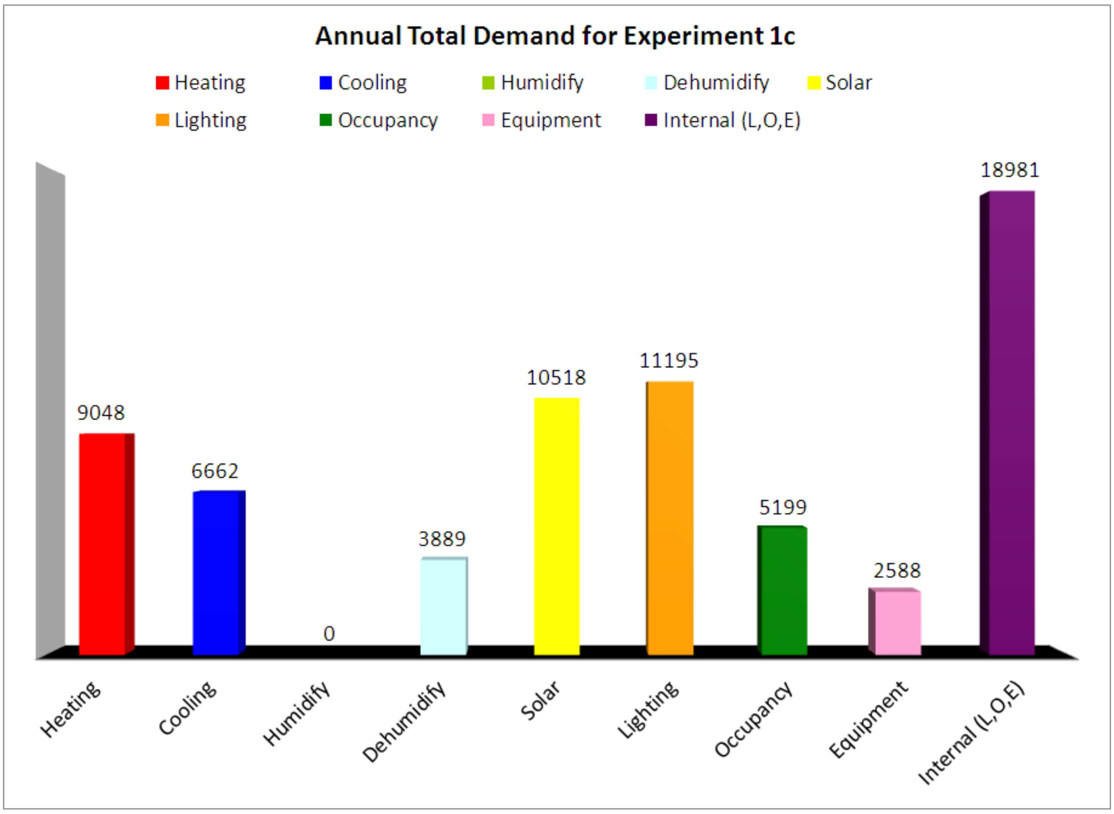


Figure 13 Experiment 1c shows the building's heat loss with improved insulation between ground floor and unheated basement

Experiment 2: Heat energy required to replace air (non-uniform ventilation)

Experiment 2 is carried out to determine the annual heat demand that is due to ventilation without heat recovery. The model for Experiment 2 is the same as for the model for Experiment 1 except for the ventilation. In this model non-uniform ventilation rates are assigned to each room according to each room's ventilation requirements. This assumes that all rooms have a ducting system with inlet and outlet.

Room type	Required ventilation rates ach	Infiltration
Ground floor day-care	1.4	0
1st floor day-care	1.1	0
Other heated rooms	0.5	0
Unheated and unoccupied space	0.00	0

Table 2 Infiltration and ventilation rates applied to Experiment 2

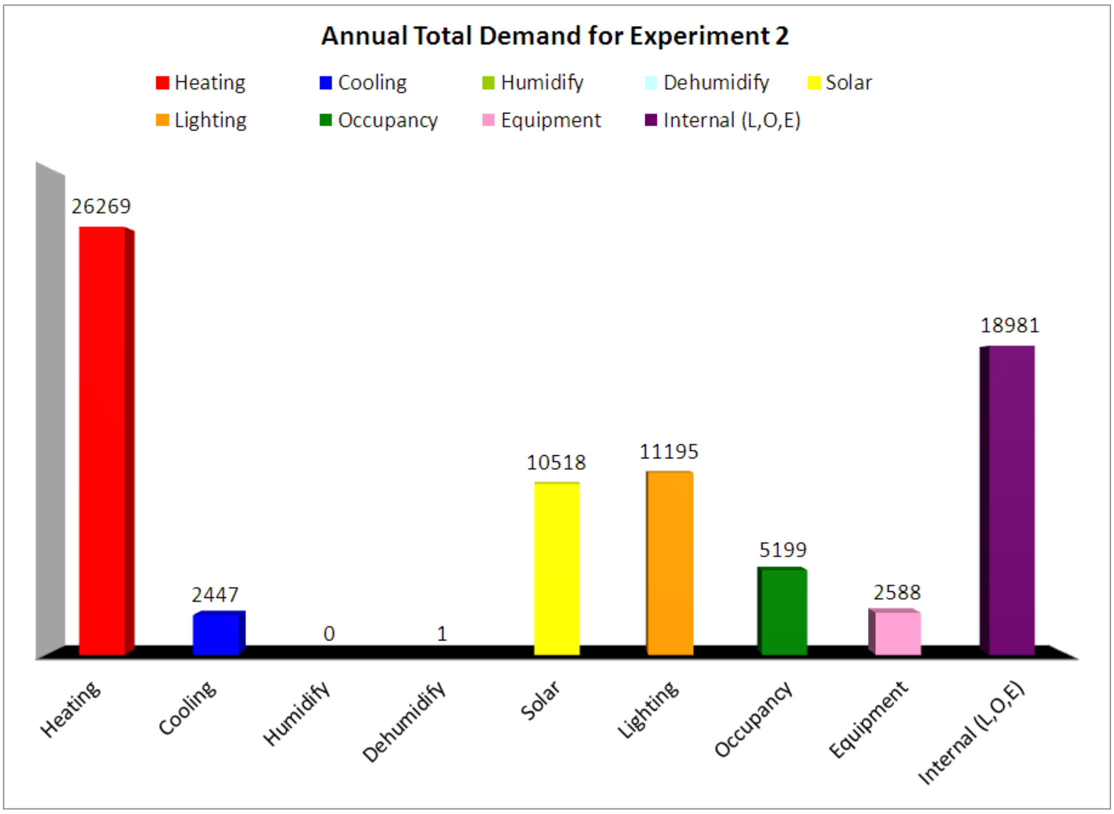


Figure 14 Experiment 2 shows the annual heating demand with non-uniform ventilation without heat recovery

The simulation shows that the heating demand due to ventilation is 26,269-13,612=12,657 kWh, since 13,612kWh are due to the building's fabric heat loss.

