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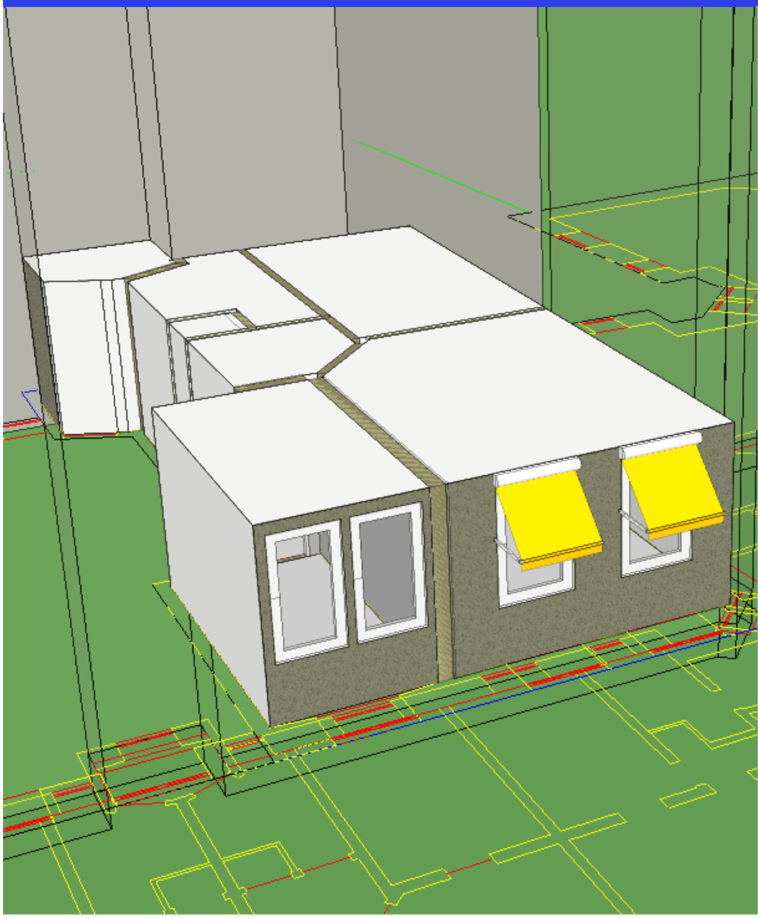

Potential of solar control solutions and ventilation for reducing overheating risk in retrofitted Danish apartment buildings from the period 1850-1970

BYG R-413, 2019

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Preface

This technical report summarizes the work on the research project "Reduction of overheating in multi-storey apartment buildings in connection with facade renovation". The project was carried out at the Section for Energy and Services, Department of Civil Engineering at the Technical University of Denmark in the period 1 January 2016 - 31 December 2018. The total budget for the project was DKK 1.98 million, where the Landowners' Investment Foundation (Grundejernes Investeringsfond) supported with DKK 990,000.

The objective of the project was to evaluate the potential of different solar control solutions combined with typical ventilation strategies to reduce indoor temperature excess in renovated Danish apartment buildings from the period 1850-1970. The target group for the project was the construction industry, building owners and residents, the community in general and the international research world.

The project dealt with a thorough examination of the overheating risk and the determination of possible solutions, based on dynamic computer simulations in IDA Indoor Climate and Energy (IDA ICE) software. An MS Excel based tool called “Result Browser” was prepared to give the user possibility to explore the project results from over 400 cases. This report describes the cases studied and the models used in details. The results regarding the effect of different windows type, solar shading solution and ventilation strategies on overheating and energy consumption based on over 700 simulations performed in IDA Indoor Climate and Energy (IDA ICE) software are discussed in the report. The research group hopes that this study will contribute to an increased attention regarding the use of solar shading and ventilation during energy renovation.

The authors would like to thank all master and bachelor students from DTU BYG who have contributed to the project.

Toke Rammer Nielsen
Project leader

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Summary

The Danish Building Regulations make increasing demands on energy efficiency and reduction of CO_2 emissions. Commonly applied renovation approaches aim to limit the heat transfer through the building envelope by adding thermal insulation and tightening the envelope. These solutions lead to energy savings during the heating season, but a limited infiltration can cause elevated indoor temperatures during periods with high internal heat loads, where solar radiation is the most pronounced contributor. The problem becomes even larger as the number of people working from home increases and external temperatures rise due to climate change. Many studies have shown that an elevated indoor temperature negatively affects health, well-being and productivity. It is therefore important that the risk of overheating in Danish dwellings receives more attention. Energy efficient solutions to the problem with overheating include limiting the solar heat gains through the glazed parts of the facade and effective ventilation.

The objective of the project was to evaluate the potential of different solar control solutions combined with typical ventilation strategies to reduce indoor temperature excess in renovated Danish apartment buildings from the period 1850-1970 with the least possible effect on the quantity and quality of daylight. The target group for the project was the construction industry, building owners and residents, the community in general and the international research world.

The project dealt with a thorough examination of the overheating risk and the determination of possible solutions, based on dynamic computer simulations with focus on three typical Danish apartment building types from the period 1850-1970 derived from buildings topology defined by Engelmark (Engelmark, J. 2013. *Dansk Byggeskik, Etagebyggeriet gennem 150 år*, ISBN: 978-87-993249-6-5). This report describes the studied cases and the models use in details. The results regarding the effect of different windows type, solar shading solution and ventilation strategies on overheating and energy consumption based on over 700 simulations performed in IDA Indoor Climate and Energy (IDA ICE) software are discussed.

The project's results show that energy renovation reduced the energy consumption by in average 64% but as expected, energy renovation intensified overheating. Implementation of a mechanical ventilation system during renovation reduced the overheating compared to cases with natural ventilation. The maximum number of overheating hours defined as any occupied hour with an indoor temperature above 27°C, was for a building without mechanical ventilation 154 hours, which is 54 hours above the tolerance limit of 100 hours defined in the Danish Building Regulations. In cases with mechanical ventilation with heat recovery, the number of occupied hours with overheating was reduced on average by 40% compared to a case without mechanical ventilation.

The results show that airflows through windows have a crucial effect on the indoor temperature and that good venting can keep overheating within tolerance limit.

Orientation of a building played only minor role regarding the energy consumption but was crucial regarding overheating. The highest number of hours with elevated temperatures occurred for west orientation of the tested buildings.

The study confirms that internal solar shading devices are less efficient in limiting overheating than external shading solutions. The three tested external solar shading devices were 50-70% more efficient in reducing the number of hours with overheating than internal shading solutions. In most cases, utilization of external solar shading was necessary to eliminate overheating in the investigated buildings. The use of solar control glass could eliminate overheating in the oldest buildings (construction period 1850-1890) which have the smallest glass area in relation to the facade area. The use of solar control glass in buildings from the periods 1920-1940 and 1940-1970 led to reduction of overheating by 100 hours a year, but overheating was not completely eliminated.

List of conference papers

The conference papers published in connection with this research project are as follows:

Ślipek M., Sarey Khanie M., Zukowska-Tejsen D., Kolarik J. and Nielsen T.R. (2017). Visual Comfort Evaluation in Residential Buildings: a Simulation-Based Study. In: Proceedings of the 13th European Lighting Conference – LUX EUROPA 2017, Ljubljana, Slovenia. Link to paper: http://orbit.dtu.dk/en/publications/visual-comfort-evaluation-in-residential-buildings-a-simulationbased-study(346631ea-e363-437c-8295-b32906e5bc2f).html

Sarey Khanie M., Ślipek M., Zukowska D., Kolarik J. and Nielsen T.R. (2017). An Evaluation Method for Façade Renovation Strategies in Residential Buildings Using Gaze Responsive Visual Comfort Assessments. In: Proceedings of the 13th European Lighting Conference - LUX EUROPA 2017, Ljubljana, Slovenia. Link to paper: http://orbit.dtu.dk/en/publications/an-evaluation-method-for-facade-renovation-strategies-in-residential-buildings-using-gaze-responsive-visual-comfort-assessments(066f41c9-cedd-4555-af1b-3559526a149b).html

Zukowska D., Kolarik J., Ananida M., Sarey Khanie M. and Nielsen T.R. (2018). Potential of mechanical ventilation for reducing overheating risks in retrofitted Danish apartment buildings from the period 1850-1890 – A simulation-based study. In: Proceedings of the 39th AIVC - 7th TightVent & 5th venticool Conference, Antibes, France, p. 10. Link to the paper: http://orbit.dtu.dk/en/publications/potential-of-mechanical-ventilation-for-reducing-overheating-risks-in-retrofitted-danish-apartment-buildings-from-the-period-18501890--a-simulationbased-study(801053f7-ae90-4b97-a648-b16ebe1af04a).html

Zukowska D., Ananida M., Kolarik J., Sarey Khanie M. and Rammer Nielsen T.R. (2019). Solar control solutions for reducing overheating risks in retrofitted Danish apartment buildings from the period 1850-1900 – A simulation-based study – In: Proceedings of the 13th REHVA World Congress - CLIMA 2019, Bucharest, Romania.

List of student projects

The following student projects were connected to this research project:

Lin Kjerulf and Maja Toft (May 2017). Strategies for facade renovation of Danish apartment buildings in order to prevent overheating. BSc. thesis.
Link:
https://findit.dtu.dk/en/catalog/2371656633?single_revert=%2Fen%2Fcatalog%3Fq%3DLin%2BKjerulf%2Band%2BMaja%2BToft%26show_single%3Doff

Milena Slipek (July 2017). A renovation challenge in Nordic climate: Simulation-based daylighting assessment in multi-storey residential buildings with heritage value. MSc. thesis.
Link:
https://findit.dtu.dk/en/catalog/2385161999?single_revert=%2Fen%2Fcatalog%3Fq%3DMilena%2BSlipek%26show_single%3Doff%26utf8%3D%25E2%259C%2593

Izabelle Laviny Lima Dantes (January 2018). Energirenovering og overtempertur risiko – Et simulations-baseret studie for renoverings guidelines for etageboliger fra 1850-1970. BSc. thesis.

Anna Paparizou (February 2018). A comparative sensitivity analysis on manual controls for solar control systems in residential buildings between 1850 and 1930. MSc. thesis.
Link:
https://findit.dtu.dk/en/catalog/2396944992?single_revert=%2Fen%2Fcatalog%3Fq%3DAnna%2BPaparizou%26show_single%3Doff%26utf8%3D%25E2%259C%2593

Alexander Olin Barfoed (June 2018). Efficient ventilation solutions for reducing overheating risks in retrofitted residential apartment buildings in Denmark from the period 1850-1970. BSc. thesis.
Link:
https://findit.dtu.dk/en/catalog/2436419315?single_revert=%2Fen%2Fcatalog%3Fq%3DAlexander%2BOlin%2BBarfoed%26show_single%3Doff%26utf8%3D%25E2%259C%2593

Myrto Ananida (October 2018). Reduction of overheating in Danish dwellings in connection with facade renovation – Effective solar control and ventilation. MSc. thesis.
Link:
https://findit.dtu.dk/en/catalog/2441736036

1. Background

The Danish Building Regulations (BR18, 2018) make increasing demands on energy efficiency and reduction of CO_2 emissions. Commonly applied renovation approaches aim to limit the heat transfer through the building envelope by adding thermal insulation and tightening the envelope. These solutions lead to energy savings during the heating season, but a limited infiltration can cause elevated indoor temperatures during periods with high internal heat loads, where solar radiation is the most pronounced contributor (REHVA, 2010). Glazing in residential buildings is primarily installed to admit daylight and allow views of the outside, but at the same time, it allows solar radiation to enter the building, which in summer may be excessive and result in overheating. Normal clear window glass allows short-wave solar radiation to get into an interior space, where the radiation is absorbed. The interior then radiates long wave, i.e. thermal radiation, which is trapped in the building, as glass is opaque to this long wave radiation. Consequently, the indoor air temperature rises. This is called the “greenhouse effect”. The fact that residential ventilation in Danish context is predominantly designed to supply sufficient fresh air and not to provide cooling only intensifies the overheating risk, especially during spring and summer. Moreover, it is not always appropriate to cool by opening windows and it has a limited effect. In busy cities, opening windows results in unwanted noise and air pollution coming from outside. In addition, open windows increase the risk of burglary. In the future, the effect will be even greater due to the general tendency to increase outside temperatures because of climate change (CIBSE, 2005).

People spend significant amount of time indoors. Additionally, the number of people who work from home is increasing. Many studies have shown that elevated indoor temperature negatively affects health, well-being and productivity (NHBC, 2012). For the majority, short periods of elevated temperature are a matter of thermal discomfort and lower productivity, but extended periods with an elevated temperature can lead to health related problems. For some vulnerable groups such as infants, children, the elderly, obese and people with chronic diseases, exposure to elevated temperatures, even during shorter periods, may lead to significant health consequences (Brown and Walker, 2008). In addition, elevated temperatures during nighttime result in the inability to recover from heat stress in the daytime (Kovats and Hajat, 2008) due to impaired sleep quality (Raymann et al., 2008; Strøm-Tejsen et al., 2016). It has been reported that a change as low as 1 K in skin temperature can affect sleep quality especially for the elderly (Raymann et al., 2008).

Energy efficient solutions to the problem with overheating in dwellings include limiting the solar heat gains through the glazed parts of the facade (REHVA, 2010) and effective ventilation (IEA EBC, 2018). Internal and external solar shading as well as solar control glazing can be used very effectively to keep rooms in dwellings cooler during high solar radiation periods. It can reduce or even eliminate elevated indoor temperatures and a need for air-conditioning. Several studies have indicated that external solar shading devices are more efficient than internal shading because they reduce solar transmittance to the indoor space (REHVA, 2010). However, the internal solar shading gives occupants possibility to prevent a discomfort due to glare of direct sunlight. The ES-SO 2014 “Cost Efficient Solar Shading Solutions in High Performance Buildings” study (Hutchins, 2015) demonstrated that dynamic solar shading leads to cooling energy savings of up to 62% for a south-west facade for the climate of Stockholm. At the same time, a few studies reported that peoples' health, well-being and social interaction benefits from daylight exposure (Veitch and Galasiu, 2012), and optimal use of solar shading is therefore essential. However, the effect of the various available solar shading solutions on daylight level, distribution and quality in living space must be carefully examined to avoid visual discomfort. The daylight controls the human biological clock and is therefore an important regulator of human physiology and performance (Duffy and Write, 2005). Inadequate daylight levels can cause lower concentration, decreased performance, decreased well-being, sleep disturbances, and tendencies to winter depression. Proper daylight increases visual perception and gives a better colour perception than most electric lamps. Visual contact with the outside world through windows affects people's state of mind, and it is proven that it increases productivity and that people feel happier and less stressed (O´Connor et al., 1998). Moreover, appropriate daylight conditions in homes reduce the use of electric lighting, which leads to energy saving and reduction in CO_2 emissions. Therefore, applied solar shading solutions should not compromise daylight conditions in the residence.

Ventilation has been proven efficient in lowering the indoor temperature in moderate climates (Heiselberg and Kolokotroni, 2015). The term "ventilative cooling" has become popular in recent years and it refers to the use of natural or mechanical ventilation strategies to cool indoor spaces by effective use of outside air (IEA EBC, 2018). Ventilative cooling reduces the energy consumption of cooling systems while maintaining thermal comfort. In rural and suburban locations, a solution may be to use window opening to help to cool dwellings but only in the case when the outside temperature is lower than the inside temperature. In urban location, the possibility to open window can be limited due to noise, pollution or security concern.

According to the Danish Building Regulations (BR18, 2018), the operative temperature in homes should not exceed 27°C for more than 100 hours per year and 28°C for more than 25 hours per year. However, in many new and renovated dwellings in Denmark the temperature during spring and summer exceeds these measures.

2. Objectives

The objective of the project was to evaluate the potential of different solar control solutions combined with typical ventilation strategies to reduce indoor temperature excess in renovated Danish apartment buildings built in the period 1850-1970. The aim was to find solutions with the least possible effect on the quantity and quality of daylight. The project dealt with a thorough examination of the overheating risk and the determination of possible solutions based on dynamic computer simulations. The target group for the project is the construction industry, building owners and residents, the community in general and the international research world.

3. Methods

IDA Indoor Climate and Energy (IDA ICE) software was used to simulate thermal conditions and energy consumption in case study buildings before and after renovation. Weather data from the Danish Reference Year, DRY 2013 (Wang et al., 2013), were used. The simulation period was set from the 1st of January to the 31st of December 2010.

3.1 Case study buildings

Overheating was studied in three typical types of Danish apartment buildings from the period 1850-1970 based on topology given by Engelmark (2013) – Figure 1. Building Type 2 in Engelmark's topology was not considered as the construction and appearance of it reminds Building Type 1.

Building Type 1 Building Type 3 Building Type 4

Figure 1. Typical Danish apartment buildings from the period 1850-1970 based on Engelmark (2013).

In order to prepare the models of the buildings in the IDA ICE software, three reference buildings corresponding to the three types were found in the area of Greater Copenhagen.

Building Type 1

Building Type 1 represents a historical residential 5-storey building from the period 1850-1900 common in Danish cities (Figure 1). The building comprises parts of a rectangular arrangement of similar buildings with the backside facing to the courtyard in the middle and the front facade facing the street with other buildings of the same height (Figure 2, left). Solid masonry and bricks are the main characteristics of the construction, especially of the outer walls. The inner walls are mainly made of timber or double brick walls. The floors and staircases are made of wood. The roofing material is brick, slate or metal carried by a wooden structure.

The reference Building Type 1 is located on Ahornsgade at Nørrebro in Copenhagen and was used to prepare the IDA ICE model of the building. The simulated apartment was located on the 2nd floor of the building and consisted of a kitchen, living room, bedroom, small bathroom and hall – a total gross floor area of 56.6 m^2 (Figure 2, right).

