LICENTIATE THESIS NO. 9

Evaluation of Thermal Comfort and Night Ventilation in a Historic Office Building in Nordic Climate

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Cover illustration: The studied historic office building / Abolfazl Hayati

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Dedicated to my parents

Abstract

Envelopes with low thermal performance are common in European historic buildings, resulting in insufficient thermal comfort and higher energy use compared to modern buildings. There are different types of applications for the European historic buildings such as historic churches, museums, theatres, etc. In historic buildings refurbished to offices, it is vital to improve thermal comfort for the occupants. Improving thermal comfort should not increase, and preferably reduce, energy use in the building.

The overall aim in this research is to explore how to improve thermal comfort in historic office buildings without increasing, and preferably reducing, energy use with the application of non-intrusive techniques. This is done in the form of a case study in Sweden. Thermal comfort issues in the case study building were determined through a field study. The methods include field measurements with thermal comfort equipment, data logging on building management system (BMS), and evaluating the occupant's perception of a summer and a winter period indoor environment using a standardized questionnaire. The responses to the questionnaire and the results of thermal comfort measurements show that the summer period has the most dissatisfied occupants, while winter thermal comfort is satisfactory – but not exceptionally good.

Accordingly, night ventilation (NV) could be used, as a non-intrusive technique, in order to improve thermal comfort in the building. For the historic building equipped with mechanical ventilation, NV strategy has the potential to both improve thermal comfort and reduce the total electricity use for cooling (i.e., electricity use in the cooling machine and the electricity use in the ventilation unit's fans). It could decrease the percentage of exceedance hours in offices by up to 33% and reduce the total electricity use for cooling by up to 40%. The optimal (maximum) NV rate (i.e., the potential of NV strategy) is dependent on the thermal mass capacity of the building, the available NV cooling potential (dependent on the ambient air temperature), COP value of the cooling machine, the SFP model of the fans (low SFP value for high NV rate is optimal), and the office door schemes (open or closed doors).

Keywords: historic buildings, office buildings, Nordic climate, thermal comfort, field (on-site) measurements, standardized questionnaire, building management system (BMS), night ventilation (NV), building energy simulation (BES), IDA-ICE.

Sammanfattning

Klimatskärm med låg termisk prestanda är vanliga egenskaper i europeiska kulturbyggnader, vilket resulterar i otillräcklig termisk komfort och högre energianvändning jämfört med moderna byggnader. Det finns olika typer av applikationer för de europeiska kulturbyggnaderna, såsom historiska kyrkor, historiska museer, historiska teatrar osv. I historiska byggnader som renoverats till kontor är det viktigt att förbättra personalens termiska komfort. Förbättring av termisk komfort bör inte öka energianvändningen i byggnaden.

Det övergripande syftet med denna forskning är att utforska hur man kan förbättra termisk komfort i typiska historiska kontorsbyggnader utan att öka, utan helst minska, energianvändningen med tillämpning av icke-förstörande tekniker. I en fallstudiebyggnad undersöktes termiska komforten. Metoderna inkluderar fältmätningar med termisk komfortutrustning, dataloggning på fastighetsautomationssystemet och utvärdering av personalens uppfattning om inomhusmiljön under en sommar- och en vinterperiod med hjälp av en standardiserad enkät. Enligt resultaten från enkäten och mätningar framkom att störst missnöje var under sommaren, medan termiska komforten på vintern var mer tillfredsställande - men inte exceptionellt bra.

Följaktligen kan nattventilation (NV) användas som en icke-förstörande teknik för att förbättra den termiska komforten i byggnaden. För den kulturbyggnad utrustad med mekanisk ventilation har NV-strategin potential att både förbättra den termiska komforten och minska den totala elanvändningen för kylning (dvs. elanvändningen för kylmaskinen och elanvändningen för ventilationsaggregatets fläktar). Detta kan minska andelen överskotts timmar på kontoren med upp till 33 % och den totala elanvändningen för kylning med upp till 40 %. Det optimala (maximala) NV-flödet (dvs. potentialen för NV-strategin) beror på byggnadens värmekapacitet, den tillgängliga NV-kylpotentialen (som beror på den omgivande lufttemperaturen), kylmaskinens årsverkningsgrad (COP-värde), fläktarnas specifika eleffekt (SFP) (lågt SFP-värde för högt nattventilationsflöde är optimalt) och om kontorsdörrarna är öppna eller stängda.

Nyckelord: kulturbyggnader, kontorsbyggnader, nordiskt klimat, termisk komfort, fältmätningar, standardiserad enkät, fastighetsautomationssystem, nattventilation, byggnadens energisystem.

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Last but not least, I would like to express my great appreciation to my parents and siblings who have always supported and inspired me throughout my life. Special thanks to my parents for their endless love, support and encouragement; I could not achieve my goals and chase my dreams without your support.

List of Papers

This thesis is based on the following papers, which are referred to in the text by Roman numerals.

Paper I

Bakhtiari, H., Akander, J., & Cehlin, M. (2019). Evaluation of thermal comfort in a historic building refurbished to an office building with modernized HVAC systems. *Advances in Building Energy Research,* 14(2): 218-237; https://doi.org/10.1080/17512549.2019.1604428

Paper II

Bakhtiari, H., Akander, J., Cehlin, M, & Hayati, A. (2020). On the Performance of Night Ventilation in a Historic Office Building in Nordic Climate. *Energies*. 13(16): 4159; https://doi.org/10.3390/en13164159

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Publications not included in the thesis

H. Bakhtiari, M. Cehlin and J. Akander. Thermal Comfort in Office Rooms in a Historic Building with Modernized HVAC System. 4th International Conference on Building Energy Environment, Melbourne, Australia, 5-9 February 2018.