If the BR10 requirement for heat recovery is met, then 70% of the heat loss due to the ventilation should be recovered. In this case, the heat loss due to ventilation is reduced to 12,657*0.30 =3,797kWh. The energy saving due to ventilation heat recovery is (12,657-3,797)/88,448), which is 10% of the current heating demand.

Note that this experiment does not consider infiltration.

Experiment 3: Heat loss due to current infiltration

Experiment 3 investigates the heat loss due to the current infiltration. Experiment 0 showed that the actual building's heating demand with the current infiltration rate is 88,448kWh. Experiment 1 showed that the heat loss due to the building's fabric is 13,612 kWh with no ventilation. Therefore the heat loss due to the building's infiltration is 74,836kWh or 85% of the current total heating demand.

Experiment 4: Heating demand after tightening

In real life it is impossible to achieve 0 infiltration even for new buildings. According to the (Appendix 2.2) air leakage test report, the consultant gives an example of the same type of building, where the infiltration rate was reduced to

0.34 l/s/m2 at 50 Pa or 0.06l/s/m2. The purpose of this experiment is to calculate what is the heat loss due to an achievable infiltration of 0.06 l/s/m2. Achievable infiltration =(0.06 x 279 x 3.6)/819=0.07 ach

In Experiment 4 the following assumption are made:

- Infiltration rate for the all rooms in heated area is set to 0.07 ach at a wind speed of 3m/s and a function of the environmental wind speed
- No ventilation
- Actual heating gains, such as solar, occupants, heating features and lighting.
- The internal blinds have been applied to all windows, as all windows have curtains or blinds, which can be manually drawn by the occupants in the building.
- Room temperatures in occupied spaces are set to 21-23 and other heated rooms 19-23

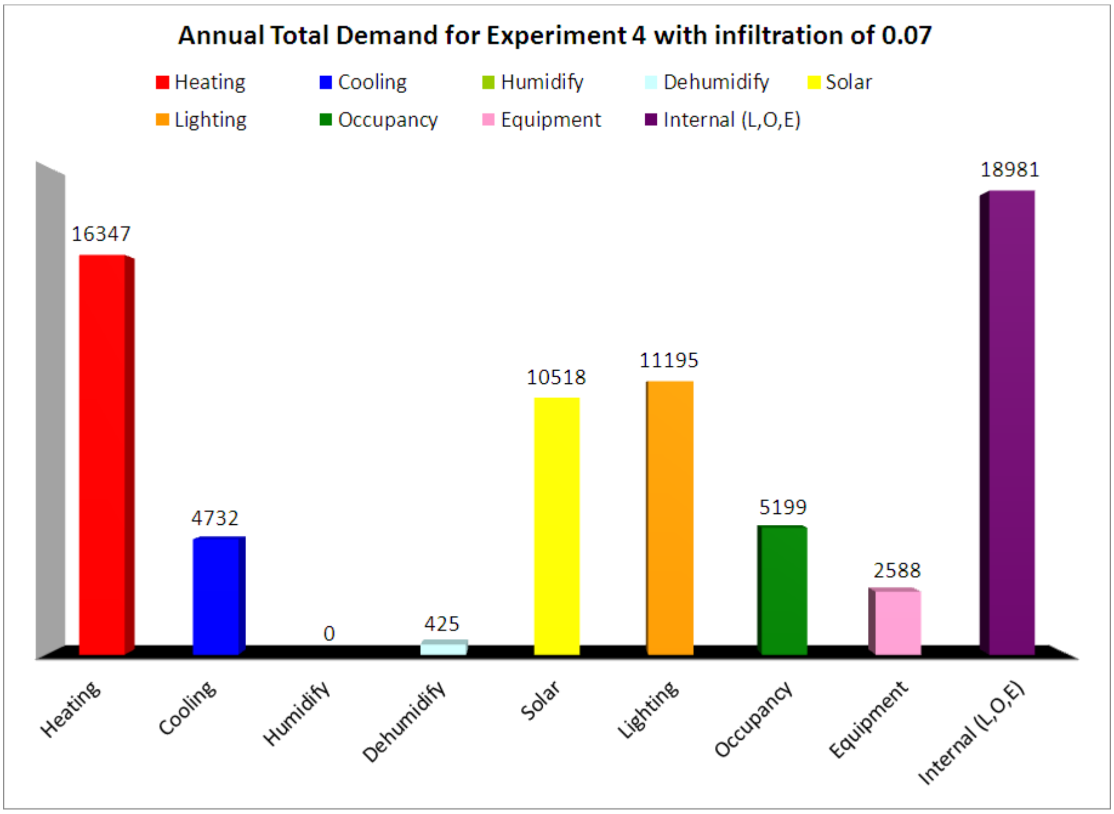


Figure 15 Experiment 4 with achievable infiltration of 0.07ach

Experiment 4 demonstrates that by reducing air infiltration from 1.68 to 0.07 ach, the annual heating demand can be reduced to 16,347kWh. The heat loss due to the air infiltration is (16,347-13,612)=2,735kWh
The energy savings from tighten the buildings envelope will be (88,448-13,126)-2,735=57,230kWh, which is 64% of the current annual heating demand.

Note, however, that by reducing infiltration rates, ventilation will be required.

The total heating demand with the reduced infiltration can be calculate as following:

Heat loss	With non-uniform ventilation and without heat recovery	With non-uniform ventilation and with heat recovery
Building fabric	13,612	13,612
Ventilation	12,657	3,797
Infiltration	2,735	2,735
Total Heating demand	29,004	20,144

Table 3 Comparison of annual heat loss with non-uniform ventilation between with and without heat recovery

The total heat demand with new infiltration and non-uniform ventilation without heat recovery will be 29,004kWh. If 70% of heat due to ventilation is recovered, the total heating demand with infiltration of 0.07 and non-uniform ventilation can be reduced to 20,144kWh.

Experiment 5: Uniform ventilation

If the building should be ventilated by passive means and avoid ducting in all rooms, all rooms should have a uniform ventilation rate of 1.4. In Experiment 5, the following assumptions have been made:

- TAS model is set as in Experiment 2, except the ventilation, which now is set to be uniform in all the rooms. No infiltration is modelled. All other parameters are kept unchanged.