The windows in the living room and in the bedroom consisted of four openable parts (the classical "Dannebrogsvindue") where the two lower parts counted for 2/3 of the window size. The fraction of the frame to the total window area was calculated in the reference building to 39% for windows in the living room and the bedroom, and 28% in the kitchen.

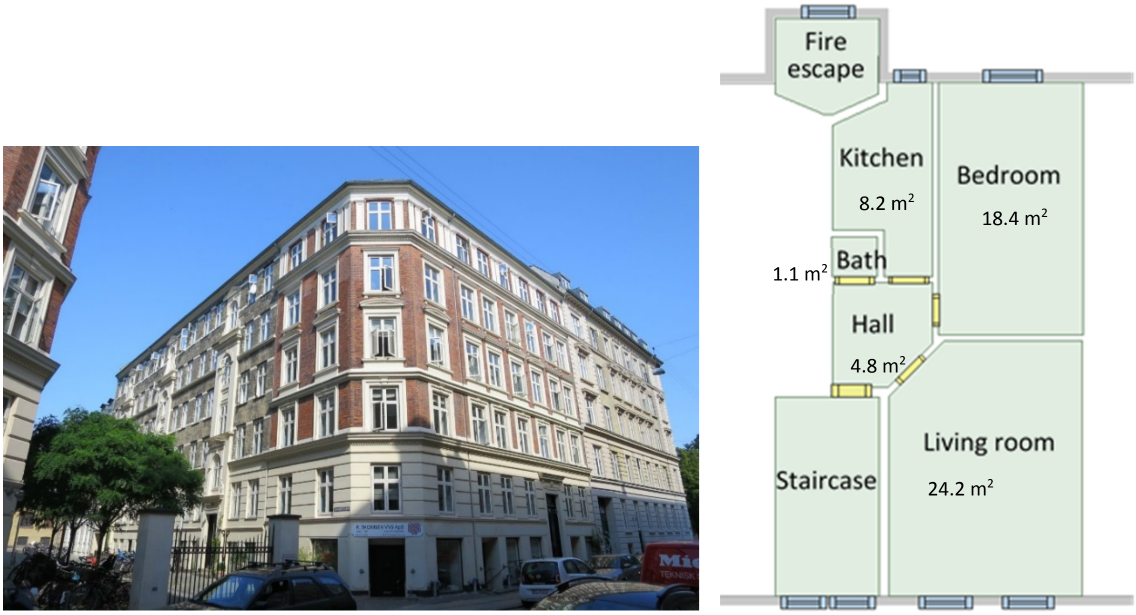


Figure 2. Reference Building Type 1 (left) and layout of simulated apartment (right).

Energy renovation for Building Type 1 included an addition of 95 mm of internal thermal insulation and limited infiltration. The Knowledge Centre for Energy Savings in Buildings (2017) recommends the thickness of the internal insulation to be below 100 mm to reduce the risk of condensation. The heat transfer coefficient for the external wall changed from U_{wall} = 1.06 W/(m^2·K) before renovation to U_{wall} = 0.30 W/(m^2·K) after renovation. The solution with internal insulation was chosen due to the architectural value of the facades in this type of buildings.

Building Type 3

Building Type 3 was widely constructed in the 1930s with solid yellow masonry outer walls and double brick inner walls. The windows are larger than in Building Type 1. Bay windows, corner windows and balconies are common in these buildings and therefore more iron was used in the structure of the outer walls. The horizontal divisions have iron beams instead of timber beams. The staircases are made of prefabricated steps and cast in-site concrete slabs. The cardboard and cement-based sheets are used as a roofing material, still on a wooden structure but usually with a lower roof inclination. Furthermore, the foundations and basement exterior walls are constructed with cast in-site concrete (Engelmark, 2013).

The reference Building Type 3 (Figure 3, left) is located on Offenbachsvej, in the historical district of Sydhavn, the southern part of Copenhagen. The building is part of a building complex with a courtyard in the middle. The plan of the simulated apartment in Building Type 3 of 56.1 m^2 consisting of a kitchen, living room, bedroom, bathroom and hall is shown in Figure 3 (right).

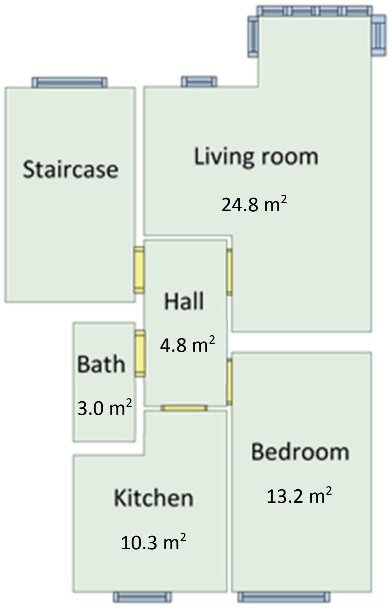


Figure 3. Reference Building Type 3 (left) and layout of simulated apartment (right).

The living room had a bay window with corners and a single window with a balcony. The fraction of the frame to the total window area was calculated to 38% for all windows in the living room, 33% in the bedroom, and 37.5% in the kitchen.

The renovation of Building Type 3 assumed an addition of 125 mm of external insulation with an additional external brick wall – U_{wall} = 1.09 W/(m^2·K) before renovation and U_{wall} = 0.23 W/(m^2·K) after renovation. The thickness of the insulation follows recommendations from The Knowledge Centre for Energy Savings in Buildings (2017).

Building Type 4

Building Type 4 has a lot in common with Building Type 3, with the main difference being the floor separations made of concrete. The external walls are massive brick walls with large windows. Staircases of concrete with prefabricated runs and landings were presented in the late 1940s. The roof and foundations were constructed in the same way and same material as Type 3. Type 4 gradually replaced Type 3 due to the lack of iron (Engelmark, 2013).

The reference Building Type 4 is located in Herlev. It is a 3-floor building with the façade of yellow bricks creating a contrast with the windows' white painted woodwork – Figure 4 (left). The plan of the simulated apartment with a total heated floor area of 65.5 m^2 is shown in Figure 4 (right). The apartment plan consists of a kitchen, living room, bedroom, bathroom, hall and additionally an office.

The renovation of Building Type 4 assumed an addition of 125 mm of external insulation with an additional external brick wall – U_{wall} = 1.39 W/(m^2·K) before renovation and U_{wall} = 0.24 W/(m^2·K) after renovation.

The fraction of the frame to the total window area was calculated to 20%, except for the window in the bathroom, where the fraction was 45%.

Figure 4. Reference Building Type 4 (left) and layout of simulated apartment (right).

3.2 Building surrounding and orientation

The real surroundings of the reference buildings are shown in Figure 5. Reference Building Type 1 is placed in a narrow street canyon of 8.8 m width, while Building Types 3 and 4 have the neighbouring buildings in a distance of 18 and 28 m, respectively.

Figure 5. Surroundings of the reference buildings: Type 1 (left), Type 3 (middle) and Type 4 (right).

The aim of the project was to simulate the most critical situation regarding overheating risk. This would be the situation when the other surrounding buildings are not present, e.g. when the building is facing a square. Therefore, the main results of the project are based on the models without surrounding buildings. However, in case of Buildings type 1 and 3 the whole building complex around the courtyard was always taken into account (Figures 6 and 7, respectively), while the other buildings were removed. Building Type 4 is a freely standing building (Figure 8). Preliminary simulations of Building Types 3 and 4 with their neighbouring buildings showed no or negligible effect on the simulation results due to rather large distance between the buildings. In case of Building Type 1, which typically is placed in a dense city area, the shading effect of the surrounding buildings cannot be neglected and therefore both situations without and with surrounding buildings were tested (Figure 6).

Greenery was neglected in all models.

Each of the three buildings was simulated in three different orientations – with the living room facing south, east and west.

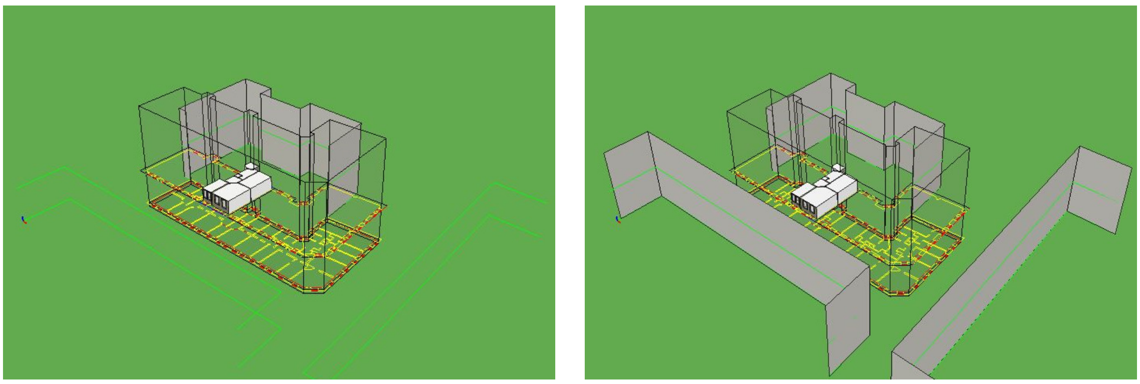


Figure 6. Model of Building Type 1 without (left) and with surrounding buildings present (right).

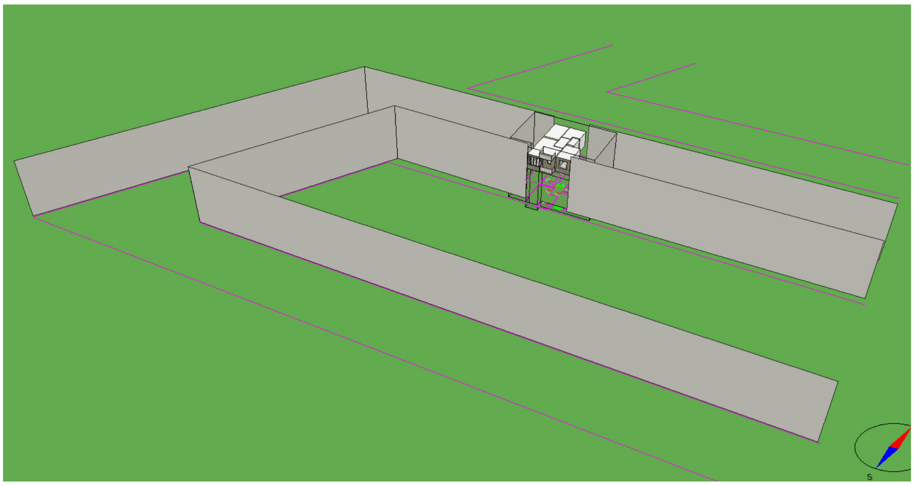


Figure 7. Model of Building Type 3.

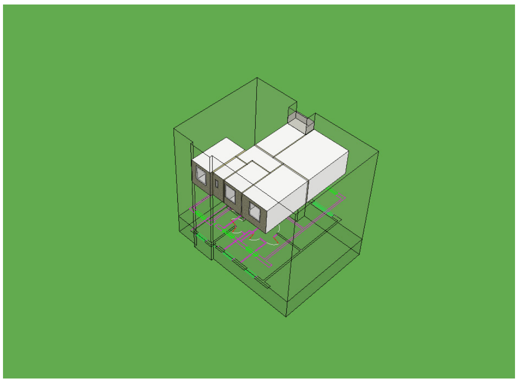


Figure 8. Model of Building Type 4.

3.3 Internal heat and moisture loads

Each of the simulated apartments was assumed to be occupied by two adults employed within standard work hours. The constant total internal heat load of 5 W/m^2 of the heated floor area (i.e. including external walls), including occupants and equipment/lighting, was assumed in the models. It followed the assumption used in the Danish energy frame calculations for dwellings (Aggerholm and Grau, 2018). The heat load from the occupants for a whole year for each room was determined based on simulations with the occupancy schedules as in Table 1. The heat load from the equipment and lighting for each room was calculated as the difference between the yearly total heat load (Table 2) and the yearly heat load from the occupancy (Table 1), and it was assumed to be constant during the whole year.

Table 1. Occupancy schedules and heat loads for the different rooms.

Room	Occupancy	Metabolic rate met	Schedule	Heat load kWh/year
Bedroom	2.0	0.9	22:00-7:00	621
Living room	1.5	1.0	7:00-8:30 16:00-22:00	430
Bathroom	0.5	1.2	7:00-8:30	35
Kitchen*	0.5	1.4	17:00-22:00	135
Hall	-	-	-	-

*Occupancy in the kitchen in the morning was neglected as it was assumed to be short.

Table 2. Heat loads and schedules for equipment and lighting for the different rooms.

Room	Total heat load* kWh/year	Heat load from equipment kWh/year	W	Schedule
Bedroom	807	186	21.3	Const.
Living room	1060	630	71.9	Const.
Bathroom	47	12	1.4	Const.
Kitchen	357	222	25.4	Const.
Hall	209	209	23.8	Const.

*Total heat load is calculated based on the assumption of 5 W/m^2 of the heated floor area.

The moisture production from typical activities occurring in the apartment was set to $2.6 \cdot 10^{-4}$ kg/s in the bathroom and $1.10 \cdot 10^{-4}$ kg/s in the kitchen (Smith and Svendsen, 2016), and it follows the occupancy schedules for these two rooms.

A detailed description of the internal loads and the schedules for internal loads can be found in the conference paper “Solar control solutions for reducing overheating risks in retrofitted Danish apartment buildings from the period 1850-1900 – A simulation-based study” (Zukowska et al., 2019).

Additionally, primary tests with other loads and schedules were performed and reported in the conference paper “Potential of mechanical ventilation for reducing overheating risks in retrofitted Danish apartment buildings from the period 1850-1890 – A simulation-based study” (Zukowska et al., 2018).

3.4 Window and door opening

The Danish energy frame calculation (Aggerholm and Grau, 2018) assumes venting in periods where the room temperature exceeds 23°C. In the present study, the window opening was controlled by proportional-integral controller (PI): $T_{set\text{-}point}$ = 23°C, K = 0.3. Two additional conditions were set to window opening that the outdoor temperature was minimum 2 K lower than the indoor temperature and at least one of the occupants was present in the apartment. The effective window opening area was assumed to be 60% during daytime according to Vorre et al. (2017) and 15% during night-time.

In Building Types 1 and 4, all windows were simulated with a 60% opening. In case of the living room in Building Type 3, only two out of the four front windows were assumed to open 60%, while the two side windows as well the window with a balcony stayed always closed.

The above assumptions were chosen to result in average airflows through the windows in the summer period corresponding to a ventilation level around 0.9 l/(s·m^2) – the value assumed in the Danish energy frame calculations for dwellings (Aggerholm and Grau, 2018).

Additional configuration of window opening was tested in Building Type 1 in order to check the effect of window opening on overheating. The situation when the occupants are not efficiently using venting was mimicked. In these cases, the upper parts of the window in the living room and the bedroom were assumed never open, while 60% of the window opening was implemented to the lower parts and for the whole window in the kitchen. Only one of the two windows in the living room was set to open.

The doors to all rooms were kept closed in each simulation case to avoid unrealistically large airflows between the rooms.

3.5 Ventilation and infiltration

The buildings before renovation were simulated as naturally ventilated (case UR_NV) with fixed infiltration of 0.5 l/(s·m^2) of the heated floor area.

The buildings after renovation were simulated with three typical ventilation solutions used in Danish dwellings: natural ventilation (case R_NV) and two balanced mechanical ventilation systems, i.e. constant air volume (CAV_{max}) and variable air volume (VAV_{RH}). The naturally ventilated building was modelled with fixed infiltration of 0.3 l/(s·m^2) of the heated floor area corresponding to the minimum fresh air supply required by the Danish Building Regulations (BR18, 2018). In the CAV_{max} system the airflows were determined to fulfil two requirements from the Danish Building Regulations (BR18, 2018) – the minimum fresh air supply and the extraction from bathroom (15 l/s) and kitchen (20 l/s). The total amount of air extracted from bathroom and kitchen was therefore 35 l/s, and the same amount of air was supplied to the habitable rooms. The VAV_{RH} ventilation system represented a decentralized ventilation solution with airflows controlled according to the relative humidity (RH) measured in the exhaust duct. The minimum supply airflows into the habitable rooms corresponded to 0.3 l/(s·m^2), while the maximum airflows were determined to fulfil the requirements to the amount of exhaust air from the bathroom and the kitchen (35 l/s). The airflow was controlled proportionally between the minimum value at RH = 30% and maximum at RH = 70%. Wind driven infiltration characterized by air tightness of 1 l/(s·m^2) of the heated floor area at 50 Pa was considered for the mechanically ventilated buildings.

A typical air handling unit used for residential ventilation in Denmark fulfilling the requirements in the Danish Building Regulations (BR18, 2018) to heat recovery and specific fan power was set (85% and 1000 J/m^3, respectively).

3.6 Heating system

A set-point temperature for heating equal to 20°C was assumed in all rooms in the three apartments and the heating system was supplied from district heating. The heating season was from the 1st of October to the 30th of April.

3.7 Glazing

The apartments before renovation were simulated with two types of glazing: clear double glazing Pilkington Optifloat Clear (4-12-4) and energy double glazing with low-E coating Pilkington Optitherm S3 (4-12Ar-S(3)4).

The apartments after renovation were simulated with two types of energy glazing: double glazing with low-E coating Pilkington Optitherm S3 (4-12Ar-S(3)4) and triple glazing with low-E coating Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-S(3)4). The properties for the glazing types are shown in Table 3 (based on Glasfakta, 2018). The heat transfer coefficient of the wooden window frame (U_f) was set to 2.0 W/(m^2·K) for the clear double glazing and 1.3 W/(m^2·K) for the energy double and triple glazing.

Table 3. Optic and thermal properties for glazing variations.