Nomenclature

Abbreviations	
ACH	Air change per hour
AHU	Air-handling unit
ATL	Ambient temperature limit
BES	Building energy simulation
BMS	Building management system
CO_2	Carbon dioxide
COP	Coefficient of performance
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DC	District cooling
DH	District heating
DHW	Domestic hot water
DR	Draught rate
EU	European Union
GHG	Greenhouse gas
GWh	Gigawatt hour
HVAC	Heating, ventilation and air-conditioning
IEQ	Indoor environmental quality
Km	Kilometer
kWh	Kilowatt hour
NMBE	Normalized Mean Bias Error
NV	Night ventilation
NVP	Night ventilation period
NVR	Night ventilation rate
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RQ	Research question
SFP	Specific fan power
TWh	Terawatt hour
Letters and symbols	
H_e	Exceedance hours
T_{op}	Operative temperature

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1. Introduction

1.1. Background

In order to break down the global warming mechanisms caused by increased primary energy use, achieving energy efficiency is an important goal. As the heart of the European Green Deal, presented on 11 December 2019 [1], and in line with the EU's commitment to global climate action under the Paris Agreement [2], the EU has set an objective to be climate-neutral by 2050. The first step in this regard is to reach the target of 32.5% energy efficiency and at least 40% reduced CO_2 emissions by 2030, following on from the existing 20% energy efficiency target by 2020 [3]. Reaching the mentioned targets will require actions by all sectors of the EU economy, among others ensuring that buildings are more energy efficient. It is pursued via a "renovation wave" initiative for the building sector as one of the actions in the provided roadmap [4]. In this regard, the European Parliament and Council have established legislative frameworks to reduce energy use and environmental impact in the European building sector including the Energy Efficiency Directive [5] and the Energy Performance of Buildings Directives [6, 7]. In order to address these directives, the EU countries must establish measures to improve their national building stock. The national Swedish energy and climate goals are to have 63% lower greenhouse gas (GHG) emissions by 2030 compared to levels in 1990, 50% more efficient energy use by 2030 compared to levels in 2005, and net zero emissions of GHGs by 2045 [8].

The building sector in its different forms (homes, work places, schools, hospitals, libraries or other public buildings) is the single largest energy consumer (40% of total energy use) and one of the largest carbon dioxide emitters (36% of GHG emissions) in the EU [9]. There is a good potential for energy use reduction in the built environment. In recent decades, the residential and services sectors has always accounted for a considerable proportion of the final energy use in the world (ranges between 36.5% in 2015 to 42.5% in 1993; see Figure 1) and in Sweden (ranges between 36.2% in 2007 to 44.1% in 1981 and 1982; see Figure 2) [10].

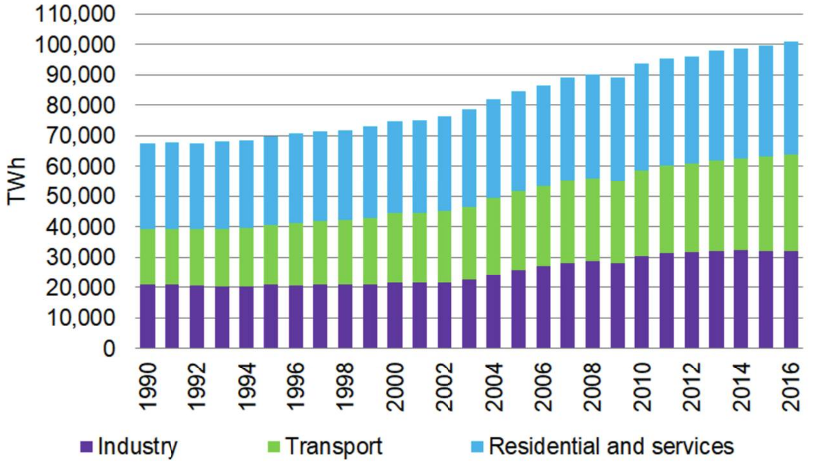


Figure 1. Final energy use in different sectors in the world during the period 1990-2016 [10]

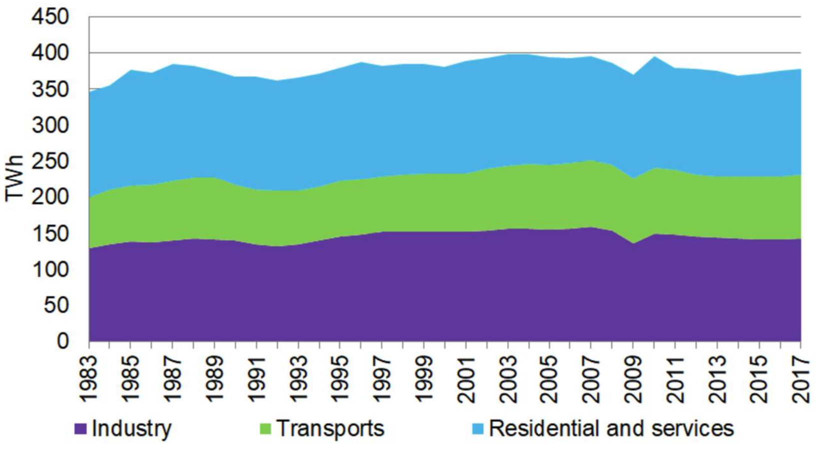


Figure 2. Final energy use in different sectors in Sweden during the period 1983-2017 [10]