Room type	Required ventilation rates ach	Infiltration
Ground floor day-care	1.4	0
1st floor day-care	1.4	0
Other heated rooms	1.4	0
Unheated and unoccupied space	0.00	0

Table 4 Ventilation rates for Experiment 5 with uniform ventilation

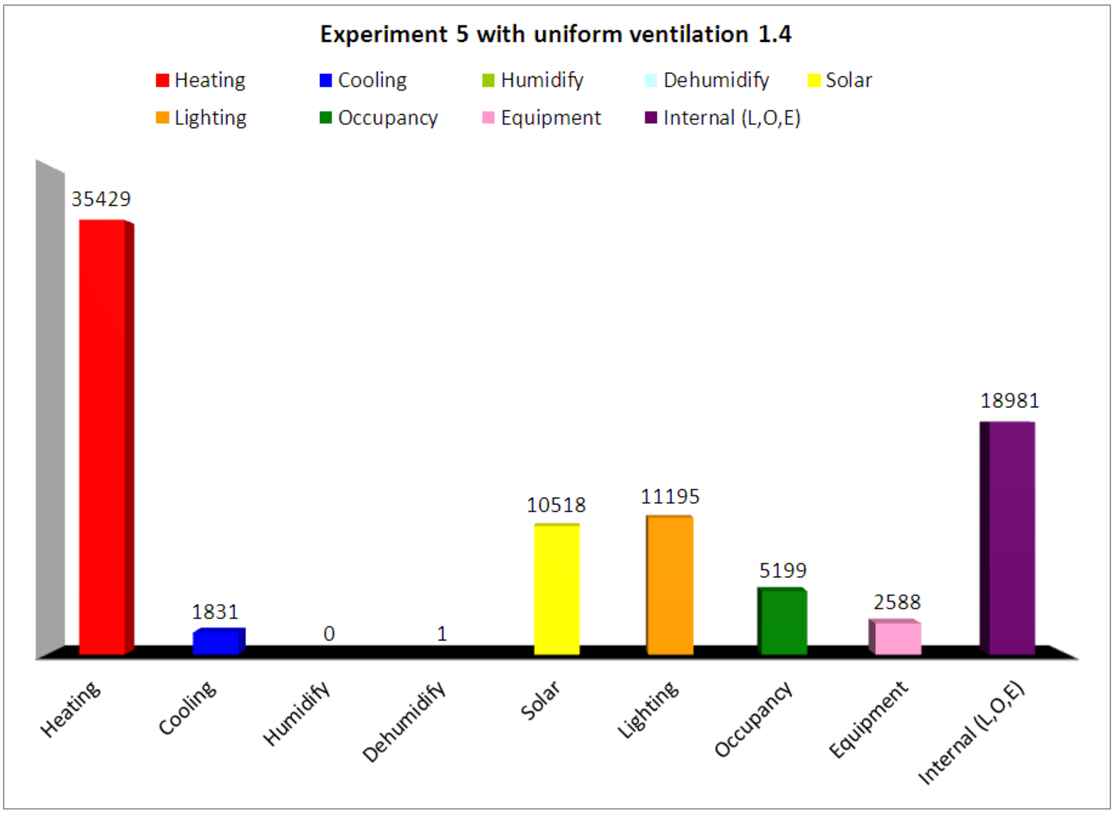


Figure 16 Experiment 5 shows heating demand with uniform ventilation in all rooms

The result of Experiment 5 demonstrates that the heating demand with uniform ventilation in all rooms, no heat recovery and no infiltration will be 35,429k Wh. The heat loss due to ventilation without heat recovery will be 35,429-13,612=21,817kWh. If the BR10 heat recovery requirement of 70% is met then 15,272 kWh should be recovered.

This model does not include infiltration, which cannot be controlled and should be added as an additional heat loss. The total heating demand including the heat loss due to building's fabric, infiltration and ventilation can be calculated:

Heat loss	With uniform ventilation and no heat recovery	With uniform ventilation and heat recovery
Building fabric	13,612	13,612
Ventilation	21,817	6,545
Infiltration	2,735	2,735
Total heating demand	38,164	22,892

Table 5 Comparison between annual heating demand due to uniform ventilation with and without heat recovery

Comparing Table 3 with Table 5, it is clear, that uniform ventilation increased the heat energy from 29,004 to 38,164 kWh (24% increase) with no heat recovery, and from 20,114 to 22,892 kWh (12% increase) with heat recovery.

Both Experiment 2 and Experiment 4 calculate the ventilation and infiltration as different heat loss. However infiltration and ventilation both provide fresh air to the building that is required to be heated. Thus, we can reduce the ventilation -

rate to account for the airflow due to infiltration. This will result in an energy saving. In this case, the ventilation rate becomes a function of infiltration rate that varies with the external conditions such as wind direction and velocity as well as external temperature and can be controlled by a meter on the roof.

Experiment 6: coupled infiltration and ventilation

In Experiment 6, the TAS model is run the same as in Experiment 5, but now the infiltration is fixed to 0.07 ach and does not vary with the wind and temperature outside, and the uniform ventilation is fixed to 1.33 in all heated rooms. The total air supply in Experiment 6 is equal to the max ventilation rate of 1.4 required for the occupied rooms as set in Experiment 5.

Note that fixed infiltration and ventilation rates are a limitation of the TAS model. In practice, if the infiltration rate increases due to external conditions, e.g. high wind, the corresponding ventilation rate should be reduced.

Room type	Required ventilation rates ach	Infiltration ach
Ground floor day-care	1.33	0.07
1st floor day-care	1.33	0.07
Other heated rooms	1.33	0.07
Unheated and unoccupied space	0.00	0