Glazing	Symbol	Heat transfer coefficient U_g, W/(m^2·K)	Solar heat gain coefficient g, %	Direct solar energy transmittance ST, %	Light transmittance T_{vis}, %
Pilkington Optifloat Clear (4-12-4)	G0	2.8	79	76	82
Pilkington Optitherm S3 (4-12Ar-S(3)4)	G1	1.3	65	57	82
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-S(3)4)	G2	0.6	53	45	74

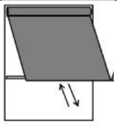
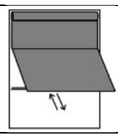
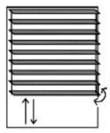
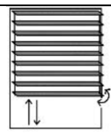
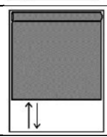
3.8 Solar control solutions

Five different solar shading devices were evaluated in regards to thermal condition for the three apartments in the case study buildings before and after renovation. For the renovated buildings, solar control glazing was additionally tested.

The solar shading devices, i.e. awning blinds, marquisolette, external venetian blinds, internal venetian blinds and roller blinds, were modelled using standard IDA ICE component models. Internal and external solar shading devices were tested together with 2-layer energy glazing with low-E coating Pilkington Optitherm S3 (4-12Ar-S(3)4), and additionally with clear 2-layer window Optifloat Clear (4-12-4) for the buildings before renovation. The use of external solar shading, especially in Building Type 1, is limited due to the architectural heritage value of the facades and therefore light colours of shadings were chosen, as the one integrating with the building appearance most. The properties of the tested solar shadings are listed in Table 4.

The open drop arm awning was simulated with fabric projected forward away from the window. The set up for the awning for each window was the same with projection angle changing between 0 and 90° (Figure 9, left). The set up for the marquisolette for each window was the same as shown in Figure 9 (right) with projection angle of the lower part between 0 and 90°. The slat angle for external and internal venetian blinds was fixed to 45°.

Table 4. Specifications of simulated solar shading devices.

Position	Solar shading	Symbol	Geometry	Colour	Optical properties
External	Awning blinds	S1		Fabric: Grey - Beige (Warema 5860)	T_{vis} = 0% R = 13%
	Marquisolette	S2		Fabric: Grey - Beige (Warema 5860)	T_{vis} = 0% R = 13%
	Venetian blinds (45° cut off angle)	S3		C-shaped slate White	T_{vis} = 0% R = 74%
Internal	Venetian blinds (45° cut off angle)	S4		C-shaped slate White 71000	T_{vis} = 0% R = 78%
	Roller blinds	S5		Fabric: White	T_{vis} = 5% R = 50%

T_{vis} - transmittance, R - reflectance

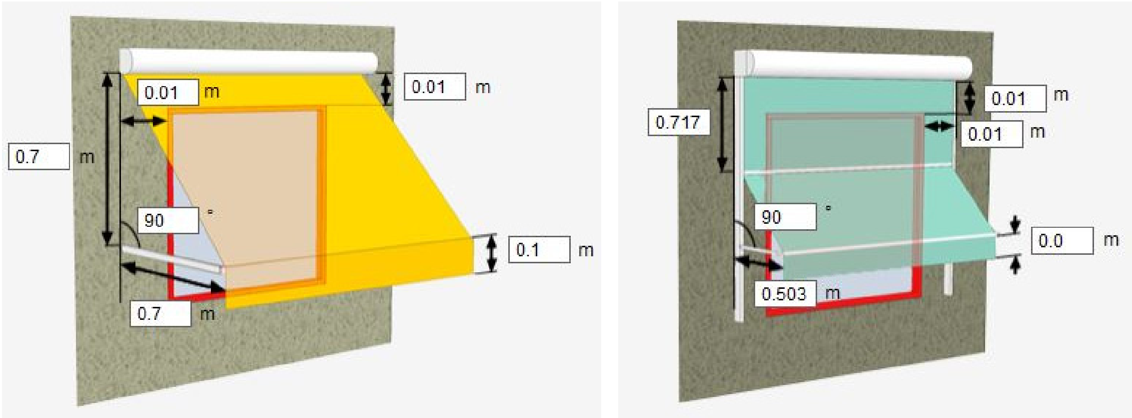


Figure 9. Drop arm awning blinds (left) and marquisolette (right) modelled in IDA ICE.

All windows in the three apartments were also simulated with 2-layer glazing with solar control coating. Pilkington Suncool 70/40 (6C(74)-15Ar-4) was used without any additional solar shading. The properties for the glazing are shown in Table 5 (based on Glasfakta, 2018). The heat transfer coefficient (U_f) of the wooden window frame was 1.3 W/(m^2·K) for the solar control glazing.

Table 5. Optic and thermal properties for solar control glazing used.

Glazing	**Symbol**	**Heat transfer coefficient U_g, W/(m^2·K)**	**Solar heat gain coefficient g, %**	**Direct solar energy transmittance ST, %**	**Light transmittance T_{vis}, %**
Pilkington Suncool 70/40 (6C(74)-15Ar-4)	SCG	1.1	43	39	71

3.9 Solar shading operation

In all simulation cases, the solar shading devices were controlled according to daylight illuminance level in the space at minimum 500 lx (PI controller: $I_{set\text{-}point}$ = 500 lx, K = 0.02; measured at 0.6 m above the floor level, 1/3 of the room depth from the window and 1/2 of the room width). This strategy assumed that building occupants would use solar shading to prevent excessive illuminance levels to eliminate glare but prioritize to use daylight to its maximum. The set point of 500 lx assumed that the occupants used daylight levels in a medium higher range maintaining daylight for the type of tasks typical for residencies.

3.10 Analysis of overheating and primary energy use

According to the Danish Building Regulations (BR18, 2018), the operative temperature in dwellings should not exceed 27°C for more than 100 hours per year and 28°C for more than 25 hours per year. Therefore, in this study, the hours with an indoor temperature above 27°C were treated as overheating with an acceptable tolerance of 100 hours with the excessive temperature. For the purpose of analysis, overheating hours for living room, kitchen, bedroom and bathroom were aggregated. The analysis of yearly primary energy use per m^2 of the heated floor area included only ventilation and heating. The heating was supplied by district heating with a primary energy factor of 0.85, while a primary energy factor for electricity used for mechanical ventilation was 1.9 (BR18, 2018). The primary energy use for lighting and domestic hot water was neglected, as it is difficult to predict occupants' behaviour in residences.

3.11 Overview of simulation cases

In total over 700 simulations were performed in IDA ICE to study the impact of different parameters on overheating. Figure 10 illustrates the overview of the changeable parameters in the simulated cases.

The cases before renovation, the three buildings (T1, T3 and T4), in three different orientations each (East, West and South), were simulated with natural ventilation (UR_NV), 2-layer energy windows (G1), and with and without each of the five solutions of solar shading devices (NS, S1-S5). Additional simulations with clear 2-layer glazing (G0) with and without solar shading devices were performed for each of the buildings in the three orientations. For Building Type 1 all simulations were performed for both cases with and without surrounding buildings (SBY and SBN, respectively), and both with standard and reduced window opening (W_60 and W_R), while for Building Types 3 and 4 only cases without surrounding buildings (SBN) were investigated and always with standard window opening (W_60).

After renovation the three buildings (T1, T3 and T4), in the three orientations each (East, West and South), were simulated with 2-layer energy glazing (G1) and six options for solar shadings (NS, S1-S5) for each of the 3 ventilation strategies (NV, CAV_{max} and VAV_{RH}). Additional simulations were made for 2-layer solar control glazing (SCG) and 3-layer energy windows (G2) without solar shading. All these combinations were simulated for Building Type 1 with and without surrounding buildings (SBY and SBN, respectively), while for Building Types 3 and 4 only cases without surrounding buildings (SBN) were investigated. All cases with Building Type 1 were simulated with the standard (W_60) and reduced window opening (W_R), while for Building Types 3 and 4 all cases were only simulated with standard window opening (W_60)

Moreover, a large number of pre-test simulations were performed. These results are not presented in this report.

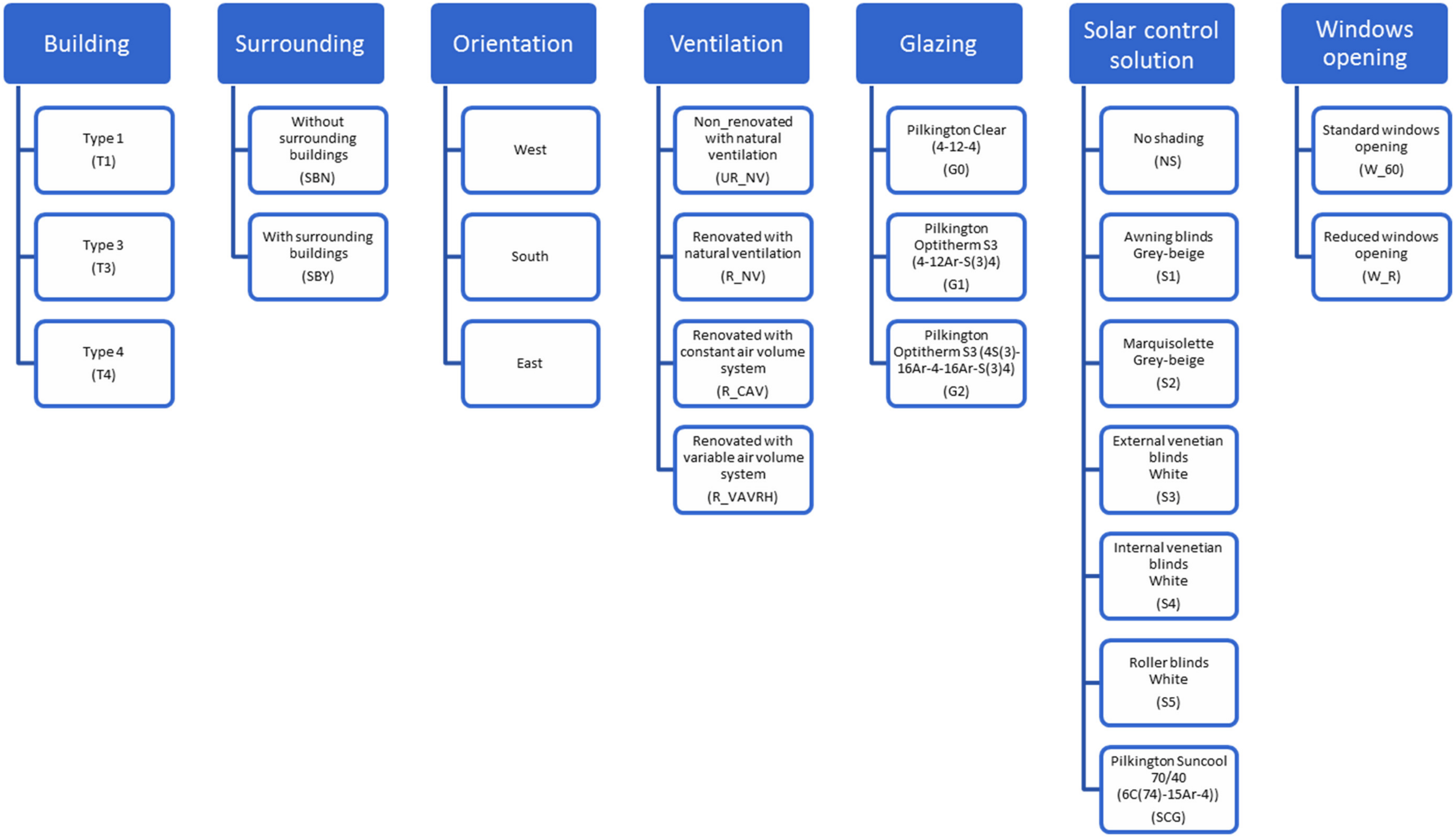


Figure 10. Overview of changeable parameters in the simulated cases (abbreviations used for the parameter shown in the brackets).

4. Results and Discussion

4.1 Impact of renovation and building orientation

The results from the IDA ICE simulations showed that a change of all windows from 2-layer windows (G0) to 2-layer energy windows (G1) in the simulated apartments in Building Types 1, 3 and 4 reduced energy consumption of approx. 9-11% (cases UR_NV_G0 and UR_NV_G1 in Figure 11). This change also decreased the number of hours with temperature above 27°C in the apartments as the energy windows have lower solar heat gain coefficient (g-value) compared to normal clear windows (see Table 3). More results regarding the effect of different glazing on overheating are included in Appendix A. The results for Building Type 1 located in a street canyon are not discussed in this section but they can be found in Appendix C. It was assumed in the project that window change would be performed years back, and therefore the basic cases for all apartments before renovation were assumed to have 2-layer energy windows (G1).

The results in Figure 11 show that energy renovation including only reduction of heat transmission and infiltration (cases UR_NV_G1 and R_NV_G1) reduced the total primary energy use for heating by approx. 58-70% in the three buildings in case of natural ventilation. The energy consumption is slightly lower for south orientation (Figure 11, top) compared to west and east orientations (Figure 11, bottom) for which the results of the simulations are almost the same. In case of the naturally ventilated buildings, the primary energy demand includes only the energy used for heating.

The total energy consumption for the three apartments in south orientation is slightly smaller compared to the other two orientations, due to more solar gains in south orientation in winter, and less energy is therefore used for heating.

The results regarding the aggregated hours with overheating in the naturally ventilated buildings are summarized in Figure 12 for the west, east and south building orientations (i.e. orientation of the living room), respectively. The figure shows the cases where the surrounding buildings were not present and no solar shading devices were used. The highest number of hours with elevated temperatures occurred for west orientation of the buildings. In cases before renovation (UR) with clear double glazing (G0) the number of hours with overheating was higher compared to the cases with 2-layer energy windows (G1) as the g-value of the normal glazing is higher. In cases with normal glazing for west and east orientations, the overheating was significantly above the tolerance limit in the apartment in Building Type 4, while overheating did not exceed the tolerance limit in any of the cases with energy windows (maximum of 99 hours in west orientation).

As expected, the energy renovation clearly intensified overheating – Figure 12. The Danish Building Regulations (BR18, 2018) regarding overheating were fulfilled only in Building Type 1, where as an example in west orientation the number of occupied hours with elevated temperature increased from 33 to 66 (Figure 12, top). In Building Type 3 the increase was from 58 to 151 and in Building Type 4 – from 99 to 154. Similarly, in case of the east (Figure 12, middle) and south (Figure 12, bottom) orientations, the number of hours with overheating above the limit was exceeded in Building Types 3 and 4. In all three buildings, elevated temperatures appeared mainly in the living rooms since the bedroom and kitchen were located in the opposite side of the apartments in all cases.

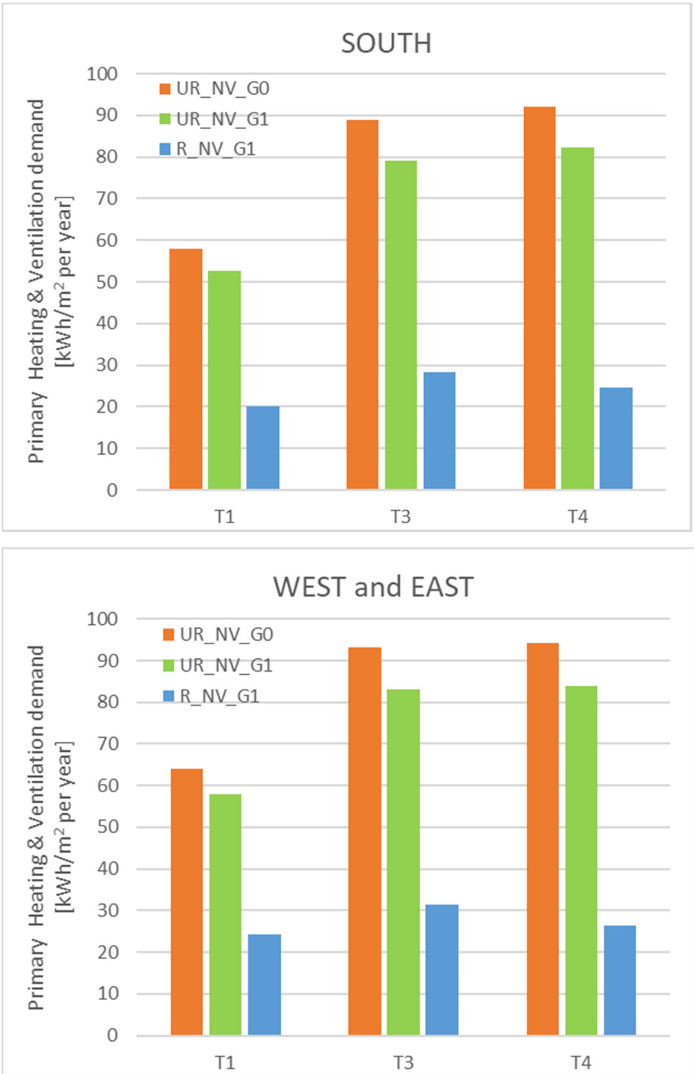


Figure 11. Yearly primary energy use in the naturally ventilated apartments in Building Types 1, 3 and 4 for cases without the surrounding buildings present. South orientation (top) and west/east orientation (bottom).