Commercial and public administration subsectors together have always accounted for a considerable proportion of the total final energy use in residential and services sectors in Sweden (average around 31%), after households (see Figure 3) [10]. Electricity and district heating have steadily pushed back oil products in the final energy use in the Swedish residential and services sectors in recent decades. In 2017, electricity and district heating accounted for more than 80% of the final energy use in the residential and services sectors in Sweden (see Figure 4) [10]. There is accordingly potential for reducing district heating and electricity use in commercial and public administration subsectors (including office buildings) through applying energy efficiency measures.

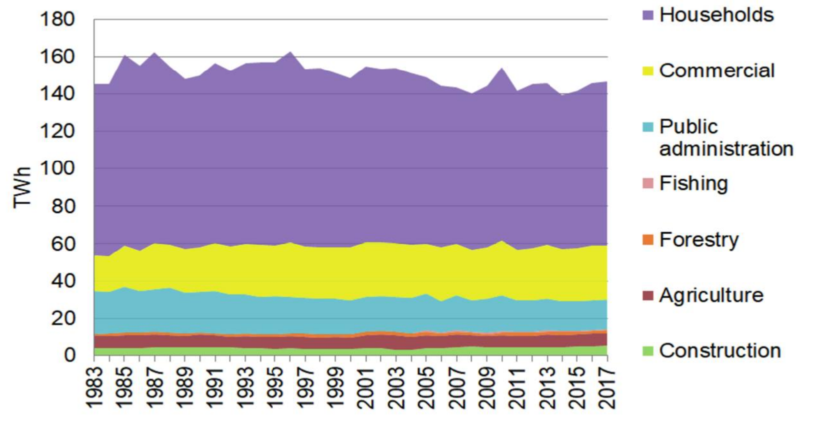


Figure 3. Final energy use in different subsectors of the residential and services sectors in Sweden during the period 1983-2017. [10]

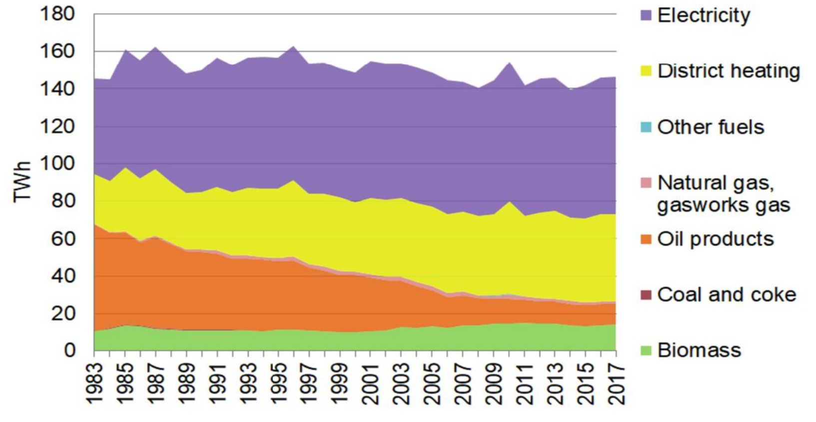


Figure 4. Final energy use by different energy carriers in the residential and services sectors during the period 1983-2017 [10]

District heating is by far the most common energy carrier in multi-dwelling buildings and non-residential facilities. In houses, the most common energy carrier for heating is electricity, followed by biofuels and district heating. [11] The electricity and district cooling (DC), among other things, are the common energy carriers for meeting space cooling demand, especially in commercial and office buildings.

Space cooling is the fastest-growing energy use amongst all end uses in buildings in the world [12]. Table 1 illustrates how the final electricity use for space cooling in residential and commercial buildings has increased worldwide during the period 1990-2016.

Table 1. Global final electricity use for space cooling in residential and commercial buildings in 1990 and 2016. [12]

Electricity use for space cooling	1990	2016
Final electricity use for space cooling	600 TWh	2 000 TWh[1]
Share of space cooling in total final electricity use in buildings	13%	18.5%

[1] corresponding to two and half times the total electricity use in Africa! [12]

In the European Union, the final energy use for space cooling in residential and commercial buildings increased from 63 to 152 TWh (about 2.5 times higher) during the period 1990-2016 [12]. In Sweden, final energy use for space cooling constitutes a considerable proportion of total final energy use for space heating, space cooling plus domestic hot water preparation in Swedish office buildings. This proportion accounted for 34% (corresponding to 5 GWh) for the year 2009 (see Figure 5) [13].