Table 6 Ventilation and infiltration rates for experiment 6

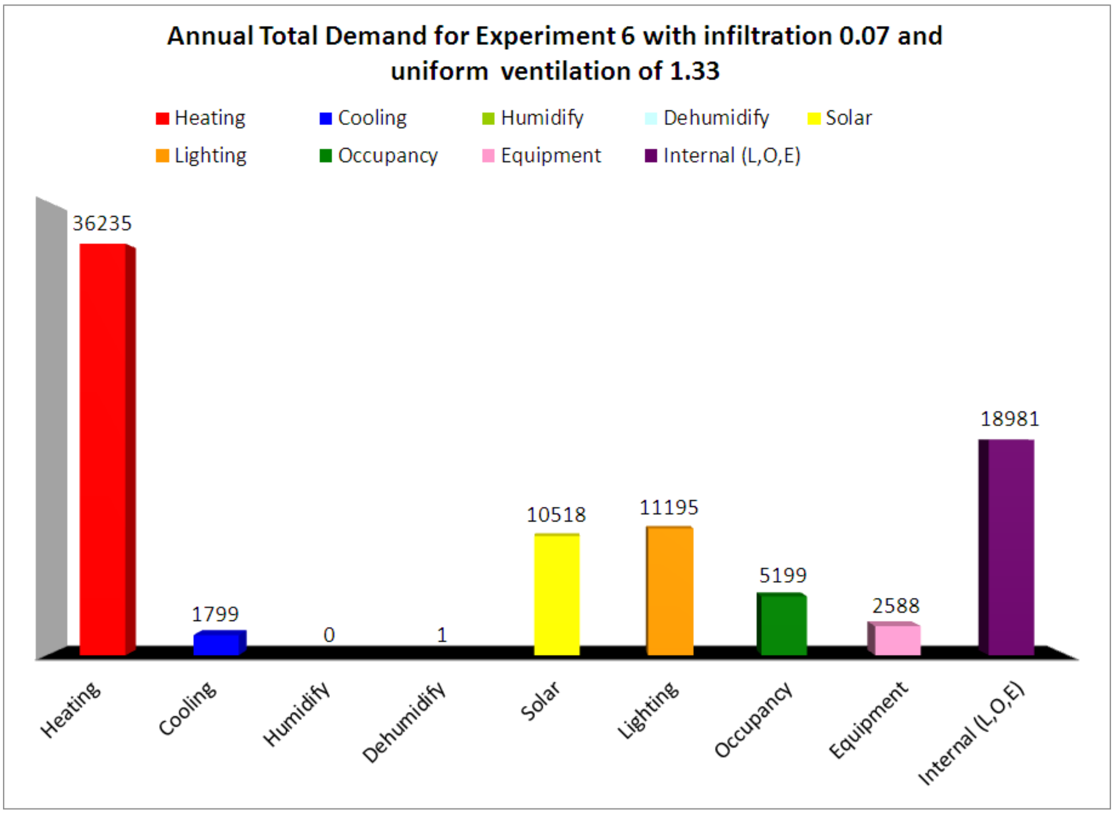


Figure 17 Experiment 6 shows annual heating demand with coupled infiltration and ventilation

Experiment 6 demonstrates that by coupling infiltration with ventilation the total heating demand is reduced to 36,235, from 38,164kWh (uniform ventilation without heat recover).

Experiment 7: Coupled infiltration and ventilation only in occupied spaces

Experiment 7 investigates the option to reduce the ventilation rates for uniform ventilation.

The model of Experiment 7 is set up as for Experiment 6. However, the infiltration is set as a function of the wind velocity outside the building. Further, the ventilation in Experiment 7 is set to 1.4 ach only in occupied areas and reduced to 0 for all other rooms, such as staircases, entrance, kitchen and bathrooms (BR10.6.3.1). It has been assumed that the unoccupied rooms receive the minimum air change due to door openings between the occupied rooms and other as well as extractors in the bathrooms.

Area	Required ventilation rates ach	Provided ach	Infiltration Ach
Ground floor day-care	1.4	1.4	0.07
1st floor day-care	1.1	1.4	0.07
Office		1.4	
Other rooms	0.5	0.0	0.07
Unheated and unoccupied space	0.0	0.0	0.07

Table 7 Ventilation and infiltration rates for Experiment 7

The simulation results of Experiment 7 show the annual heating demand is reduced from 38,164kWh (uniform ventilation at 1.4 ach without heat-recovery) to 26,783kWh.The reduction of the heating demand is due to the reduced air volume from 1,146m^3/h to 641m^3/h that is required to be replaced, as well as infiltration, which is now used as a part of ventilation.

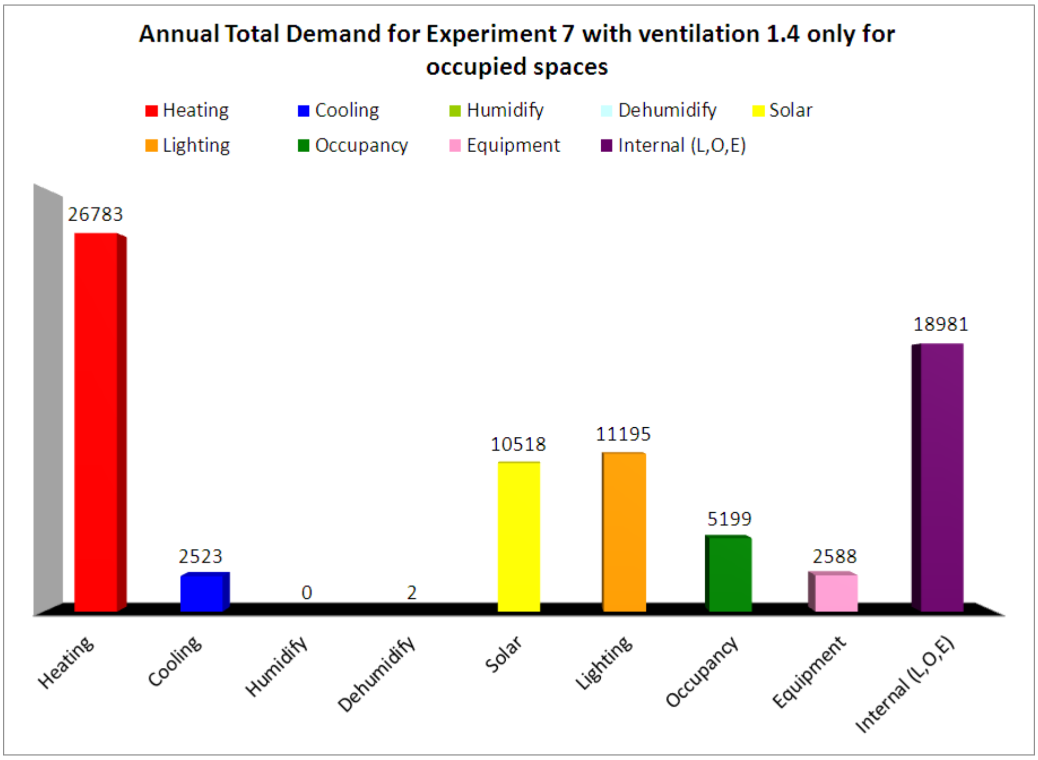


Figure 18 Experiment 7 with ventilation of 1.4 in all occupied spaces and coupled infiltration

Summary of Experiments 0-7

Figure 20 summarizes the energy saving due to (i) improved window u-value, (ii) insulation of the external façade, (iii) insulation of the basement, and (iv) reducing the infiltration. It is clear that improving the infiltration provides by far the most saving. Note, however, that tightening the building will require adding ventilation to provide required fresh air to the occupied spaces. Note, that the current building has an infiltration higher than the maximum required ventilation and therefore does not require any additional form of ventilation.