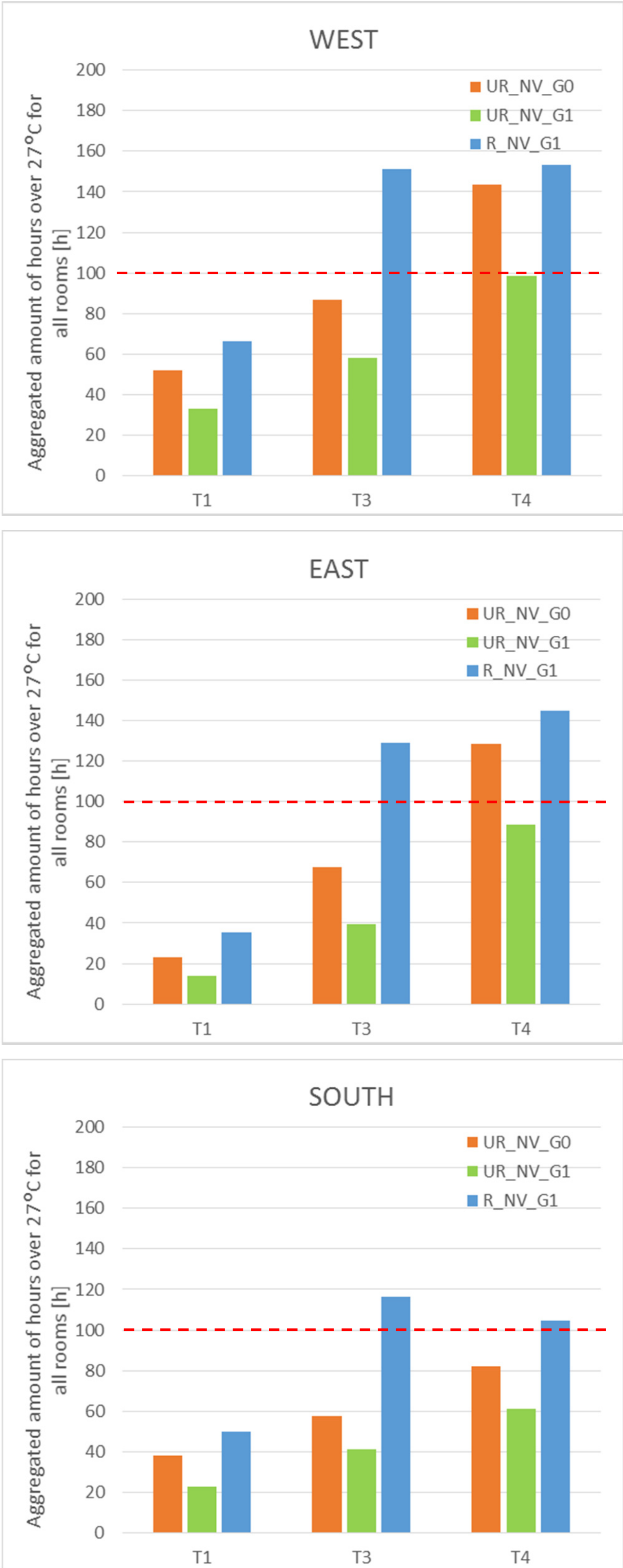


Figure 12. Aggregated number of occupied hours with indoor temperatures above 27°C in the naturally ventilated apartments in Building Types 1, 3 and 4 for cases without the surrounding buildings present. West (top), east (middle) and south (bottom) orientations.

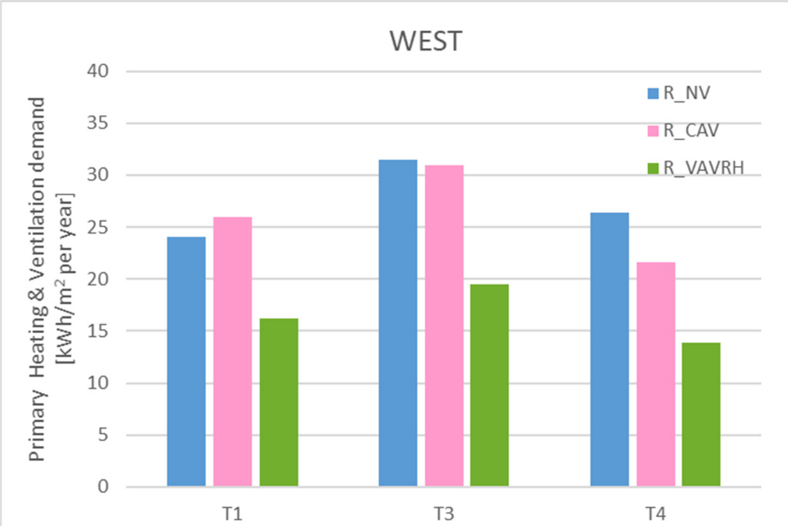
In general, rooms with windows to the south receive solar gains throughout the whole year. In winter and the mid seasons, the sun is relatively low and solar gains will pass deep into rooms through unshaded parts of windows. During summer, the high-angle position of the sun causes limited penetration of the solar radiation into rooms. Windows to the east and west are subject to significant solar gains in both the mid-season and summer due to the low sun elevation. On an east facade, solar radiation occurs early in the morning, which may not be a significant problem for overheating as the outside air temperature is at its lowest level. However, windows on a west façade receive low sun late into the day exacerbating gains in a space where the temperature may already have built up over the day. Therefore, rooms with glazing on the west facades are the one where overheating occurs most.

Building Type 1 showed the lowest risk of overheating when simulating it without surrounding buildings. This was caused by the fact that this type of buildings has traditional Danish windows with a relatively small glass area and massive outer walls of bricks, which can accumulate some heat during daytime. The apartment in Building Type 3 had a large glazing area in the living room, however, the façade was shaded by the part of the building complex around the courtyard and the solar radiation penetrated to the indoors through the windows only when the sun was positioned highly. One window was additionally shaded by a balcony. The apartment in Building Type 4 had the highest risk of overheating even though the building had relatively small windows, but there was nothing in the building surroundings, which could shade its façade.

4.2 Impact of ventilation strategy

Implementation of a mechanical ventilation system after renovation reduced overheating compared to the cases with natural ventilation. Figure 13 shows the results for different ventilation strategies for the west-orientated apartments (the orientation with the highest overheating risk). In case of Building Type 4, the use of mechanical ventilation with the airflows as determined in this study was not effective enough to keep the number of hours with overheating within the tolerance limit defined by the Danish Building Regulations (BR18, 2018). Generally, the use of the CAV_{max} system, which provided constant airflow, had stronger effect on reducing overheating compared to the VAV_{RH} system, which modulated the airflow according to the relative humidity. Obviously, the CAV_{max} system is associated with a higher energy use for ventilation. The primary energy used for heating and ventilation in the three buildings dependently on ventilation strategy is shown in Table 6. For the three buildings, the energy demand for the CAV_{max} ventilation system is between 72-100% larger than for the VAV_{RH} system. Additionally, the primary energy use for heating in case of CAV_{max} increased between 43-62% compared to VAV_{RH}. This results in an increase of the total primary energy demand of approx. 55-74% in case of the CAV_{max} systems. In case of the naturally ventilated building, the total primary energy use is approx. 2% and 25% larger than in case of the CAV_{max} system in Building Types 3 and 4, respectively, and smaller by approx. 7% in case of Building Type 1.

According to the Danish Building Regulations (BR18, 2018), ventilation in new and renovated Danish dwellings should be designed to supply fresh air and avoid moisture related problems, thus cooling is not its primary purpose. However, it is clear from the results that mechanical ventilation even operating with minimum required airflow can reduce overheating.



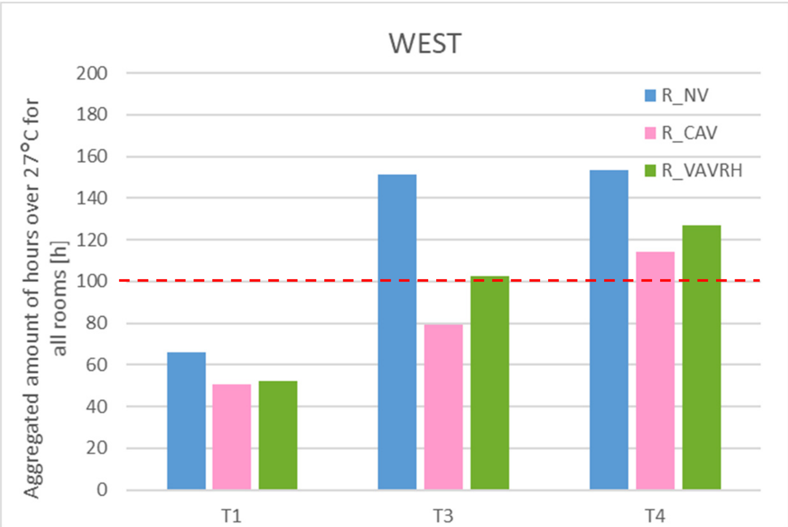


Figure 13. Yearly primary energy use (top) and aggregated number of occupied hours with indoor temperatures above 27°C (bottom) in the west-oriented apartments in Building Types 1, 3 and 4 for cases without the surrounding buildings present and without solar shading.

Table 6. Primary energy use for heating and ventilation system for different ventilation strategies in the apartments in renovated Building Types 1, 3 and 4 (cases with 2-layer energy windows, no solar shading and no surrounding buildings present).

Orientation	Ventilation type	Type 1		Type 3		Type 4	
		Heating kWh/m²	Ventilation kWh/m²	Heating kWh/m²	Ventilation kWh/m²	Heating kWh/m²	Ventilation kWh/m²
South	**NV**	20.0	-	28.3	-	24.5	-
	CAV_{max}	11.6	10.0	17.3	10.1	10.4	8.7
	VAV_{RH}	7.1	5.3	11.2	5.1	7.0	5.0
East	**NV**	24.2	-	31.4	-	26.6	-
	CAV_{max}	15.9	10.0	20.7	10.1	12.9	8.7
	VAV_{RH}	11.0	5.4	14.4	5.1	9.0	4.9
West	**NV**	24.1	-	31.4	-	26.4	-
	CAV_{max}	16.0	10.0	20.8	10.1	12.9	8.7
	VAV_{RH}	11.0	5.3	14.5	5.0	9.0	4.8

4.3 Impact of solar control solutions

The combined effect of ventilation strategies and solar control solutions on overheating in the west-oriented apartments in Building Types 1, 3 and 4 is presented in Figures 14, 15 and 16. The results show that the two internal solar shading devices: roller blinds and venetian blinds performed similarly in regards to reducing overheating. The use of the internal solar shading in Building Type 1 decreased overheating in the simulated apartment, however, it did not eliminate overheating completely, even though the number of hours with elevated temperature was the lowest of the three buildings. In general, the internal solar shadings reduced number of hours with the excess temperature in the apartment in Building Type 1 in average by 32% in case of the west orientation and by 40% in case of the east and south orientations. Building Types 3 and 4 had more problems with overheating. In the cases with natural ventilation, the use of internal solar shading in the west-oriented Building Type 3 could not keep the number of hours with exceeded indoor temperature within the tolerance limit of 100 hours until mechanical ventilation was established. For the other two orientations, roller blinds and internal venetian blinds were effective enough to reduce the number of hours with overheating to the accepted limit. The two solar shading devices combined with one of the three tested ventilation strategies could reduce the number of occupied hours with overheating by in average 50% for the east orientation and 35% for the other two orientations. The highest number of hours with overheating occurred in Building Type 4, where the tolerance limit was exceeded when no solar shading was used even in the case with the CAV ventilation system. The internal solar shading combined with any of the three tested ventilation strategies could keep indoor temperatures within the required tolerance as the decrease in the number of hours with overheating was approx. 50% compared to the cases without solar shading.

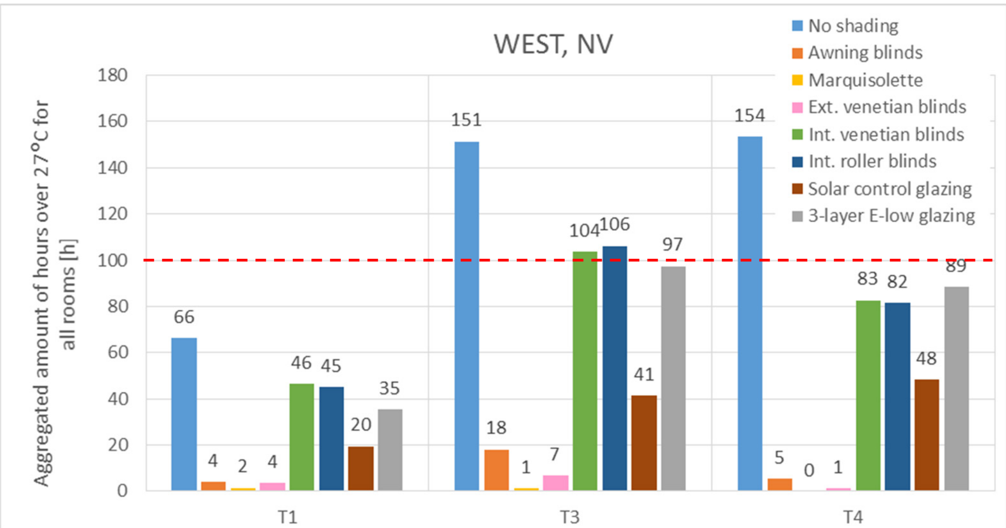


Figure 14. Aggregated number of occupied hours with indoor temperatures above 27°C in the west-oriented apartments in Building Types 1, 3 and 4 for cases with natural ventilation (NV) and without the surrounding buildings present.

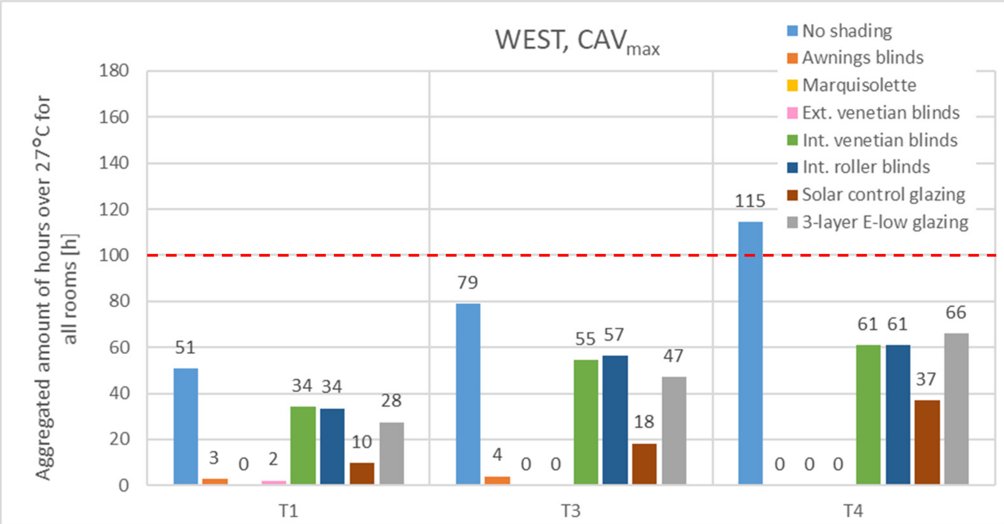


Figure 15. Aggregated number of occupied hours with indoor temperatures above 27°C in the west-oriented apartments in Building Types 1, 3 and 4 for cases with constant air volume (CAV_{max}) ventilation system and without the surrounding buildings present.

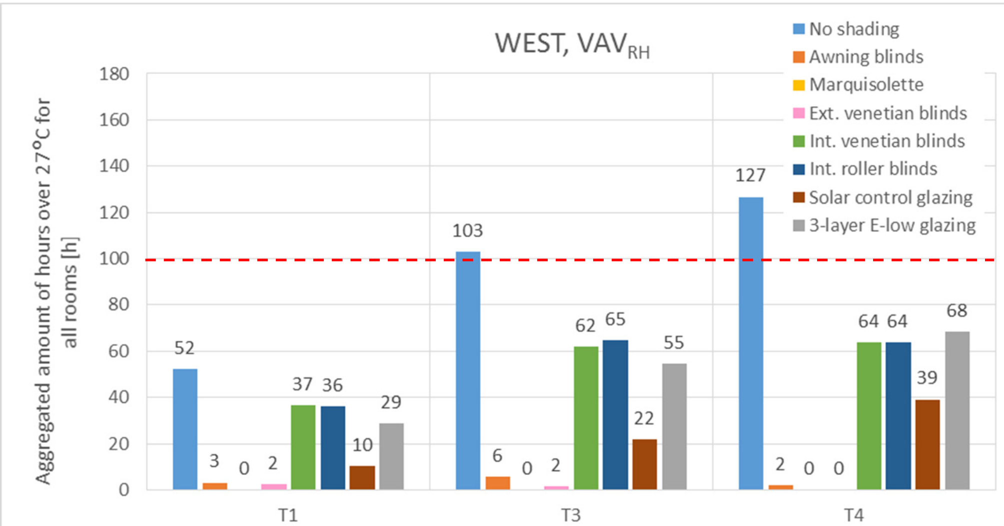


Figure 16. Aggregated number of occupied hours with indoor temperatures above 27°C in the west-oriented apartments in Building Types 1, 3 and 4 for cases with variable air volume (VAV_{RH}) ventilation system and without the surrounding buildings present.

All external solar shading devices were proved to be very efficient solutions for keeping the indoor temperature within the tolerance limit defined by the Danish Building Regulations (BR18, 2018) independently on the apartment orientation and the chosen ventilation solution. Overheating was reduced to a few hours or completely eliminated in many cases. The results show that there was only a small difference in performance between the three tested external devices – the results for the west-oriented apartments are presented in Figures 14, 15 and 16 as an example. The marquisolette was always the most efficient and reduced overheating to 0 hours for most cases. The external venetian blinds and the drop arm awning caused decreased the overheating hours to maximum 7 and 19, respectively.

Moreover, the results in Figures 14, 15 and 16 indicate that the solar control glazing could effectively keep the number of hours with elevated indoor temperature within the tolerance limit of 100 in all cases. The solution is slightly less efficient than the external solar shading but much more efficient than internal solar shading.

The 3-layer energy glazing showed a comparable effect on reducing the number of hours with overheating to the internal solar shading, however, with slightly lower number of hours with temperature above 27°C in most cases (Figures 14, 15 and 16).

The use of solar control glazing, internal and external solar shading had very small effect on the total primary energy consumption. It was due to the relatively small size of the windows in Building Types 1 and 4, and because of a large shading effect of the part of Building Type 3 on the apartment façade despite the large glass area in the living room. In general, the 3-layer E-low glazing could reduce the primary energy consumption by up to 30% compared to the cases with 2-layer E-low glazing and solar control glazing. The comparison of primary energy use in different cases for the west-orientated apartments is shown in Figure 17 as an example.