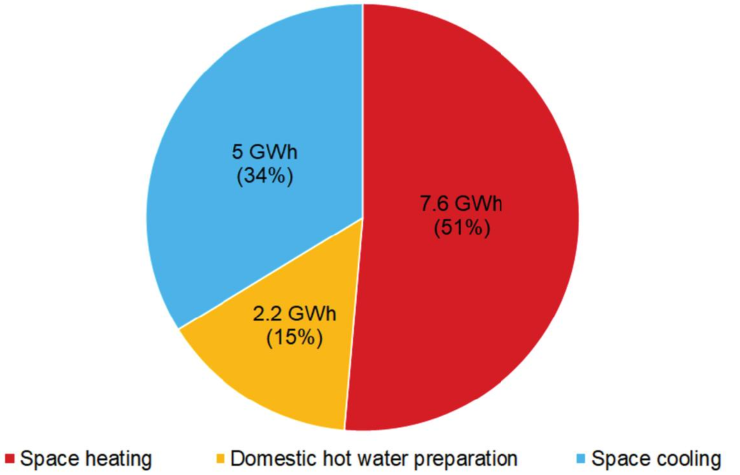


Figure 5. Final energy use for space heating, space cooling and domestic hot water preparation in Swedish office buildings in 2009 [13]

The supply and network length of the Swedish DC have increased 10 times and 16 times respectively (100 GWh and 40 km to 991 GWh and 639 km) during the period 1996-2019 (see Figure 6). The highest amount of DC is supplied to commercial and office buildings (see Figure 7) [14].

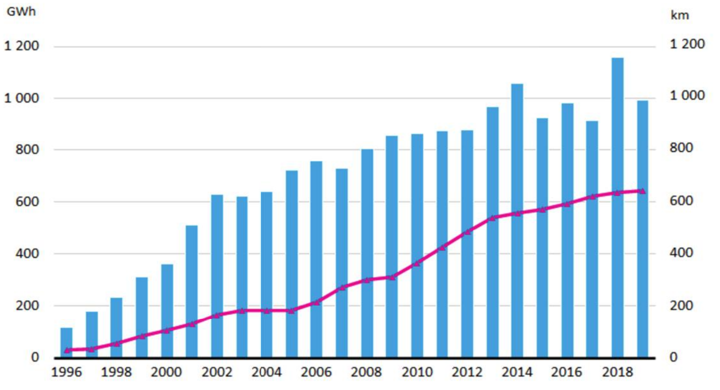


Figure 6. District cooling (DC) supply in GWh (blue bars) and network length in km (red trend line) in Sweden during the period 1996-2019 [14]

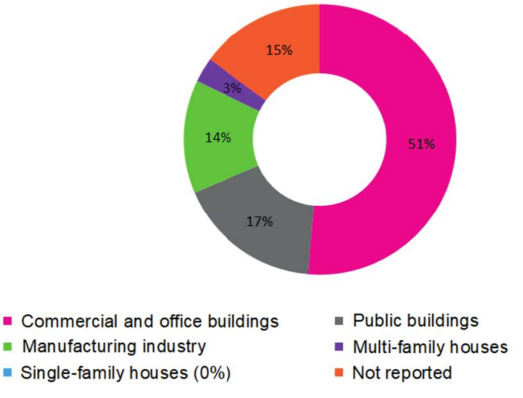


Figure 7. Distribution of district cooling (DC) supply in different sectors in Sweden in 2019 [14]

According to a baseline scenario proposed by the International Energy Agency (IEA), energy needs for space cooling will triple by 2050 and the space cooling will be the strongest driver of growth in electricity demand for buildings [12].

The mentioned statistics about the energy use for space cooling illustrate the important potential for improving energy efficiency in this energy end-use in the building sector, especially commercial and office buildings, with the help of energy efficiency measures.

Over 25% of the European buildings are historic [15], which illustrates the considerable potential for improving energy efficiency in historic buildings in contributing to reaching the mentioned EU goals. Improving energy efficiency should not compromise and, if possible, should actually improve indoor environmental quality (IEQ) in the building sector. Accordingly, studies related to improving energy efficiency are normally accompanied by investigations of IEQ in the built environment.

There are various types of historic buildings with different applications. Depending on the type of application, specific criteria for IEQ in the historic building are recommended. In a typical historic church [16], museum [17] or theatre [18], the heritage value and artwork conservation as well as improvement of thermal comfort for churchgoers, visitors and audiences are all important factors. In historic buildings refurbished to offices, one of the important factors is to improve the IEQ and thermal comfort for the staff. This is important especially taking into account the fact that envelopes with low thermal performance are common in historic buildings which could result in insufficient IEQ and also higher energy demand.

Several field studies on the concept of IEQ and thermal comfort have been carried out in office buildings with different objectives, methods, and in different climates. Roulet et al. [19] investigated the IEQ in a number of office and apartment buildings in nine European countries, mainly using interviews and questionnaire surveys, with the aim to propose a series of recommendations to improve the buildings' performance. Zagreus et al. [20] performed the same type of investigation in several office buildings in the USA, Canada and Europe using both questionnaire surveys and field measurements. Morhayim and Meir [21] investigated the environmental disturbing factors in a university building including offices and laboratories using questionnaire surveys, field measurements, and walk-through. More recent field studies on IEQ and thermal comfort using both questionnaire surveys and field measurements in office buildings equipped with HVAC systems include Choi and Moon [22], Deuble and de Dear [23], Indraganti et al. [24] and Luo et al. [25]. These office buildings, however, do not include old historic buildings.