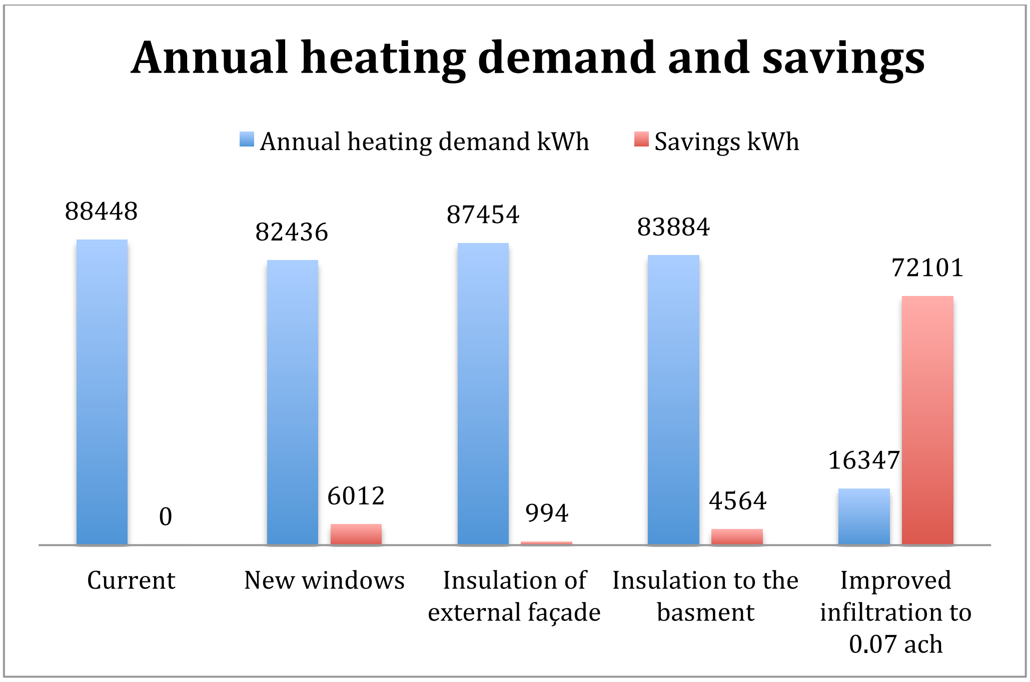


Figure 19 Annual heating demand and savings with current infiltration

Figure 21 considers the annual heating demand for (i) non-uniform ventilation with heat recovery (minimum energy consumption) and (ii) non-uniform ventilation without heat recovery, (iii) uniform ventilation with heat recovery and (iv) uniform ventilation without heat recovery, (v) coupled infiltration and ventilation, (vi) coupled infiltration and ventilation in only occupied spaces. With heat recovery, the annual energy cost for uniform ventilation is only 12% higher than for non-uniform, but does not require the installation of additional ductwork. If no heat recovery is provided, uniform ventilation increased annual energy costs by 24%. By applying coupled infiltration and reduced ventilation the heating demand can be reduced to 26,783kWh, which is only 3,891 kWh more than non-uniform ventilation with heat recovery. In the next set of experiments the simulation results will be compared to coupled infiltration and ventilation in only occupied spaces (Experiment 7).

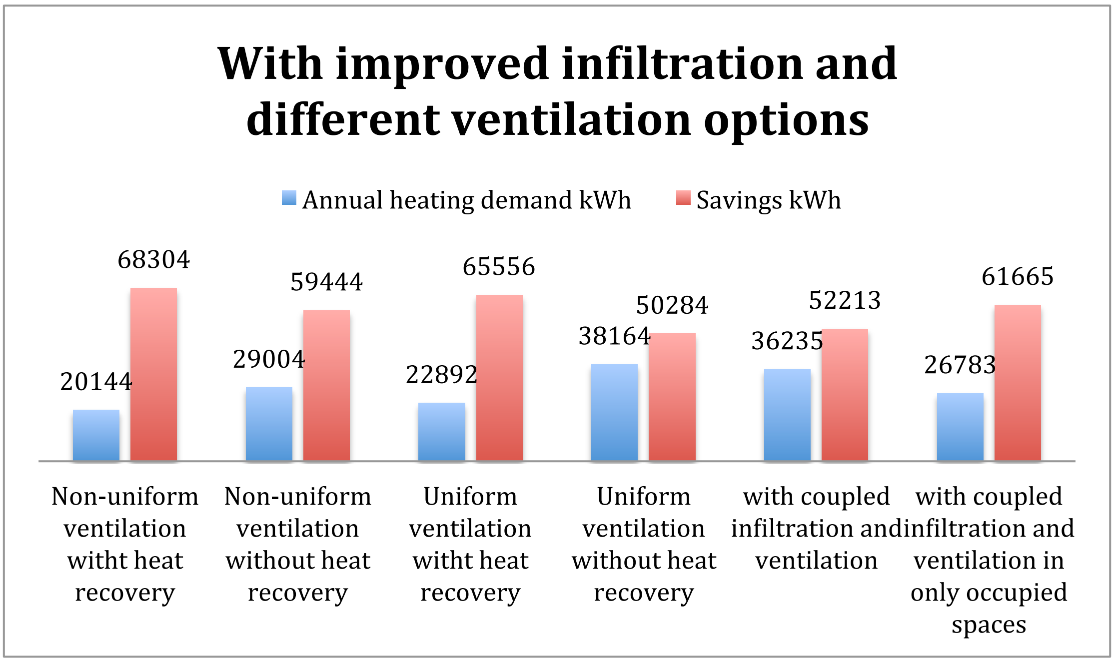


Figure 21 Annual heating demand and savings with the improved infiltration and different options of ventilation

PART 2: Passive ventilation options

In this Part 2, I look at four possibilities for providing passive ventilation to the building. These are

1. Chimneys – use the existing 2 chimneys, currently not used for heating, as an inlet and outlet for passive natural ventilation without heat recovery
2. Chimneys with pipe- the same as Option 1, with the addition of a metal pipe in the exhaust air chimney as a passive heat exchanger
3. Windows only – the supply air is provided through the selected top windows openings in the all occupied rooms
4. Chimneys and windows –The combination of the options 1-3 to provide most comfortable environment.

From Experiment 7, we require that any passive ventilation method provide 641 m3/h of airflow. In the following, we consider whether each of the four methods is capable of doing so.

Experiment 8 –Chimneys

For Experiment 8 the, openings were added for inlets on the lower part of chimney 1 and with opening for outlets in the top part of chimney 2 on each floor: basement, ground floor and 1st floor