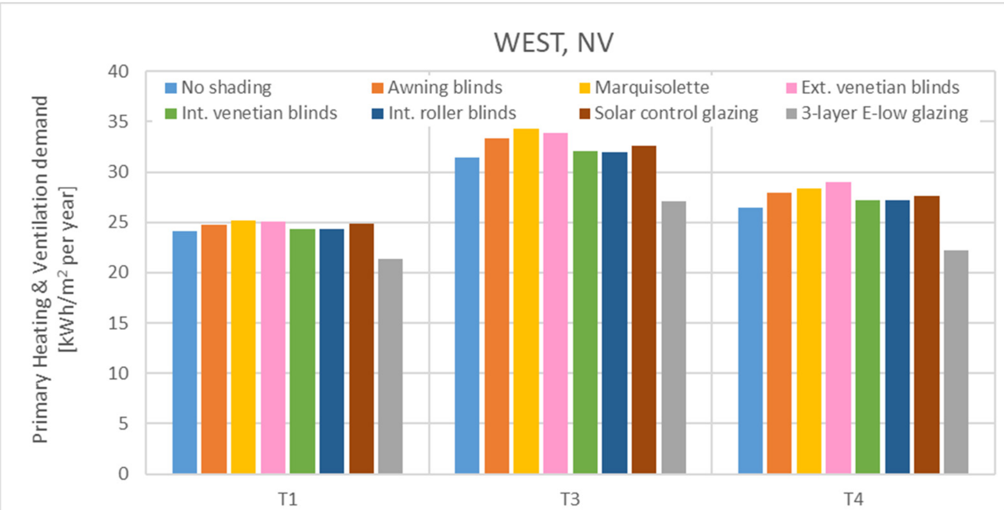


Figure 17. Yearly primary energy use in the west-oriented naturally ventilated (NV) apartments in Building Types 1, 3 and 4 for cases without the surrounding buildings present.

The present study confirms that internal solar shading devices are less efficient in limiting overheating than external shading solutions. With the assumptions made in this investigation, the three tested external solar shading devices were 50-70% more efficient in reducing the number of hours with overheating than the internal shading solutions. With the internal shadings, the solar energy that enters the indoors is absorbed by the shading device causing it to warm up. In the next step, the heat from the shading is transferred by radiation and convection to the indoor space. The external venetian blinds, the drop arm awning blinds and the marquisolette reflect most of sunrays back to the surroundings. Therefore, the solar energy transmitted to the windowpane by radiation is substantially limited, while the solar energy stored in the external shading device is transmitted to the outside by radiation and convection. The marquisolette showed the highest effectiveness from the three tested external solar shading device as its top part parallel to the glass pane effectively blocks the solar radiation. The drop arm awning blinds and the lower part of the marquisolette block only part of the solar radiation dependently on the sun elevation, and a portion of the sunrays can reach the glass pane through the open sides of the device. In case of the external venetian blinds with a fixed slot angle of 45°, a portion of the solar radiation is reflected and directed to the indoor space. The effect of other positions of the slots has not been simulated as well as adjustable slot angle due to solar irradiance on the façade.

More results regarding combined effect of solar shading solutions and different ventilation strategies for Building Types 1, 3 and 4 are included in Appendix B. The results for Building Type 1 located in a street canyon can be found in Appendix D.

4.4 Airflows through windows and impact of window opening

Airflows through windows have a crucial effect on the indoor temperature. Tables 7, 8 and 9 show the airflows through the windows (including infiltration) in the apartments in Building Types 1, 3 and 4 respectively, in case of west orientation of the buildings. The assumptions regarding window opening from the Danish energy frame calculation (Aggerholm and Grau, 2018) were followed. The windows open up to 60% of the maximum possible area and open to keep set point indoor temperature of 23°C. In the simulations for Building Types 1 and 3, the average airflow through the windows in summer period in the naturally ventilated apartments got close to the value assumed in the energy frame calculations of 0.9 (l/s·m^2). The airflows are slightly lower in case of Building Type 1 compared to Building Type 3 due to smaller window area. In case of Building Type 4, the average airflow was 1.18 (l/s·m^2) in the naturally ventilated apartment as the building has large window area in the living room and additionally window in the bathroom and in the office causing more cross ventilation through the apartment. In all models, the window opening was controlled by the indoor temperature and therefore in the cases with the CAV system, which effectively reduced indoor temperature, the windows were less open than in the cases with the VAV system or natural ventilation.

Table 7. Monthly mean supply airflows through windows and mechanical ventilation for summer months in the west-oriented apartment in Building Type 1 in case of standard window opening; Q – monthly mean, $\bar{Q}$ – grand mean.

Summer months	NV				CAV_{max}				VAV_{RH}			
	Q_{LR} l/s	Q_B l/s	Q_K l/s	Qm l/s	Q_{LR} l/s	Q_B l/s	Q_K l/s	Qm l/s	Q_{LR} l/s	Q_B l/s	Q_K l/s	Qm l/s
May	18.1	7.1	3.3	-	10.6	2.0	4.0	35.0	13.7	3.7	3.3	21.1
June	27.2	10.5	4.8	-	17.2	2.7	6.5	35.0	19.8	4.4	4.8	25.2
July	39.6	17.2	8.1	-	26.6	7.2	12.1	35.0	28.6	8.6	8.1	28.8
August	36.5	17.1	8.7	-	23.2	7.0	12.9	35.0	25.4	8.5	8.7	28.2
September	19.3	7.4	3.8	-	8.7	0.5	3.7	35.0	11.1	1.2	3.8	26.2
$\bar{Q}$ l/s	28.1	11.9	5.7	-	17.3	3.9	7.8	35.0	19.7	5.3	5.7	25.9
$\bar{Q}_{ra}$ l/(s·m^2)	1.2	0.6	0.7	-	0.7	0.2	1.0		0.8	0.3	0.7	**-**
$\bar{Q}_{ta}$ l/(s·m^2)	**0.81**			**-**	**0.51**			**0.62**	**0.54**			**0.46**
$\bar{Q}_{tot}$ l/(s·m^2)	**0.81**				**1.13**				**1.0**			

Indexes: LR – living room, B – bedroom, K – kitchen, m – mechanical supply, ra – normalized with room heated floor area, ta – normalized with total apartment heated floor area, tot – total airflow normalized with total apartment heated floor area.

Table 8. Monthly mean supply airflows through windows and mechanical ventilation for summer months in the west-oriented apartment in Building Type 3 in case of standard window opening; Q – monthly mean, $\bar{Q}$ – grand mean.

Summer months	NV				CAV$_{max}$				VAV$_{RH}$			
	Q_{LR} l/s	Q_B l/s	Q_K l/s	Qm l/s	Q_{LR} l/s	Q_B l/s	Q_K l/s	Qm l/s	Q_{LR} l/s	Q_B l/s	Q_K l/s	Qm l/s
May	15.4	8.8	7.4	-	5.8	4.0	7.6	35.0	8.7	6.2	7.9	20.4
June	20.6	13.0	10.8	-	9.3	6.1	11.1	35.0	11.9	8.3	11.3	24.2
July	29.0	22.4	17.2	-	14.8	13.9	18.7	35.0	16.9	15.6	18.3	27.2
August	27.8	21.2	16.5	-	13.2	13.0	18.7	35.0	15.5	14.9	18.1	26.7
September	17.8	9.5	8.7	-	5.9	2.5	8.2	35.0	8.3	4.4	8.6	24.9
$\bar{Q}$ l/s	22.1	15.0	12.1	-	9.8	7.9	12.8	35.0	12.3	9.9	12.8	24.7
$\bar{Q}_{ra}$ l/(s·m^2)	0.9	1.1	1.2	-	0.4	0.6	1.3	**-**	0.5	0.7	1.2	**-**
$\bar{Q}_{ta}$ l/(s·m^2)	**0.88**			**-**	**0.54**			**0.62**	**0.62**			**0.44**
$\bar{Q}_{tot}$ l/(s·m^2)	**0.88**				**1.16**				**1.06**			

Indexes: LR – living room, B – bedroom, K – kitchen, m – mechanical supply, ra – normalized with room heated floor area, ta – normalized with total apartment heated floor area, tot – total airflow normalized with total apartment heated floor area.

Table 9. Monthly mean supply airflows through windows and mechanical ventilation for summer months in the west-oriented apartment in Building type 4 in case of standard window opening; Q – monthly mean, $\bar{Q}$ – grand mean.

Summer months	NV						CAV$_{max}$						VAV$_{RH}$					
	Q_{LR} l/s	Q_{B} l/s	Q_{K} l/s	Q_{O} l/s	Q_{BA} l/s	Q_{m} l/s	Q_{LR} l/s	Q_{B} l/s	Q_{K} l/s	Q_{O} l/s	Q_{BA} l/s	Q_{m} l/s	Q_{LR} l/s	Q_{B} l/s	Q_{K} l/s	Q_{O} l/s	Q_{BA} l/s	Q_{m} l/s
May	22.5	9.8	8.3	10.2	2.5	-	14.7	5.4	9.1	6.8	4.2	35.0	17.1	7.0	9.1	7.80	3.9	22.8
June	30.3	13.7	12.0	14.2	3.0	-	21.1	7.5	12.8	10.4	5.2	35.0	23.1	9.0	12.8	11.3	4.7	26.3
July	41.2	21.5	19.9	19.6	3.9	-	29.9	13.5	20.8	15.1	7.8	35.0	31.5	14.6	20.5	15.8	6.9	28.9
August	38.8	20.5	18.6	18.3	3.9	-	26.5	12.9	19.9	12.9	8.5	35.0	28.3	14.0	19.6	13.7	7.5	28.3
September	22.4	10.2	8.5	9.9	3.0	-	12.8	3.9	8.6	5.8	4.4	35.0	14.7	5.3	8.7	6.7	4.3	26.9
$\bar{Q}$ l/s	31.1	15.1	13.4	14.4	3.2	-	21.0	8.6	14.2	10.2	6.0	35.0	22.9	10.0	14.1	11.1	5.4	26.6
$\bar{Q}_{ra}$ l/(s·m²)	1.3	1.0	1.7	1.5	0.8	-	0.9	0.6	1.8	1.0	1.5	**-**	1.0	0.7	1.8	1.1	1.4	**-**
$\bar{Q}_{ta}$ l/(s·m²)	**1.18**					**-**	**0.92**					**0.54**	**0.97**					**0.41**
$\bar{Q}_{tot}$ l/(s·m²)	**1.18**						**1.46**						**1.38**					

Indexes: LR – living room, B – bedroom, K – kitchen, O – office, BA – bathroom, m – mechanical supply, ra – normalized with room heated floor area, ta – normalized with total apartment heated floor area, tot – total airflow normalized with total apartment heated floor area.

In order to study the effect of reduced window opening on the indoor temperature, additional simulations for Building Type 1 were performed. The average airflow through the windows in the naturally ventilated apartment in the summer period, when only one of two windows in the living room and only lower parts of the windows in the living room and the bedroom were open, was 0.62 (l/s·m^2) – see Table 10. In comparison, the airflow through windows when all windows were open was 0.81 (l/s·m^2) - Table 7. Figure 18 shows the number of occupied hours with overheating in case of the two different window opening assumptions. As the results show that more intensive venting during summer can reduce overheating significantly. Even in case of no solar shading, more intensive venting reduced the number of hours with temperatures above 27°C from 173 hours above the tolerance limit to 60 hours within the limit.

Table 10. Monthly mean supply airflows through windows and mechanical ventilation for summer months in the apartment in Building Type 1 in case of reduced window opening; Q – monthly mean, $\bar{Q}$ – grand mean.

Summer months	**NV**				**CAV$_{max}$**				**VAV$_{RH}$**			
	Q_{LR} l/s	**Q_B l/s**	**Q_K l/s**	**Qm l/s**	**Q_{LR} l/s**	**Q_B l/s**	**Q_K l/s**	**Qm l/s**	**Q_{LR} l/s**	**Q_B l/s**	**Q_K l/s**	**Qm l/s**
May	13.4	7.0	3.4	-	6.0	1.8	4.0	35.0	8.4	3.5	4.4	20.9
June	18.0	9.4	5.2	-	8.4	2.3	6.8	35.0	10.5	3.7	7.1	24.5
July	22.9	13.7	9.0	-	11.3	5.2	13.0	35.0	12.7	6.3	12.6	27.3
August	21.4	14.3	9.4	-	10.0	5.4	13.7	35.0	11.6	6.7	13.3	27.1
September	15.8	7.5	4.0	-	5.7	0.5	3.9	35.0	7.9	1.4	4.7	27.6
$\bar{Q}$ l/s	18.3	10.4	6.2	-	8.3	3.1	8.3	35.0	10.2	4.3	8.4	25.5
$\bar{Q}_{ra}$ l/(s·m^2)	0.8	0.6	0.8	-	0.3	0.2	1.0	-	0.4	0.2	1.0	**-**
$\bar{Q}_{ta}$ l/(s·m^2)	**0.62**			**-**	**0.35**			**0.62**	**0.41**			**0.45**
$\bar{Q}_{tot}$ l/(s·m^2)	**0.62**				**0.97**				**0.86**			

Indexes: LR – living room, B – bedroom, K – kitchen, m – mechanical supply, ra – normalized with room heated floor area, ta – normalized with total apartment heated floor area, tot – total airflow normalized with total apartment heated floor area.

More results for Building Type 1 in case of reduced window opening are included in Appendices E and F for cases without the surrounding buildings present and in Appendices G and H for Building Type 1 located in a street canyon.

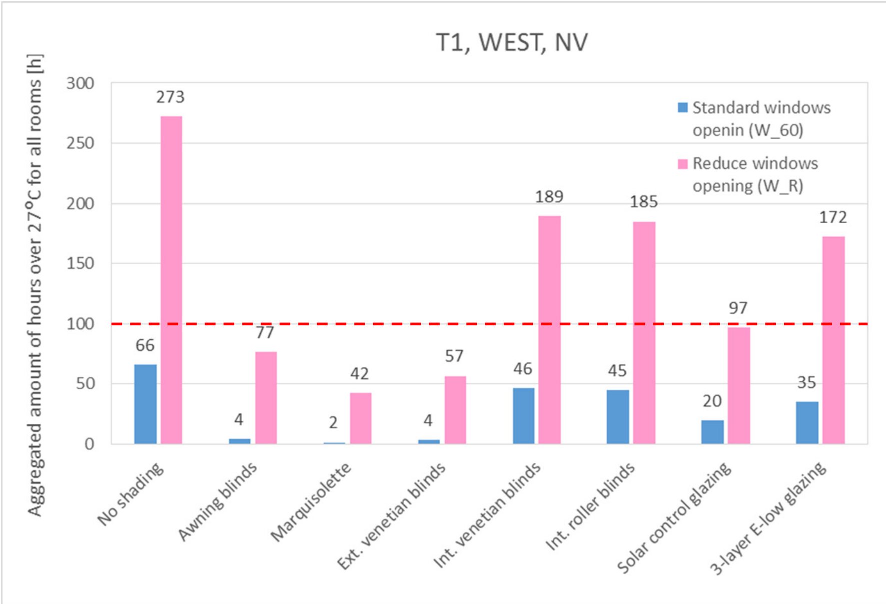


Figure 18. Aggregated number of occupied hours with indoor temperatures above 27°C in the west-oriented apartment in Building Type 1 for cases with natural ventilation and without the surrounding buildings present. Standard and reduced window opening.

4.5 Impact of surrounding buildings

Preliminary simulations showed that in case of Building Types 3 and 4, the effect of surrounding buildings on the overheating risk, energy consumption and daylight is negligible as the neighbouring buildings are in a large distance from the simulated building.

In case of Building Type 1, the effect of surroundings buildings cannot be neglected. The comparison of the results for the apartment in the building located in the open area and in the street canyon is shown in Figure 19. The figure shows the worse situation regards overheating, i.e. the results for the west-oriented apartment and reduce window opening. The results show a strong shading effect of the surrounding building. For the worse case (no solar shading and natural ventilation), the number of occupied hours with elevated temperatures was reduced from 273 to 60 hours. A similar result was obtained for two other orientations. The total energy use in the shaded apartment increased by approx. 4 kWh/m^2 due to a higher heating demand compared to the corresponding cases without the surrounding buildings. The results prove that even in the building located in the street canyon, the solar shading devices have a potential to decrease the number of hours with elevated temperatures.

More results regarding Building Type 1 for cases without the surrounding buildings are presented in Appendices A and B and for cases with location in a street canyon in Appendices C and D (standard venting). The results for reduced venting can be found in Appendices E, F, G and H.