Several other field studies have been performed on IEQ and thermal comfort in historic buildings. Some of them related poor indoor climate to poor thermal resistance of the building envelope, lack of ventilation system with heat recovery, and negative effects of thermal bridges and air leakage (e.g. Alev et al. [26] and Buvic et al. [27]). Moreover, stratification and insufficient lighting, poor acoustics and poorly performing heating system are common according to some other field studies (e.g. Balocco and Calzolari [28], Li et al. [29] and Varas-Muriel et al. [30]). These field studies have been performed on old historic buildings with different categories of applications including historic buildings for residential, religious, academic and palace, museum, library and theatre uses as well as historic buildings in urban areas; they do not include old historic buildings refurbished to office buildings. Rohdin et al. [31] studied indoor climate during winter in a town hall in Sweden that provided space for offices as well as city archives. The occupants in the studied building had complaints about too low temperature, draught and varying temperature. These problems were related to infiltration and cold surface temperatures.

As shown, various thermal comfort field studies have been carried out on historic buildings located in different climates. However, such studies on historic office buildings have not been widely covered in the literature and a research gap is recognized in this field.

One of the promising non-intrusive techniques which has shown to significantly improve thermal comfort and reduce energy use in the building is night ventilation (NV) [32], especially when applied to massive/heavy buildings [33]. Several parametric studies, mostly using building energy simulation (BES), were carried out on the parameters influential for NV efficiency. Some studies investigated the influence of current climate conditions in Europe [34], future climate scenarios [34, 35], and the urban heat island phenomenon [37] on the potential of NV for cooling. High building thermal mass has been shown to improve the NV cooling potential [37-41]. The results of some parametric studies have illustrated that longer NV duration and closer NV period to the active ventilation period, improve the cooling potential of the NV [32], [42-44]. Higher NV rates lead to higher effectiveness of the strategy. However, there is a maximum threshold which depends on the thermal mass capacity of the building. Several parametric studies illustrated the beneficial effect of increased NV rate (up to the maximum threshold) on improved thermal comfort [32, 37, 41, 45]. These studies, afterward, calculated the amount of saved energy for cooling based on this maximum ventilation rate. However, for mechanically driven NV, the electricity use in the ventilation unit's fans also needs to be taken into account. In other words, the optimal NV rate is, in fact, the ventilation rate which results in the minimum total energy use which consists of energy use for active cooling and electricity use in the ventilation unit's fans. For NV rates above this optimal ventilation rate, the amount of increase in electricity use in fans outweighs the amount of decrease in energy use for cooling and, therefore, the total energy use for cooling starts increasing. The optimal NV rate is dependent on some influential parameters, including the coefficient performance (COP) of the cooling machine and the specific fan power (SFP) of the ventilation unit's fans. Research studies, using BES modelling, on the potential of NV strategy with taking account of the mentioned influential parameters have not been widely covered in the literature and a research gap is also recognized in this field.

1.2. Motivation of the performed research

Envelopes with low thermal performance are common in historic buildings, which could result in insufficient and lower IEQ and also higher energy demand compared to modern buildings. If historic buildings are used as office buildings, improving the IEQ and thermal comfort for the staff is vital. Through improvement of thermal comfort and IEQ in historic office buildings equipped with HVAC systems, it is also, preferably, desired to reduce energy use in different possible energy end uses, among other things electricity use, district heating and space cooling demand. The research presented in this thesis provides a case study for assessing the thermal comfort status in a historic office building along with evaluating the potential of NV on improving energy efficiency and reducing building's energy use considering the influential parameters from the cooling machine and ventilation unit's fans.

1.3. Aim and research questions

The overall aim is to explore how to improve thermal comfort in historic office buildings without increasing, and preferably reducing, energy use and using non-intrusive techniques. This is done in the form of a case study. The identified research questions (RQs) are:

1. Which thermal comfort issues can be expected in a historic office building with mechanical ventilation?
2. What is the effect of different office door schemes on thermal comfort?
3. How can NV strategy resolve thermal comfort issues without increasing energy use?

1.4. Research methods

The main research methods presented in this thesis are on-site experimental field measurements, questionnaire survey study and parametric investigation through Building Energy Simulation (BES) in a case study. Field measurement methods include: weather station to measure ambient air temperature, ambient air relative humidity and wind speed and direction; measurements with thermal comfort equipment; room air and indoor surface temperature measurements; and electrical radiator power measurements using energy logger. A model was created in the simulation program IDA-ICE 4.8 and the field measurement results were used as input data and for calibration of the created model.

1.5. Research process

Both Papers I and II are part of the same case study. Figure 8 illustrates an overview of the research process including the connections to the RQs. The steps connected to RQ 1 were taken in Paper I. Thermal comfort issues in a historic office building equipped with mechanical ventilation were identified with the help of questionnaire survey and field measurements. Regarding RQs 2 and 3, a floor plan of the building, as the representative floor level, was modelled in the simulation program in Paper II. In order to get the materials and the thermal performance of the structures reasonably accurate, a simulation model of a non-occupied office room was calibrated. The calibration data were gathered through on-site measurements of room air and surface temperatures and power of an electrical radiator used for heating the room during the measurement period. The BES model of the floor was used to investigate the effect of different office door schemes and night ventilation (NV), as the non-intrusive technique, on improving thermal comfort and reducing electricity use for cooling in the historic office building.