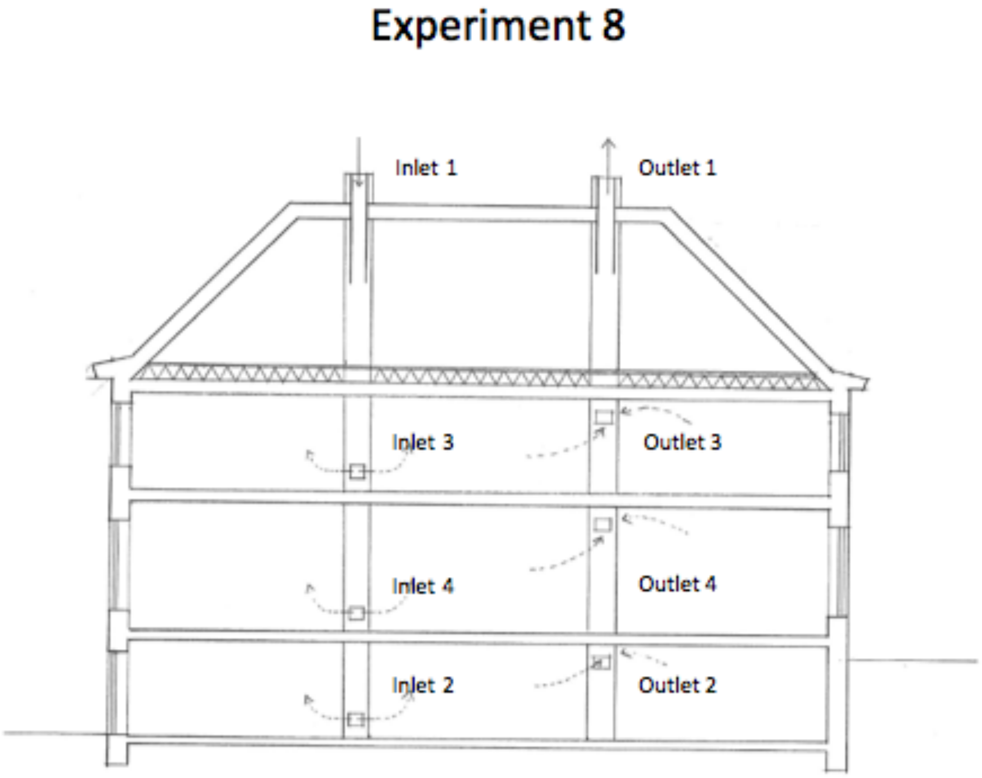


Figure 20 Diagram for inlet and outlet for Experiment 8

It is assumed that the lowest opening in chimney 1 in the basement (Inlet 2 in Figure 22) receives cold air from the top of chimney 1 (Inlet 1 in Figure 22). The incoming air from chimney 1 (top) also moves partly to the inlet openings on the ground floor and 1st floor (Labels inlets 3 and 4) and partly to the basement heat exchanger room. The heat exchanger room has been insulated (walls, ceiling and floor) to reduce the heat-loss to the surrounding unheated basement. From the basement the air moves up chimney 2 where it is extracted by the buoyancy effect.

Diagram for air supply and outlet for Experiment 8

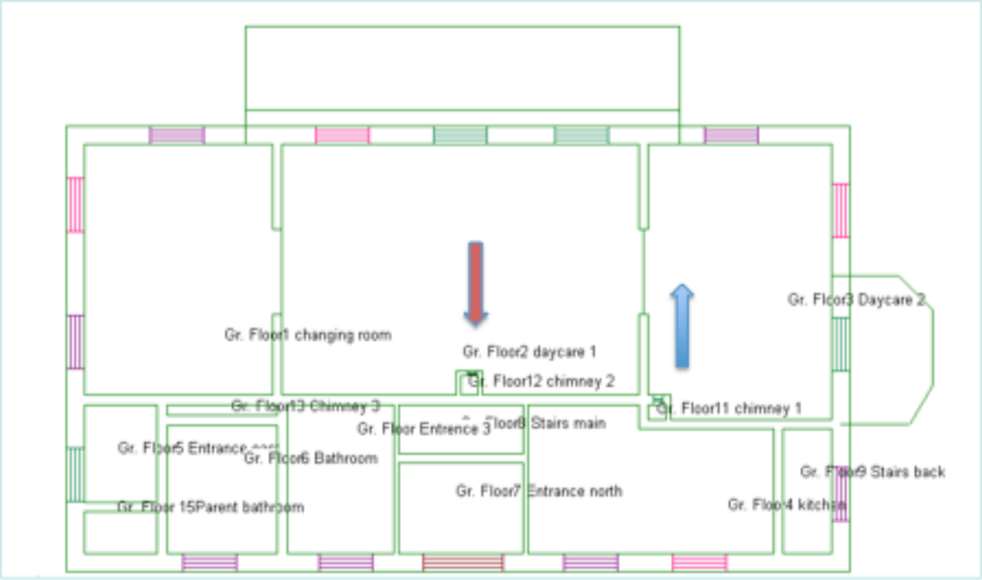


Figure 21 Diagram for air intake and extract for Experiment 8

Two options have been investigated: Experiment 8a –passive and Experiment 8b, where the air is heated in the heat exchange room in the basement to provide fresh air at a temperature 21°C.

Table 8 shows the airflow as a function of outside temperature when the inside basement temperature is assumed to be 8°C. It is observed that when the temperature is less than -12C, the airflow is sufficient to meet 100% of the ventilation requirements. In contrast, when the outside temperature is greater than 10°C, there is no inflow of air through the chimney, the air is flowing out the chimney.

Pressure difference between inside and outside through the chimneys for Experiment 8a					
A=0.25*0.25	c=0.686	H =	13.8		
	Q=c*A*(2*g*h*√(Ti-Te)/Te))			Incoming air to chimney 1	
Temperature outside	Temperature inside the basement	Δ P	Q m^3/s	v m/s	Volume of air m^3/h
-12	8	13.03	0.20	3.12	703
-5	8	8.25	0.16	2.49	559
0	8	4.98	0.12	1.93	435
5	8	1.84	0.07	1.17	264
10	8	-1.20	0.06	0.95	-214
12	8	-2.39	0.08	1.34	-301

Table 8 Calculation of the air flow through the chimneys at different outside temperatures

To improve the flow of air through the chimney, we next considered heating a basement room to 22°C. Table 9 shows the corresponding airflow rates. We observe that in this case, 100% of ventilation requirements can be met for temperatures less than 0°C, and an inflow of air continues even for outside temperatures of 12°C.

Down drought airflow through the chimneys for Experiment 8b

A=0.25*0.25	c=0.686	H =		13.8	
	Q=c*A*(2*g*h*√((Ti-Te)/Te))			Incoming air to chimney 1	
Temperature outside To	Temperature inside Te	ΔP	Q m^3/s	v m/s	Volume of air m^3/h
-12	22	21.11	0.25	4.07	917
-5	22	16.32	0.22	3.58	806
0	22	13.06	0.20	3.20	721
5	22	9.91	0.17	2.79	628
10	22	5.69	0.15	2.32	523
12	22	5.69	0.13	2.11	476

Table 9 Airflow and air velocity and air volumes at different external temperatures

Note that this calculation does not take into account wind forces, which will increase the airflows.