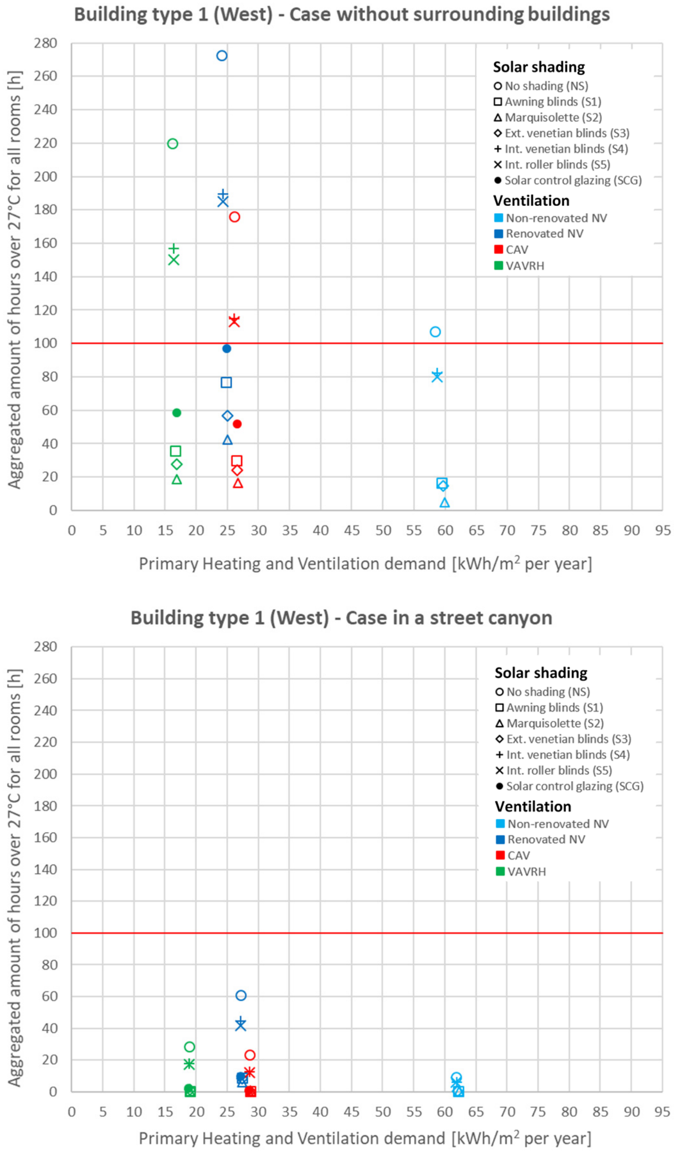


Figure 19. Yearly primary energy use and aggregated number of occupied hours with indoor temperatures over 27°C in the west-oriented apartment in Building Type 1 for case without the surrounding buildings present (top) and for the building in a street canyon (bottom). The cases with reduced venting.

4.6 Overview of results

A summary of the project results regarding the overheating risk in the three typical Danish apartment buildings from the period 1850-1970 (as described in section Case study buildings) is presented in Table 11. Overheating is defined as any occupied hours with an indoor temperature above 27°C with the tolerance limit of 100 hours as stated in the Danish Building Regulations (BR18, 2018). The table presents the overview of the project results for the three different orientation of the buildings in cases of different ventilation strategies and solar control solutions used. The surrounding buildings are not present, and the assumptions to venting follow the assumptions used in Danish energy frame calculations (Aggerholm and Grau, 2018).

Table 11. Overheating risk for Buildings Types 1, 3 and 4 located in an open area (in brackets: number of occupied hours with indoor temperatures above 27°C).

Solar control	Ventilation	T1			T3			T4		
		W	E	S	W	E	S	W	E	S
No solar shading	NV	66	35	50	151	129	117	154	145	105
	VAV	52	22	42	103	74	81	127	116	86
	CAV	51	21	39	79	57	65	115	100	81
Internal shading	NV	46	22	32	106	76	79	83	70	52
	VAV	37	13	24	65	33	57	64	58	43
	CAV	34	13	22	57	27	45	61	54	39
External shading	NV	4	5	5	18	19	14	0	0	0
	VAV	0	4	0	6	0	9	0	0	0
	CAV	0	4	0	0	0	7	0	0	0
Solar control glazing	NV	20	9	6	41	26	29	48	44	36
	VAV	10	4	7	22	11	14	39	32	25
	CAV	10	4	6	18	8	11	37	30	22
3-layer E-low glazing	NV	35	19	30	97	73	73	89	85	66
	VAV	29	13	19	55	31	48	68	65	55
	CAV	28	12	17	47	26	38	66	59	50

Green – 0 occupied hours with temperature above 27°C (no overheating); Red – more than 100 occupied hours with temperatures above 27°C (above the tolerance limit).

One needs to be aware that a choice of CAV ventilation system instead of VAV system will lead to higher primary energy consumption for ventilation. In case of natural ventilation, the total energy use will be comparable to the CAV system or higher, as the energy demand for heating will increase substantially.

5. "Result Browser"

An MS Excel based tool called "Result browser" was prepared to give the user an opportunity to see the project's results. The tool contains a database of results from the project's main simulations, i.e. more than 400 cases. It is possible to compare different refurbishment solutions by selecting the following parameters: Building type, Room (overheating results can be shown for a particular room or aggregate for the whole apartment), Building orientation, Window type, Solar shading solution, Building surrounding (the choice available only for Building Type 1). The tool shows the results as the number of occupied hours with temperatures above 27°C and energy consumption for the examined ventilation scenarios: natural ventilation before and after renovation, mechanical ventilation with constant airflow and with variable airflow controlled by the relative air humidity in the exhaust air. The results are presented both graphically and in tabular form.

6. Conclusions

The simulation study was focused on three typical types of Danish apartment buildings from the period 1850-1970. The study shows that energy renovation reduced energy consumption by an average of 64%. However, as expected the number of hours with overheating increased after renovation. Renovation led to the largest number of overheating hours in Building Type 4 but the same trend was seen for the other two building types. In case of renovation where mechanical ventilation was not implemented, the number of overheating hours increased on average from 51 hours before renovation to 106 hours after renovation. The maximum number of overheating hours for a building without mechanical ventilation in the present study was 154 hours in case of standard venting, which is 54 hours above the tolerance limit of 100 hours defined in the Danish Building Regulations. In the cases with mechanical ventilation with heat recovery, the number of occupied hours with overheating was reduced on average by 40% compared to a case without mechanical ventilation.

The main focus of the study was on the use of solar shading during the renovation. Cases without and with internal and external solar shading devices were investigated with 2-layer energy glass. In old buildings, mostly internal solar shading devices as curtains, venetian blinds or roller blinds are used. The results show that internal solar shading in combination with mechanical ventilation could keep overheating hours within the tolerance limit in most cases. However, utilization of external solar shading was necessary to eliminate overheating completely in the investigated buildings. The use of solar control glass could eliminate overheating in the oldest building (Building Type 1, construction period 1850-1890) which has the smallest glass area in relation to the facade area. The use of solar control glass in Building Types 3 and 4 (the construction periods 1920-1940 and 1940-1970) led to reduction of overheating by 100 hours a year, but overheating was not eliminated. The 3-layer energy glazing showed a comparable effect on reducing overheating to the internal solar shading, but it reduced the primary energy demand for heating by up to 30% compared to the cases with 2-layer E-low glazing and solar control glazing

Orientation of the building played only a minor role in regards to energy consumption. For all three types of building after renovation, the difference in energy consumption due to orientation was on average 3 kWh/(m^2·year). Buildings with a south-facing living room had the least energy consumption due to large solar heat gains during the heating season.

Orientation affected overheating in all simulated buildings. The number of hours with temperatures above 27°C was the highest for the west orientation and the least for the east orientation. On average, the difference between the west and east orientation was 36 overheating hours.

In case of Building Type 1, the presence of surrounding buildings cannot be neglected as they give a strong shading effect and increase the total energy use by approx. 4 kWh/m^2 due to a higher heating demand.

Venting through windows have a crucial effect on the indoor temperature. In the Danish climate, frequent opening of windows in summertime can reduce overheating or even fully prevent it.

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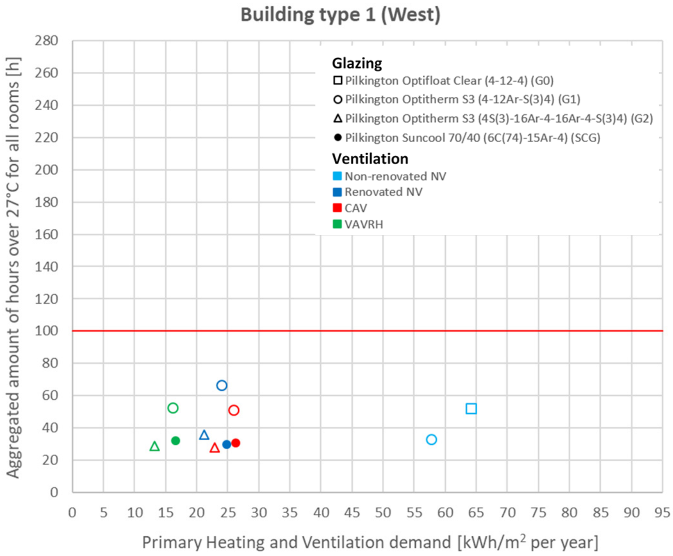
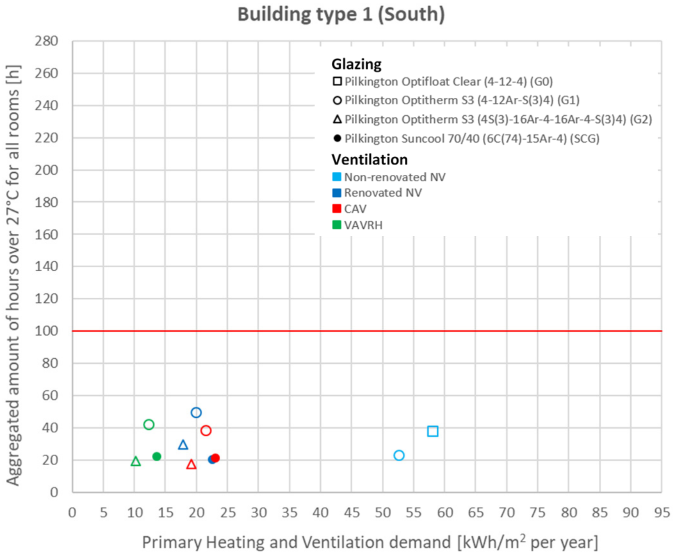
Appendix A. Combined results for different glazing types and different ventilation strategies for Building Types 1, 3 and 4 without surrounding buildings present


Building type 1 (West)
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]


Building type 1 (South)
Glazing
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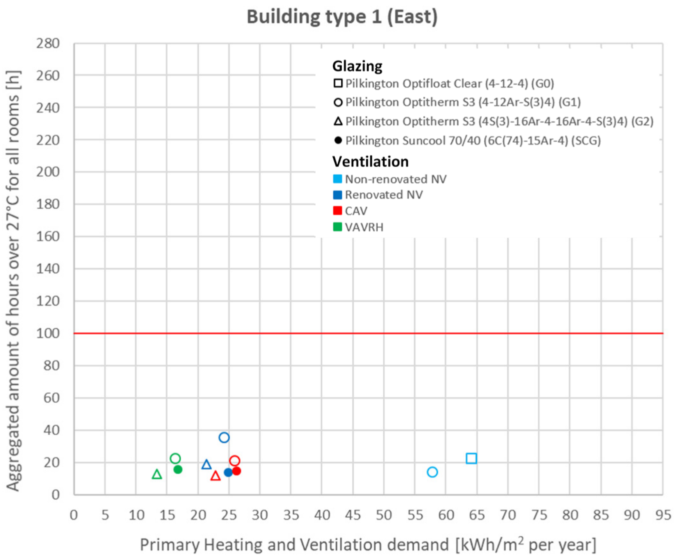
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]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Glazing
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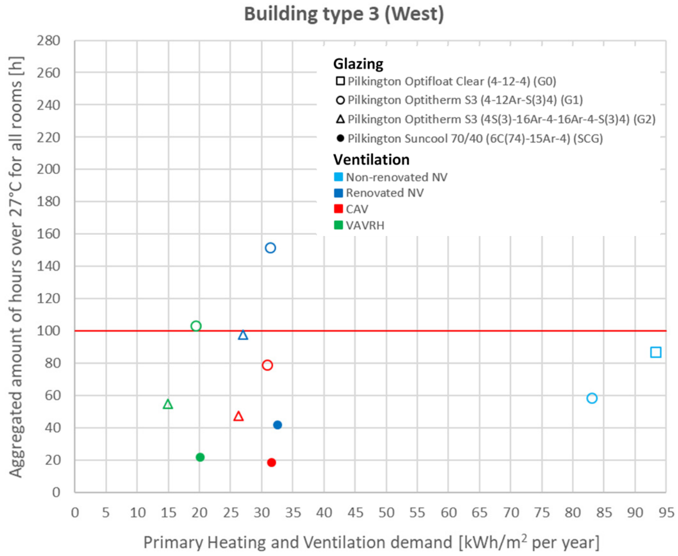
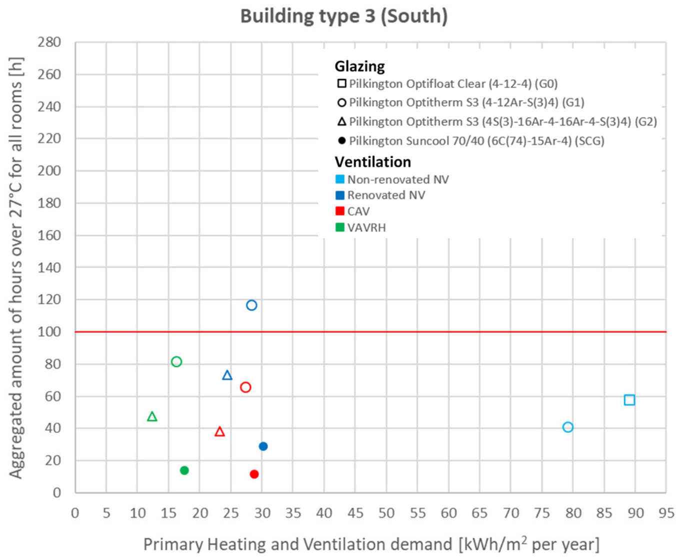
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]