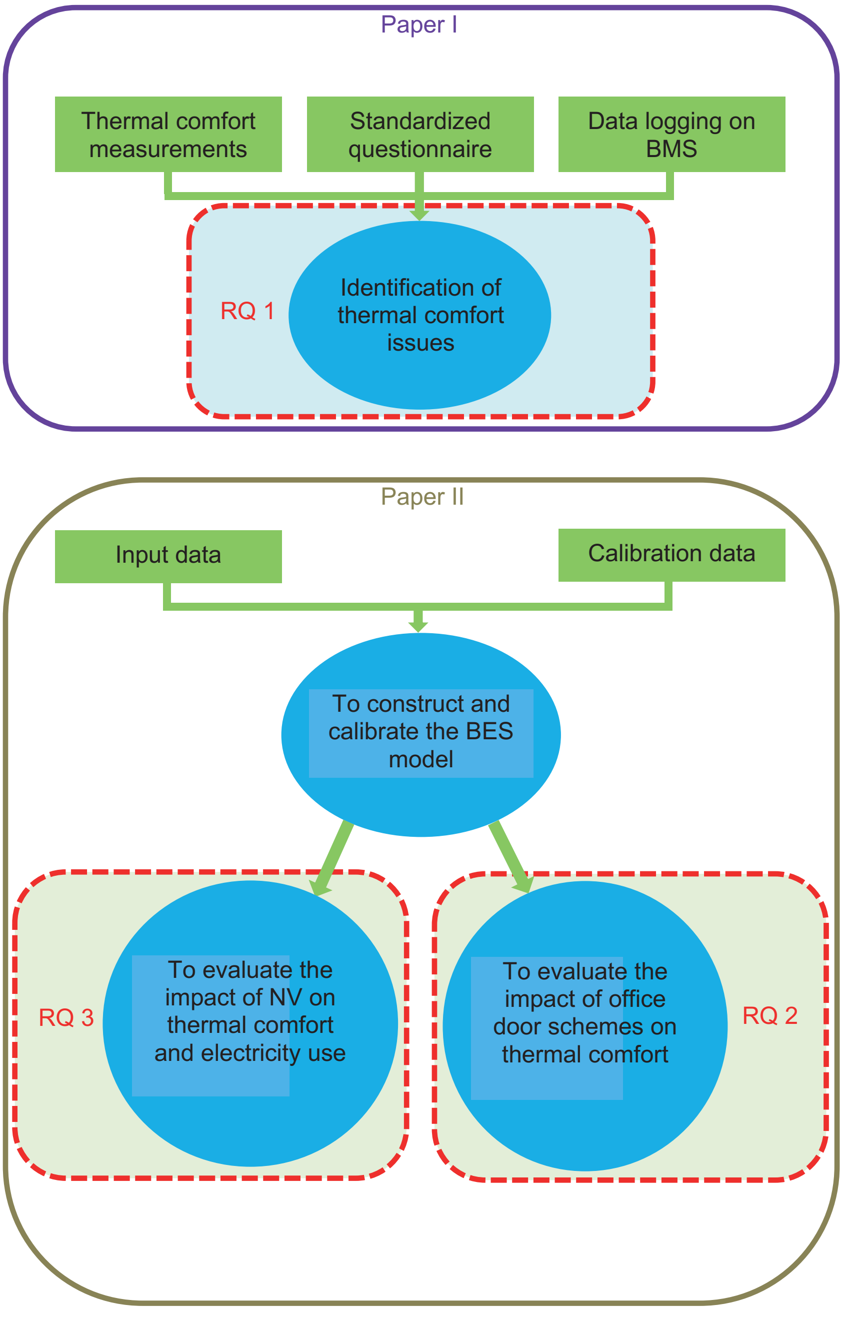


Figure 8. An overview of the research process including the connection between thesis RQs and Papers I and II.

1.6. Scope and limitations

The research in this thesis is on improving thermal comfort in a historic office building as the case study. Although it is possible to apply the methodology in a more general sense to other buildings in different climates, the results from this case study are more limited to Swedish historic office buildings.

In this research, the indoor environmental variables, especially those related to thermal comfort, were investigated through performing field measurements. The effect of non-intrusive techniques on improving thermal comfort and reducing energy use was evaluated through BES modelling along with field measurements for the purpose of model calibration. The evaluation was carried out mainly for the cooling season since thermal comfort investigations illustrated that thermal comfort issues appear mostly during summer.

1.7. Summary of the appended papers

Paper I:

The aim of this study is to investigate IEQ, with special focus on thermal comfort, in the historic City Hall of Gävle, as a historic office building in north central Sweden. The research methods include on-site measurements, data logging on the Building Management System (BMS) and evaluating the occupants' perception of a summer and a winter period indoor environment using the standardized MM- questionnaire. In conclusion, the indoor environment quality is unsatisfactory in this historic building. Stuffy air, too high, too low and varying temperatures, lighting problems and noise are constant problems during both summer and winter. Although the building has been equipped with a mechanical ventilation system, it is illustrated that the historic building thermal comfort issues have not completely been resolved. This also indicates that there should be opportunities for further thermal comfort improvement through improving control strategies, since upgrading the building's envelope, which risks changing the building's external characteristics and appearance, is not allowed according to the Swedish National Heritage Board [47]. The questionnaire results primarily indicate that thermal comfort problems appear during the summer season, whereas both questionnaire and measurement results indicate that winter thermal comfort is satisfactory – but not exceptionally good. This indicates that modern HVAC systems in cold climates may improve conditions concerning "traditional" historic building winter problems, but have summer problems since there often are no design requirements or focus on design issues during summer conditions in cold climates. Future research should in these cases focus on making HVAC systems more efficient and investigate how both heating and cooling loads during winter and summer can be reduced.