Experiment 9 (Chimneys with pipe)

Experiment 9 was set up in the same way as for Experiment 8, except for a steel pipe, which was inserted into chimney 2 and through which warm exhaust air flows. Chimney 1 is closed just above the 1st floor, so the air only has the possibility to move through the lower openings to the rooms and has no possibility to escape through Chimney 1 above the 1st floor level (see Label 4 in Figure 23). The warm air will exhaust through Chimney 2, where the warm air from the rooms will move up and out through the chimney, via the outlets 3 and 4. The assumption was made that the out-going air will partly pre-heat the incoming cold air through the steel pipe. In this model incoming and outgoing air is passing through chimney 2. Therefore the supply and extract areas are reduced. It was assumed that cold fresh air moves through the pipe to the basement.

Experiment 8a demonstrated that the air supply without pre-heating the basement room will be insufficient to supply fresh air for the building. Experiment 9 therefore only considers the air supply with added heating in the preheated room.

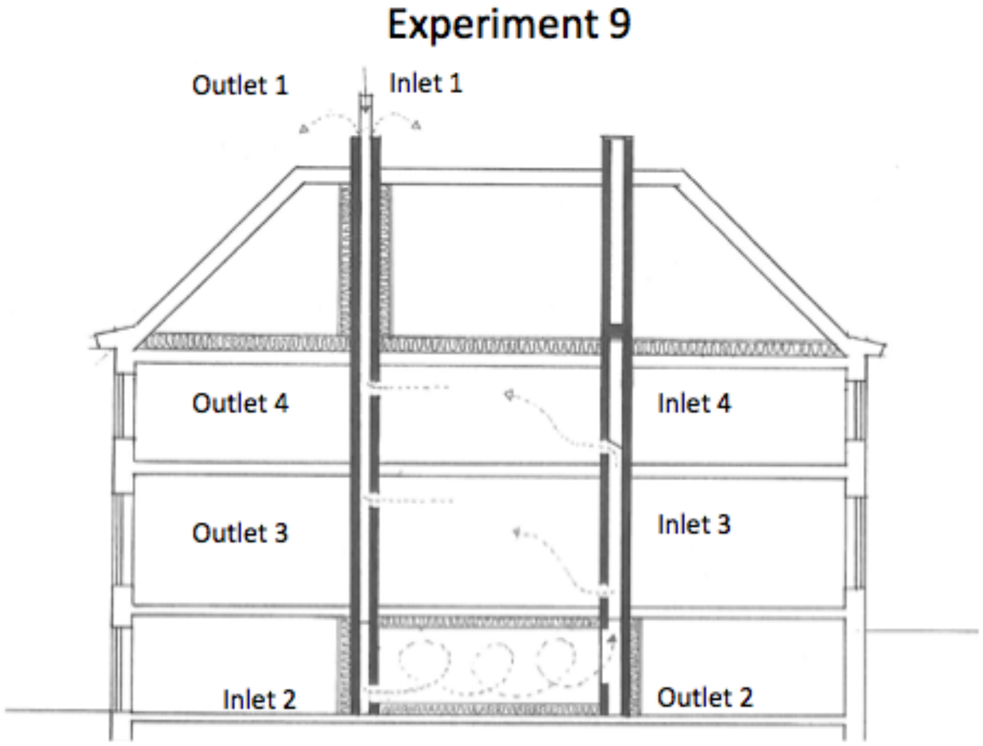


Figure 22 Diagram showing air movements for the Experiment 9

Table 10 enumerates the airflow through the metal pipe for various outside temperatures, when the basement room is kept at 22°C. Compared with Table 9, we observe that the airflow is reduced by about 46% due to the smaller outlet pipe.

Down drought airflow through the chimneys for Experiment 9

Ai=0.15*0.15 Ao=Ach-Ai	c=0.686	H =	14.3		
	Q=c*A*(2*g*h*√((Ti-Te)/Te))			Incoming air to chimney 1	
Temperature outside To	Temperature inside Te	ΔP	Q m^3/s	v m/s	Volume of air m^3/h
-12	22	21.87	0.09	1.49	336
-5	22	16.91	0.08	1.31	295
0	22	13.53	0.07	1.17	264
5	22	10.27	0.06	1.02	230
10	22	7.12	0.05	0.85	192
12	22	5.89	0.05	0.77	174

Table 10 Airflow and air velocity and air volumes at different external temperatures

The Experiments 8b and 9 demonstrated that the fresh air supply provided by the chimneys by adding additional heating in the pre-heated room is sufficient only for the coldest periods of the year, when the external temperature is below 5°C. However, additional air supply is needed when the external temperature exceeds 5°C. The next Experiment considers how the ventilation can be achieved by using only windows.

Experiment 10 (Open windows)

In this configuration, the chimneys are closed and a few selected top windows, see Figure 24, are open 50%, to provide fresh air.

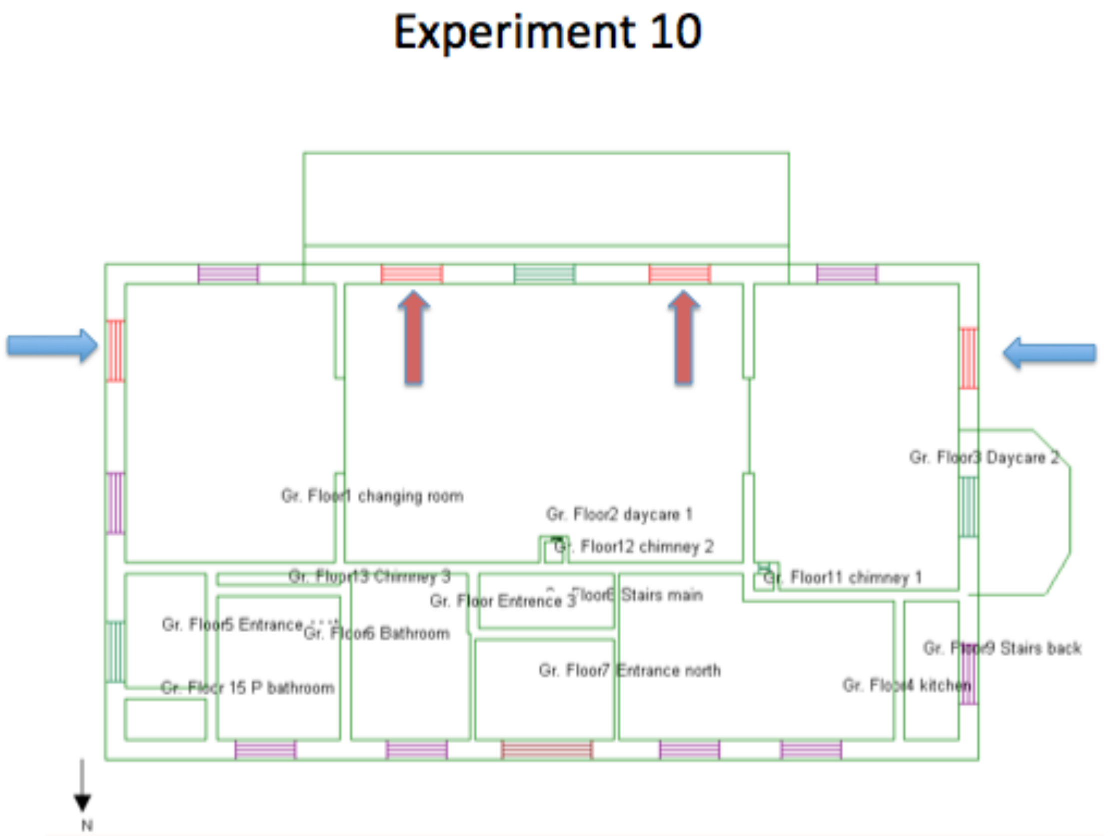


Figure 23 Air supply for the Experiment 10 through the windows

The calculation below shows the amount of air that is supplied through the windows, due to the pressure difference between inside and outside.