Building type 3 (West)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH


Building type 3 (South)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]
Glazing
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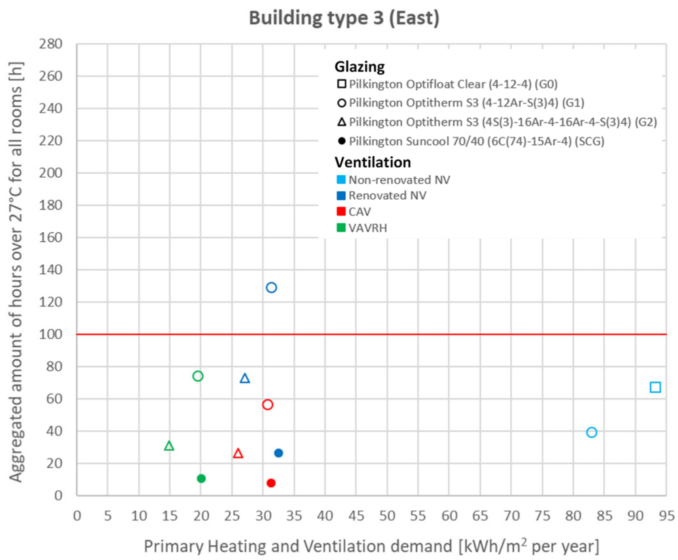
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH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Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]
Glazing
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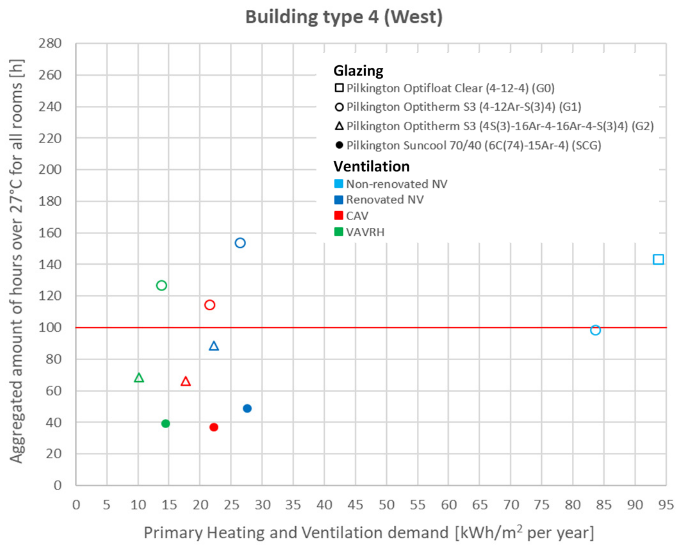
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH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Glazing
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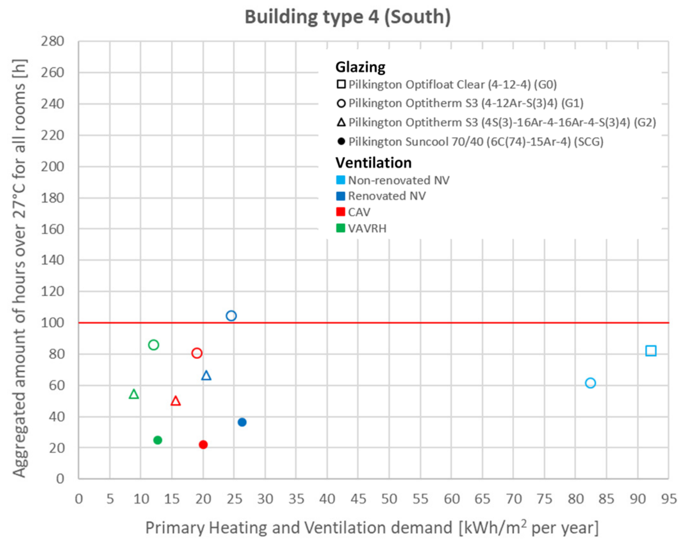
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]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Glazing
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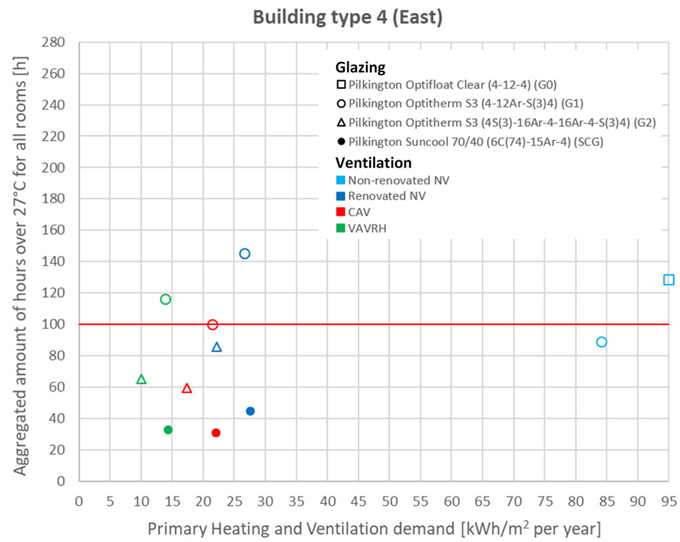
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]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Glazing
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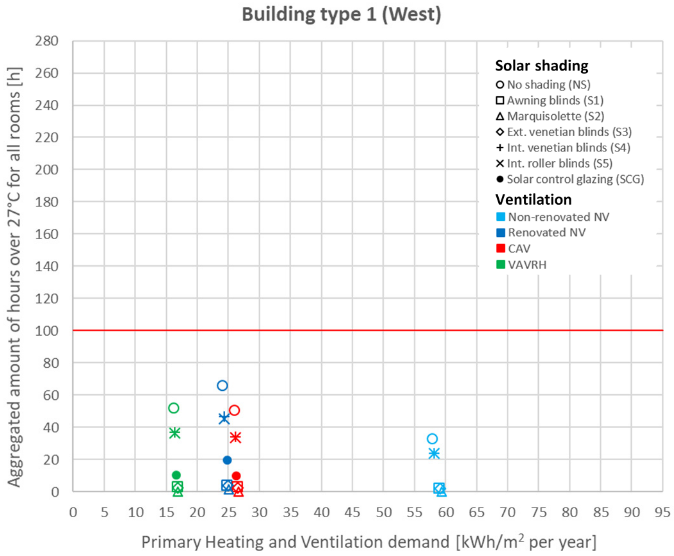
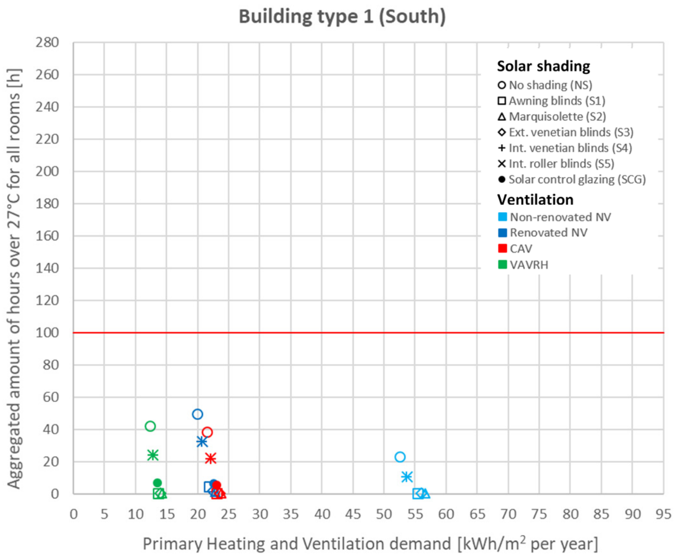
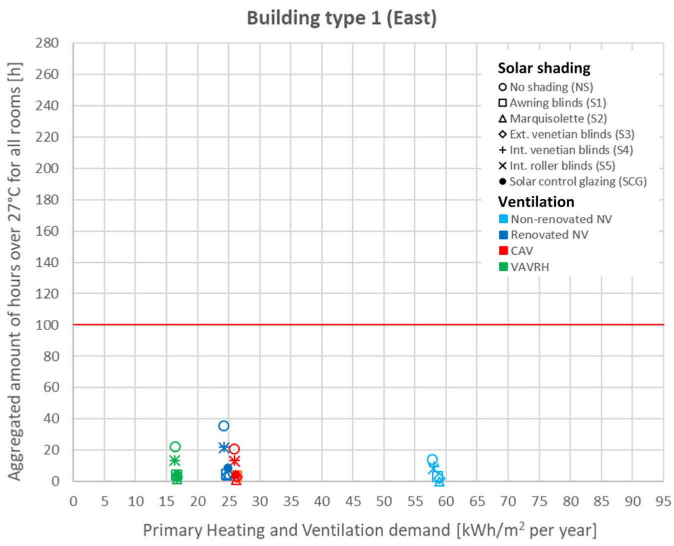
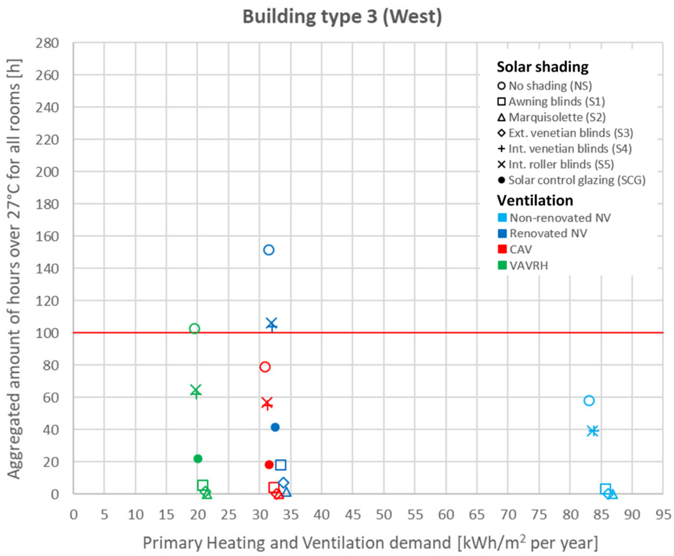
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]

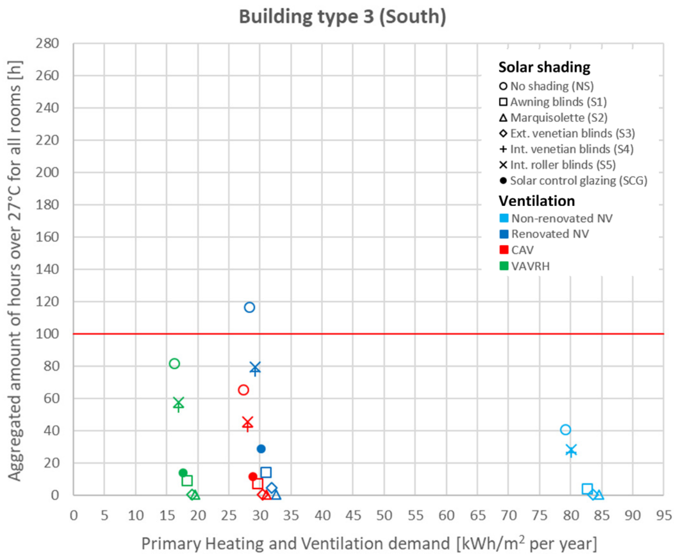
Appendix B. Combined results for different solar shading solutions and different ventilation strategies for Building Types 1, 3 and 4 without surrounding buildings present

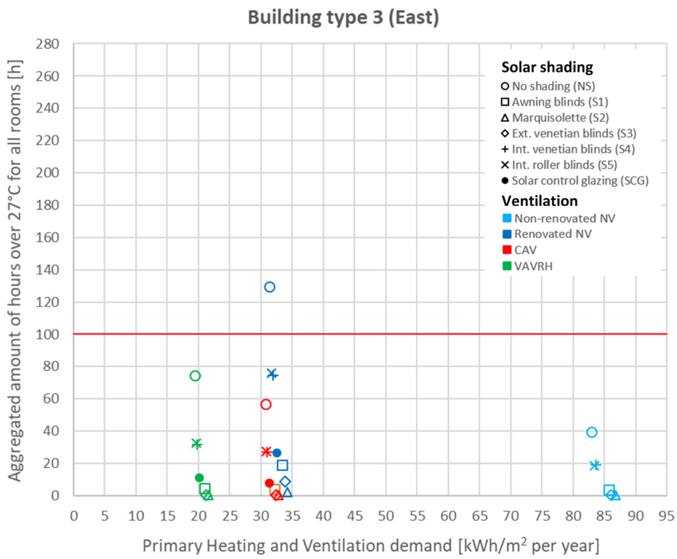

Building type 1 (West)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

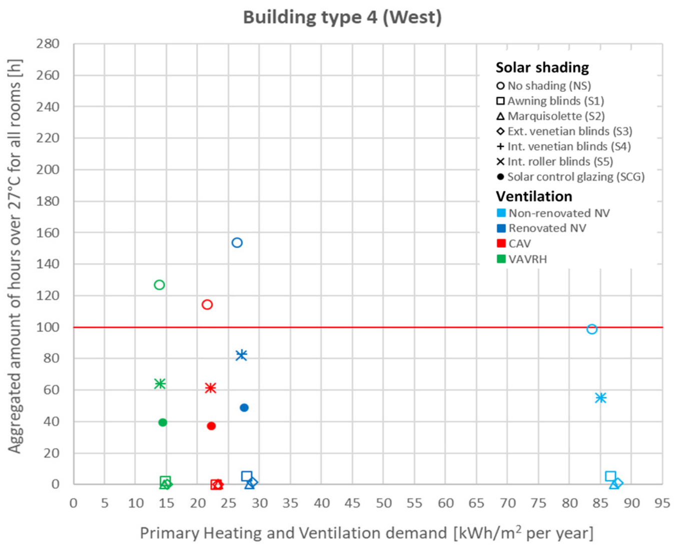

Building type 1 (South)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH


Building type 1 (East)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

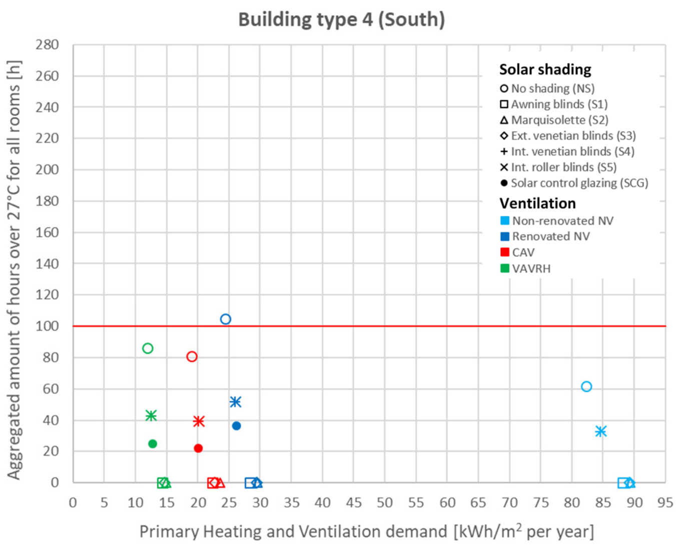

Building type 3 (West)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH


Building type 3 (South)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

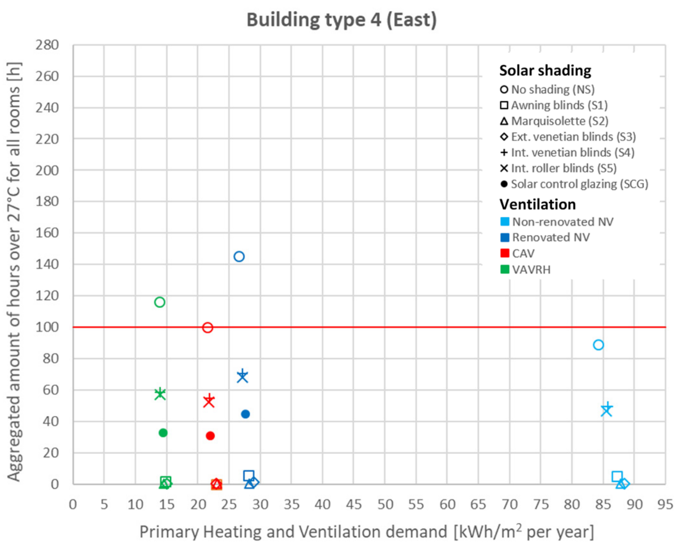

Building type 3 (East)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH



Building type 4 (West)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

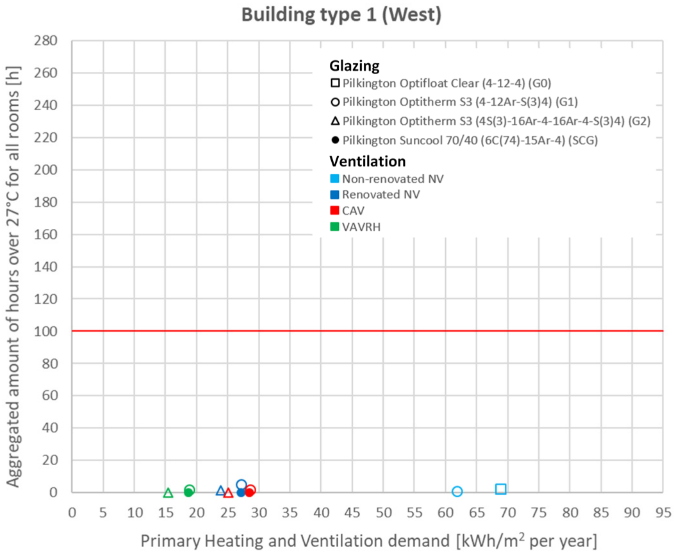


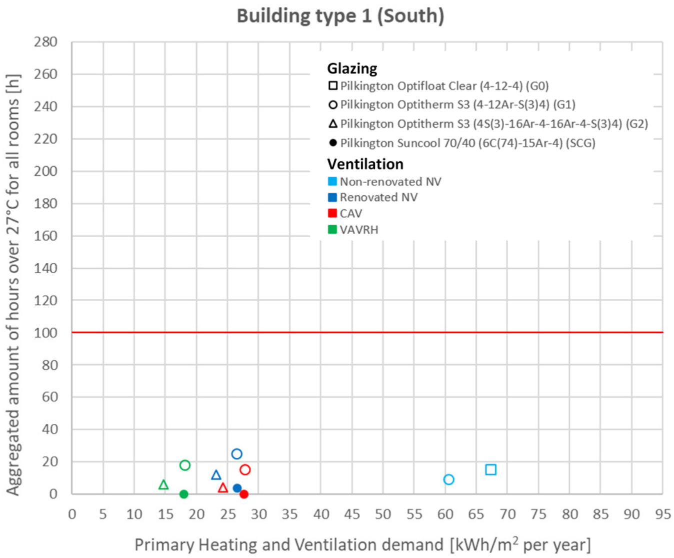
Building type 4 (South)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

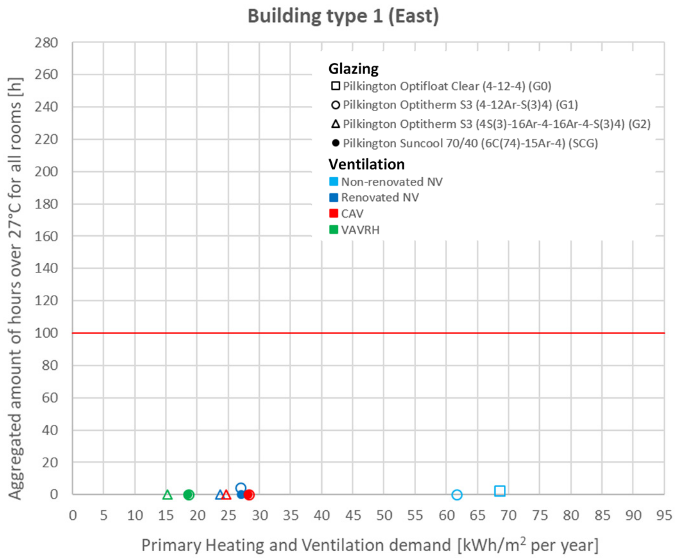


Building type 4 (East)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

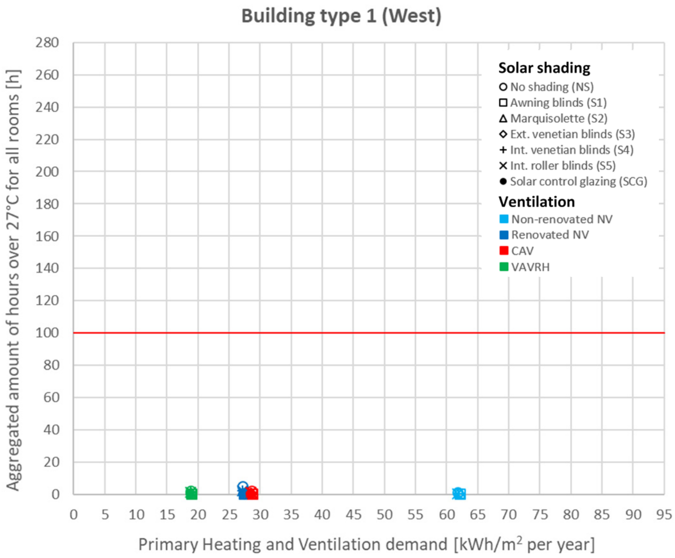
Appendix C. Combined results for different glazing types and different ventilation strategies for Building Type 1 in a street canyon

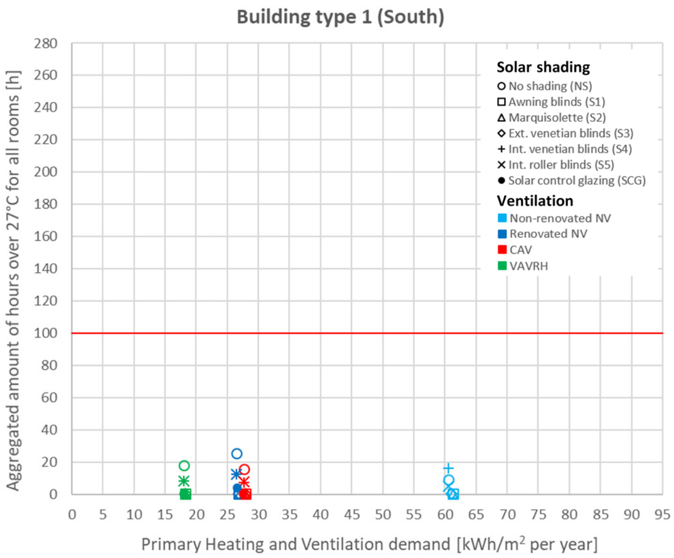

Building type 1 (West)
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]