Paper II:

The aim of this study was to assess the effect of mechanical NV on thermal comfort and electricity use for cooling of the historic City Hall of Gävle, as a historic office building in north central Sweden. The potential of NV cooling in improving thermal comfort and electricity savings was modelled using the

IDA-ICE simulation program. The parametric study comprised different outdoor climates, flow rates, cooling machine's coefficient of performance (COP) and ventilation units' specific fan power (SFP) values. Additionally, the effect of different door schemes (open or closed) on thermal comfort in offices was investigated. Even though the building is located in a cold climate, it was shown that NV alone is not capable of meeting the building's total cooling demand and auxiliary active cooling is required. NV had the potential of decreasing the percentage of exceedance hours in offices by up to 33% and decreasing the total electricity use for cooling by up to 40%. Higher NV rates lead to more saved electricity for cooling. There is, however, an optimum ventilation rate above which the increase in electricity use in fans outweighs the decrease in electricity use in cooling machine. This optimum ventilation rate depends on thermal mass capacity of the building, cooling machine's COP, design ventilation rate, and available night ventilation cooling potential (ambient air temperature). SFP is defined at the design (maximum) ventilation rate. Therefore, the optimum case is important in the design of the ventilation for new building projects, so that a low SPF is obtained for high NVR (this will require large size ventilation ducts). It is more difficult to achieve in buildings with an already installed duct system. For higher COP values, the minimum total electricity use for cooling occurs at lower NV rates. Thus, for buildings with equal weight (same time constant), for the ones equipped with cooling machines with higher COP values, lower NV rates are recommended.

1.8. Co-authors' statement

Paper I

The studies were planned by the author (Hossein Bakhtiari) and by Doc. Mathias Cehlin and Dr. Jan Akander. The measurements and the questionnaire study were planned and performed by the author. The results were analyzed and interpreted and data curation and calculations were performed by the author under the supervision of Doc. Mathias Cehlin and Dr. Jan Akander. Paper I was written and edited by the author with comments and advices from Doc. Mathias Cehlin and Dr. Jan Akander.

Paper II

The studies were planned by the author (Hossein Bakhtiari) and by Doc. Mathias Cehlin, Dr. Jan Akander and Dr. Abolfazl Hayati. The measurements for the purpose of IDA-ICE model calibration were planned and performed by the author. Other measurements were planned and performed by the author, Doc. Mathias Cehlin, Dr. Jan Akander and Dr. Abolfazl Hayati. The numerical simulation as well as IDA-ICE model calibration were planned and performed by the author. The results were analyzed and interpreted and data curation and calculations were performed by the author under the supervision of Doc. Mathias Cehlin, Dr. Jan Akander and Dr. Abolfazl Hayati. Paper II was written and edited by the author with comments and advice from Doc. Mathias Cehlin, Dr. Jan Akander and Dr. Abolfazl Hayati.

2. Case Study Description

The City Hall in Gävle is a historic building refurbished to an office building for municipal staff, with a usable floor area of around 2100 m^2. The heritage value of the building prohibits any change in the building's envelope, especially the external appearance. Situated in Gävle, the annual mean temperature is 5.5℃ with winter temperature plummeting to about -22℃ and summer temperature rising to around 30˚C. The building consists mainly of 66 spaces: small office rooms, corridors, open-plan offices/seminar rooms, stairwells/entrance halls, a basement, and an attic. It has heavy weight construction and large double-glazed windows with wooden frames. The building's average floor to ceiling height is around 4 m, except for open-plan offices/seminar rooms (around 5 m). Longer facades of the building have northwest and southeast and shorter ones have northeast and southwest orientations. The building is shown in Figure 9.

Thermostats in office rooms adjust the air flow supplied by the air handling units (AHUs). Cooling comes from an electric heat pump that ejects heat into the exhaust ventilation air and supplies space cooling via supply air. The heat pump was not in operation due to technical problems during a long period during summer 2016. The control and regulation of AHUs, which is equipped with a rotary heat recovery unit, includes NV cooling strategy. The local district heating (DH) network supplies heat to the hydronic radiators located below the windows, to the domestic hot water (DHW) preparation heat exchanger, as well as to the heating coils in AHUs.

Figure 9. The City Hall in Gävle – A historic office building (photo: Abolfazl Hayati)

3. Methods

The methodology in this research is presented in a two-stage framework.

3.1. Assessment of thermal comfort status in the historic office building (with regard to seasonal differentiation)

With the aim to identify thermal comfort issues in the building during both summer and winter seasons, a field study was performed. The necessary information was collected through on-site technical measurements and inquiries with the occupants. The methods included inquiries with MM-questionnaire, assessment measurements with thermal comfort equipment and data logging on BMS.

3.1.1. Standardized questionnaire survey

The information about the experiences and perceptions of the indoor environment, in general, can be collected from the users by standardized questionnaires. The MM- questionnaire is one of the standardized questionnaires used in many studies and large nationwide surveys in Sweden [48]. It has various types of questionnaires for different environments including offices, schools and hospitals/healthcare establishments. The MM- questionnaire for offices (MM 040 NA Office) [49] was used in this research to investigate the occupants' perception of indoor environment during two periods including summer 2016 and winter 2016 to spring 2017 (see Appendix). The anonymity of the respondents was ensured. The original questionnaires were slightly modified. Detailed information about standardized questionnaire survey can be seen in section 2.2 in Paper I.