Pressure difference between inside and outside window opening					
$q_v=v_o*A_o=c_v*vc_k*A=c_d*A*\sqrt{(2\Delta p)/\rho)}$					
To K	Ti K	Δ P	qv m/s	Air flow per window m^3/h	8 windows m3/h
-12	20	3.19	0.27	104	834
-5	20	2.25	0.23	89	709
0	20	1.73	0.20	78	628
5	20	1.22	0.17	67	533
10	20	0.74	0.13	52	418
12	20	0.58	0.12	46	370

Table 11 Airflow and velocity through windows opened 50% (2 top windows per floor).

Table 11 indicates that each window provides airflow of approximately 12% of the required ventilation. Opening 8 windows should therefore meet the ventilation requirement.

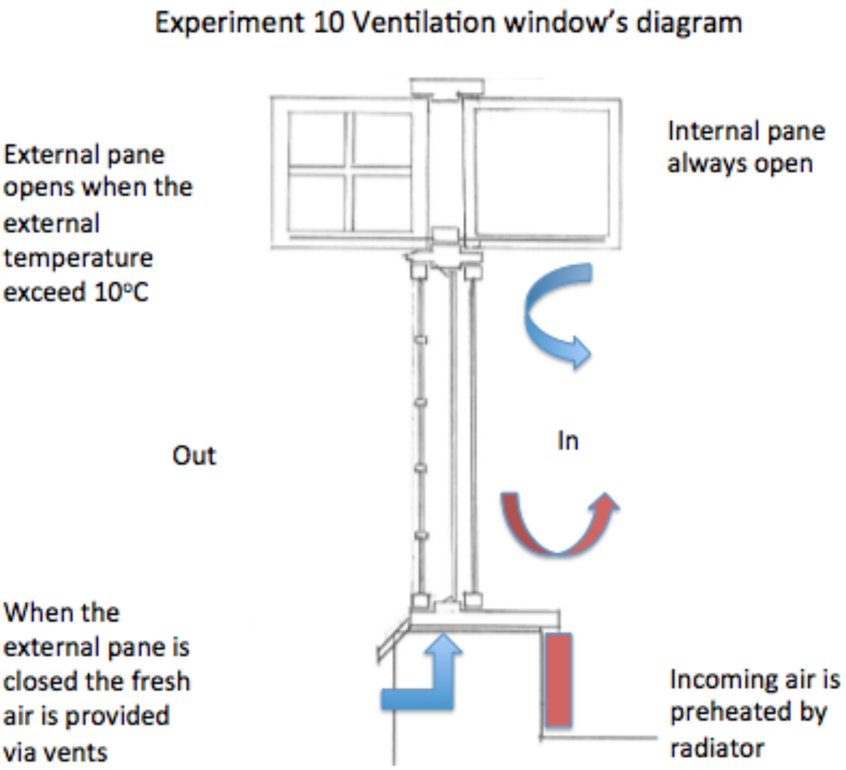


Figure 24 Diagram showing the fresh air supply through the window

The window opening is configured as shown in Figure 24. The external pane is not open, and the air between the first and second pane is provided through a vent in the window base.

Experiment 11: Chimneys and windows

To achieve the most comfortable thermal environment and avoid draughts, the configuration of Experiment 11 was investigated.

Fresh air supply through the chimneys and windows

		Incoming air through the chimneys		Incoming air through the windows	
Temperature outside	Temperature inside	v_{ch} m/s	Volume of air m^3/h	v_w m/s	Volume of air through 8 windows
-12	22	4.07	917	1.49	834
-5	22	3.58	806	1.27	709
0	22	3.20	721	1.12	628
5	22	2.79	628	0.95	533
10	22	2.32	523	0.75	418
12	22	2.11	476	0.66	370

Table 12 Calculated air flow rates through the windows and the chimneys for Experiment 11

Table 12 demonstrates that a combination of airflow through the chimneys and windows can provide the required ventilation for all outside temperature conditions.

The windows openings could be controlled automatically and set as the function of the internal and external temperature. For example the windows could start opening when the external temperature is 5°C and are open 50% of the window's area when the external temperature reaches 7C°. The remaining top windows could start opening when the internal temperature reaches 22°C and external temperature is above 14-16°C.

Summary of the results and conclusion

The investigation of the building's annual heating demand estimates the heat losses due to (i) the building's fabric, (ii) infiltration and (iii) ventilation. The current building has no active ventilation, but the current infiltration provides more than the required fresh air as determined by BR10. The high infiltration is problematic, because it is uncontrollable and varies with outdoor conditions. This makes it difficult to heat the building and provide comfortable thermal conditions. The high infiltration rate also causes high-energy bills and requires an increased capacity for the heating devices.

The improvement of the building's fabric will provide only limited savings unless the infiltration rate is significantly reduced.

The most cost effective improvement for villa Bagatelle will be to tighten the building's envelope - mostly windows and doors. The tightening of the building will provide not only significant energy savings but will also improve thermal comfort for the occupants. However, tightening of the building will require the building to be ventilated. The non-uniform ventilation with heat recovery will be most energy effective, but will require ducting. To avoid ducting, uniform ventilation has been suggested. The advantage of uniform ventilation is that ducting is not needed.

Experiments 2-5 show the possible savings by applying uniform and non-uniform ventilation with and without heat recovery. In all these cases, the ventilation was set to the maximum required ventilation of 1.4 ach. However, the ventilation rate of 1.4 ach is only required for the ground floor day-care, where the amount of children varies from 10-25. In Experiment 7 the ventilation rate is applied only to the occupied spaces. Unoccupied and non-occupied spaces, such as toilets and entrances, are to receive the ventilation from the occupied rooms, as suggested for natural ventilated buildings (BR 10 6.3.1.3.). Additionally, the ventilation rates can be further reduced by applying variable ventilation to the occupied space as the function of occupants, by, for example, measuring CO_2.

Two forms of passive ventilation were considered, chimneys and windows. It was shown that a combination of chimneys and windows could meet the required ventilation for all exterior temperatures.