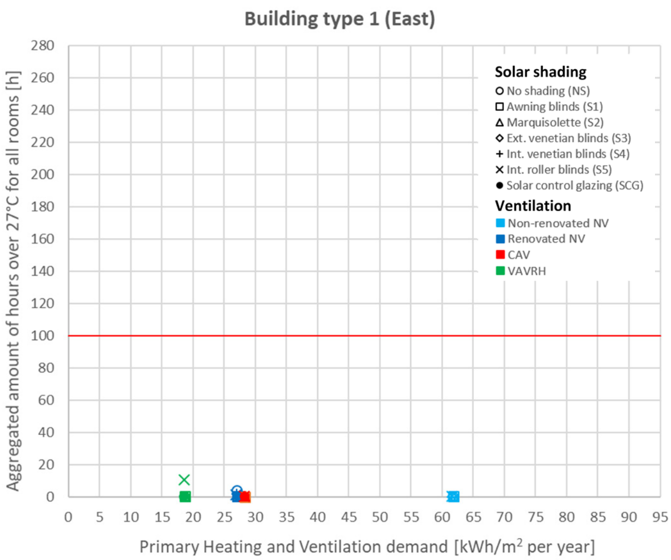

Building type 1 (South)
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]


Building type 1 (East)
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]

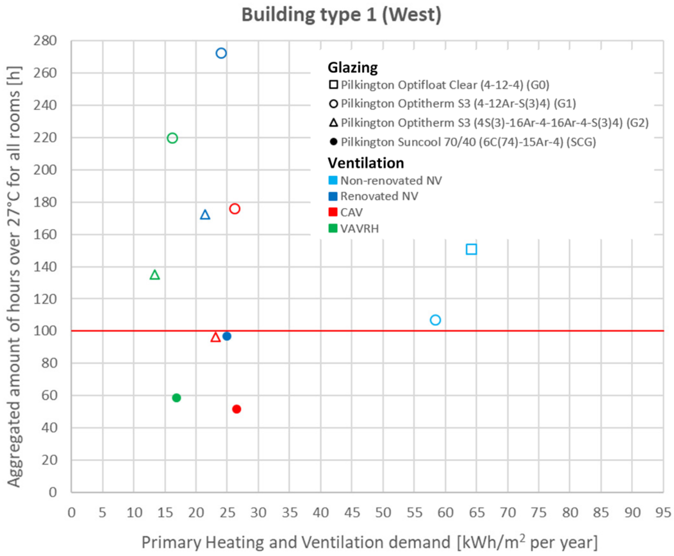
Appendix D. Combined results for different solar shading solutions and different ventilation strategies for Building Type 1 located in a street canyon

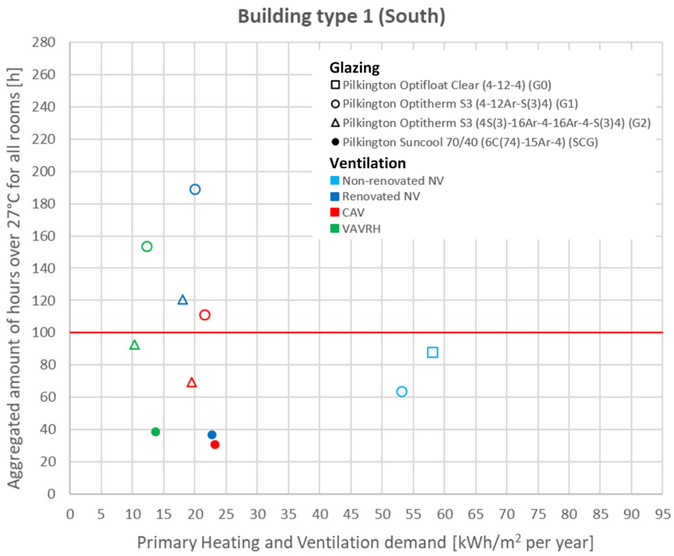

Building type 1 (West)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

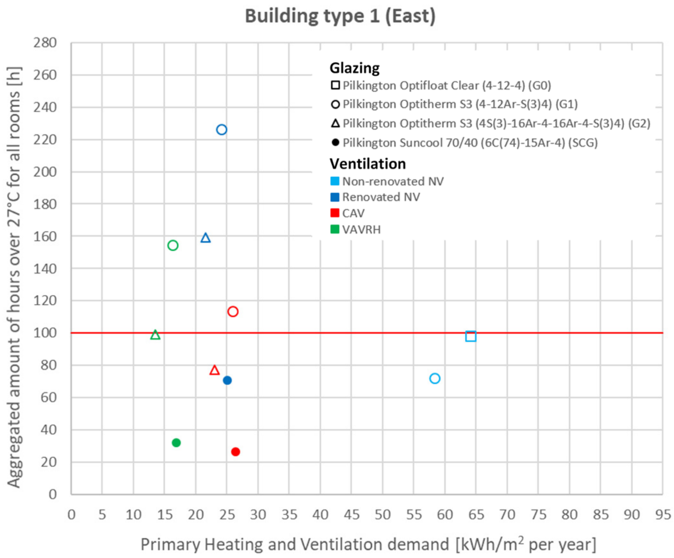

Building type 1 (South)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH


Building type 1 (East)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

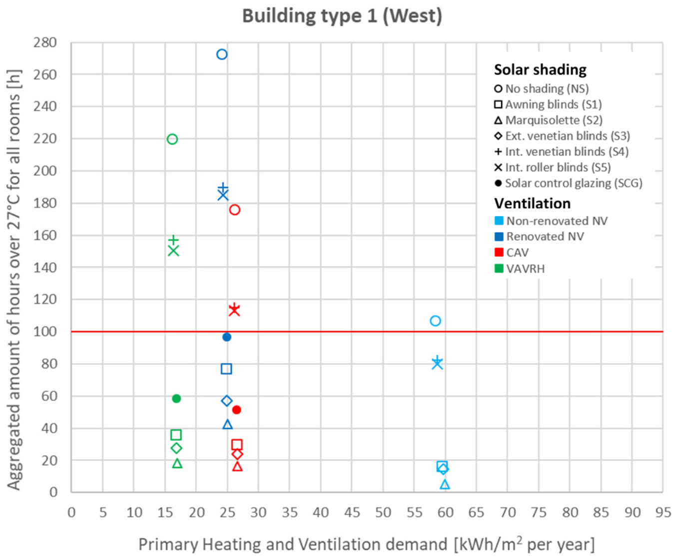
Appendix E. Combined results for different glazing types and different ventilation strategies in case of Building Type 1 without surrounding buildings present (reduced venting)

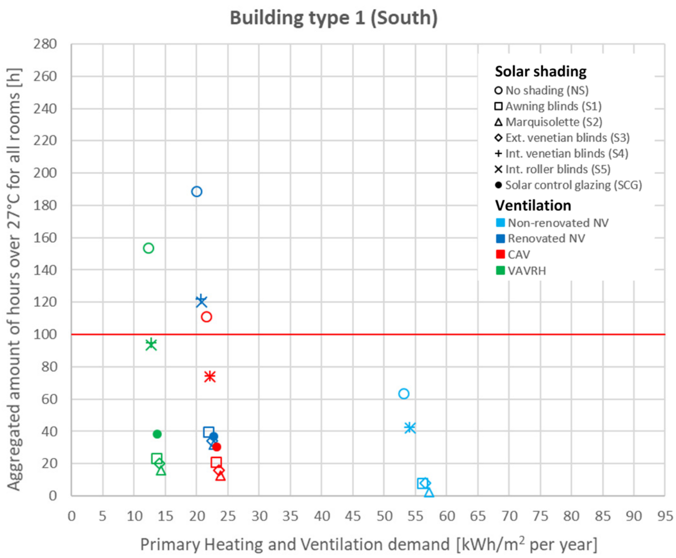

Building type 1 (West)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

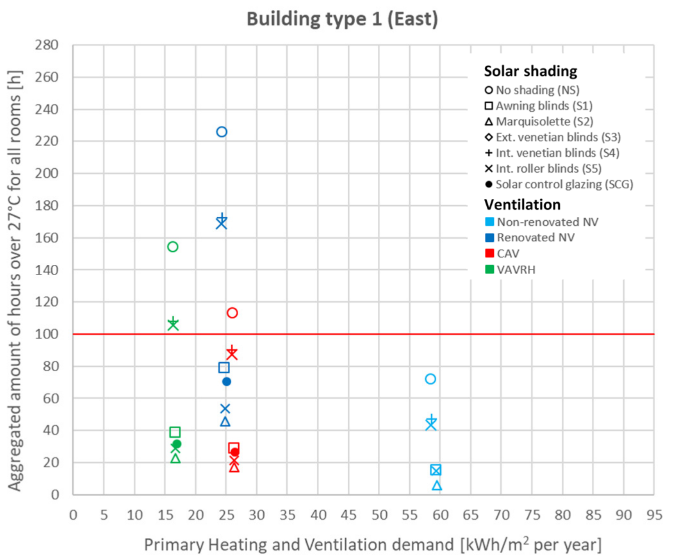

Building type 1 (South)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH


Building type 1 (East)
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH

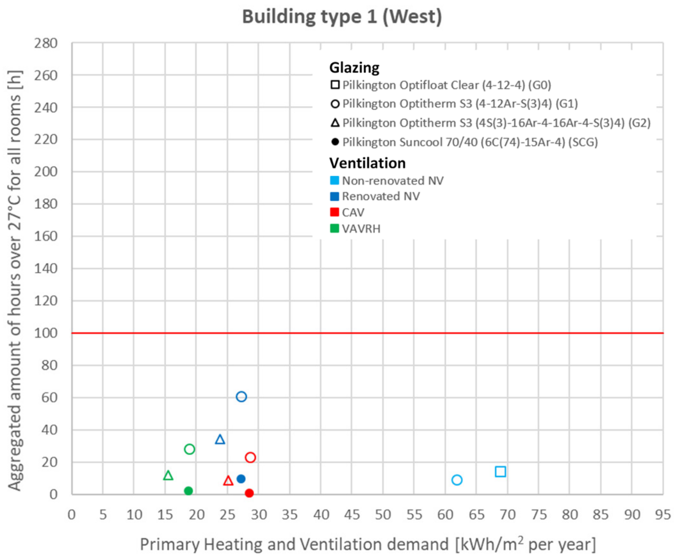
Appendix F. Combined results for different solar shading solutions and different ventilation strategies in case of Building Type 1 without surrounding buildings present (reduced venting)

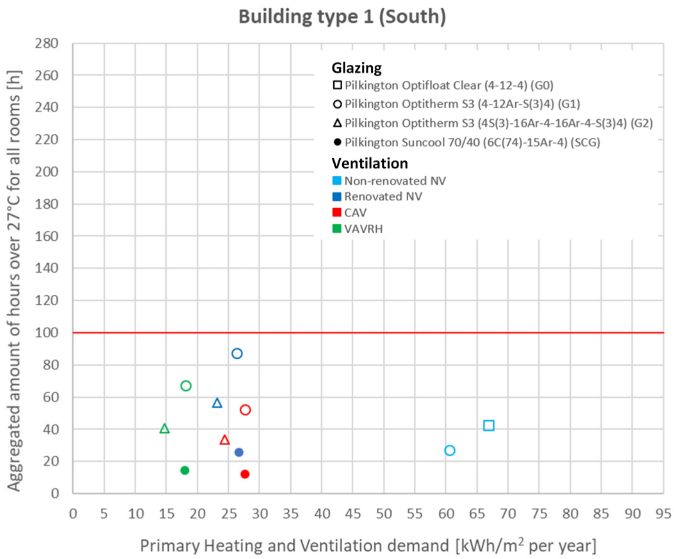

Building type 1 (West)
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]

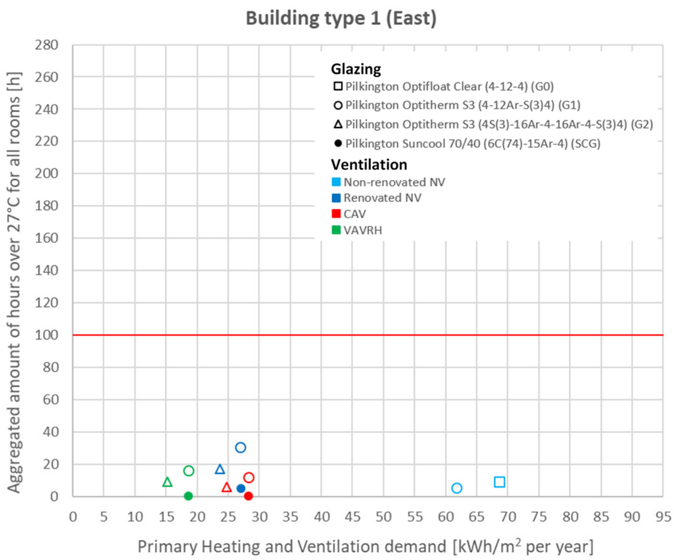

Building type 1 (South)
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]


Building type 1 (East)
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m2 per year]

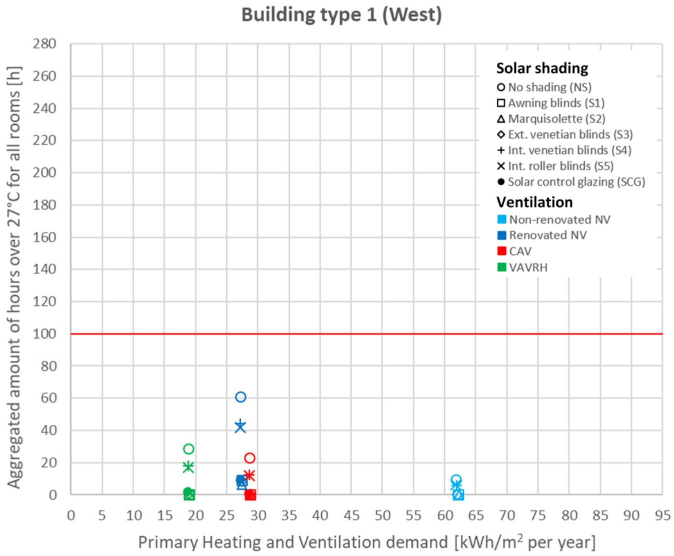
Appendix G. Combined results for different glazing types and different ventilation strategies in case of Building Type 1 located in a street canyon (reduced venting)

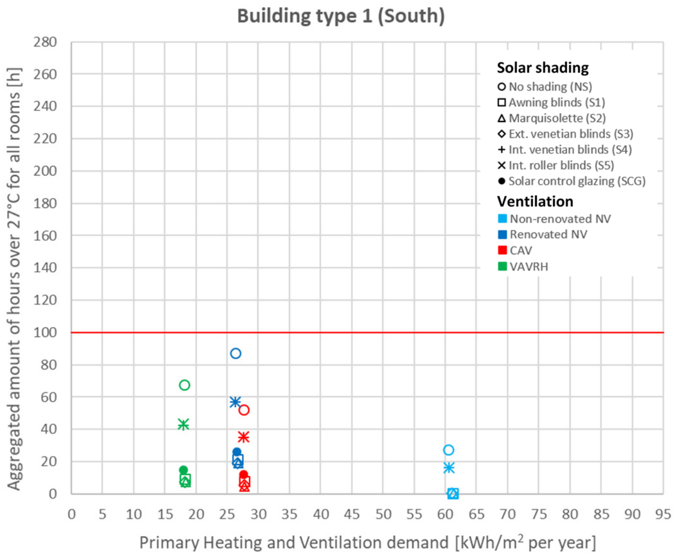

Building type 1 (West)
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]

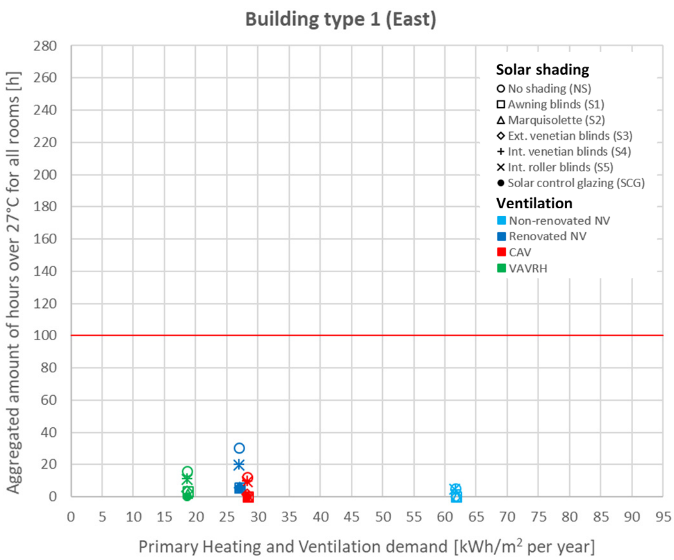

Building type 1 (South)
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]


Building type 1 (East)
Glazing
Pilkington Optifloat Clear (4-12-4) (G0)
Pilkington Optitherm S3 (4-12Ar-S(3)4) (G1)
Pilkington Optitherm S3 (4S(3)-16Ar-4-16Ar-4-S(3)4) (G2)
Pilkington Suncool 70/40 (6C(74)-15Ar-4) (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]

Appendix H. Combined results for different solar shading solutions and different ventilation strategies in case of Building Type 1 located in a street canyon (reduced venting)


Building type 1 (West)
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]


Building type 1 (South)
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]


Building type 1 (East)
Solar shading
No shading (NS)
Awning blinds (S1)
Marquisolette (S2)
Ext. venetian blinds (S3)
Int. venetian blinds (S4)
Int. roller blinds (S5)
Solar control glazing (SCG)
Ventilation
Non-renovated NV
Renovated NV
CAV
VAVRH
Aggregated amount of hours over 27°C for all rooms [h]
Primary Heating and Ventilation demand [kWh/m² per year]

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