The employees were asked whether or not they had experienced disturbing factors and present symptoms in the work environment during the mentioned periods. The alternatives to the multiple-choice answers to the related questions included "yes, often", "yes, sometimes", and "no, never". As an additional design, a plan of the building divided into four main zones for all floors was appended to the questionnaire and two more questions were added asking the staff on which floor and in which zone their offices were located. With such division, in analysis of the responses, it was possible to consider the different influences of solar radiation on indoor environment in various zones according to their orientation and height from the ground surface. This plan is shown in Figure 10. Totally, 23 and 36 responses (corresponding to 76% and 65% response rates) were collected for summer and winter, respectively. It needs to be mentioned that more staff worked in the building during winter due to relocation of new staff from another nearby office building to the City Hall. Single or two-person offices were the common types; only a few employees worked in open-plan offices.

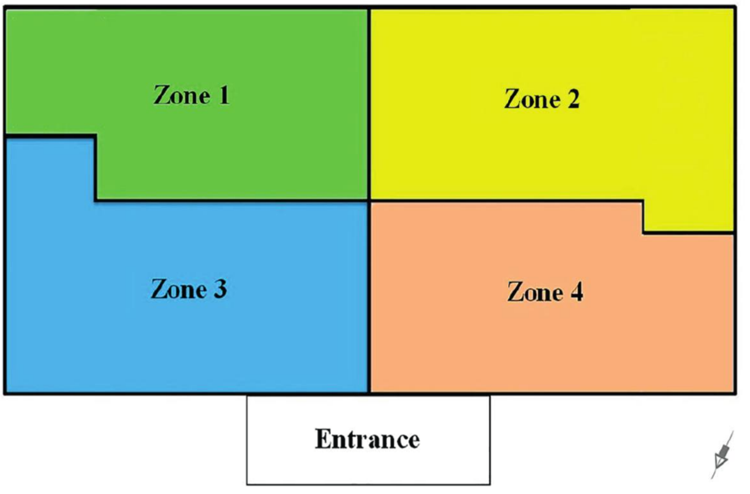


Figure 10. Building plan divided into four zones per floor. The arrow points to the north.

An important part of the assessment of the results is comparisons made with other groups and environments as references. The two references which were referred to in this research include:

(1) Well-functioning and healthy buildings (Reference 1): Reference data for working environments without known indoor climate problems. The reference data was collected in 1989 from a study covering seven offices and two schools, considered to be ”healthy”. Later studies confirmed the validity of these reference values and, therefore, no need was recognized for collecting new reference data.

(2) Typical Swedish office buildings (Reference 2): Reference data from 91 offices scattered all over Sweden, in some cases with indoor climate problems.

3.1.2. Measurements with thermal comfort equipment

The steady-state model for evaluation of moderate thermal environment based on the standard ISO 7730 [51] was applied. Thermal comfort measurements were carried out using INNOVA thermal comfort data logger model 1221 in a representative office room located at the southeast-southwest corner on the first floor. The data logger time stamped and saved the measurements made by four transducers including operative temperature, air temperature, air humidity and air velocity measurements. Figure 11 illustrates the transducers used for thermal comfort measurements.

Figure 11. Transducers used for thermal comfort measurements

Technical specifications of the transducers are presented in Table 2

Table 2. Technical specifications of thermal comfort measurements' transducers

Manufacturer	INNOVA (Air Tech Instruments)		
Model	Thermal comfort data logger - 1221		
Transducers	Model	Measurement range	Accuracy
Air temperature	MM0034	-20 ℃ to +50 ℃	±0.2 ℃ for 5 ℃ to 40 ℃ ±0.5 ℃ for −20 ℃ to 50 ℃
Air velocity	MM0038	0-10 m/s	V_a< 1 m/s: ±(0.05 V_a + 0.05)m/s[a] 1 < V_a< 10 m/s: typically better than ± 0.1 V_a[b] and ± 0.25 V_a[c] 2% drop in displayed reading[d]
Air humidity	MM0037	$T_a - T_d$ < 25 ℃[e]	$T_a - T_d$ < 10K: ±0.5 K or ± 0.05 kPa 10 K < $T_a - T_d$ < 25K: ±1.0 K or ± 0.1 kPa
Dry heat loss[f]	MM0057	-20 ℃ to +50 ℃	±0.5 ℃ for 5 ℃ to 40 ℃ ±1.0 ℃ for −20 ℃ to 50 ℃

[a] For any flow direction greater than 15° from rear of transducer axis [b] For flow directions perpendicular to transducer axis [c] For flow directions more than 15° from rear of transducer axis [d] Displayed reading will drop 2% when a standard 6 m extension cable is used [e] Dew-point range: T_a is the air temperature and T_d is the dew-point temperature [f] Used also for measuring operative temperature.

The measurements were carried out in three different locations in the room (in the middle of the room, in front of the window, at the corner of the room) at four heights: 0.1 m (representing the ankle level), 0.6 m (representing the middle of the body for a seated person), 1.1 m (representing both the neck level for a seated person and the middle of the body for a standing person), and 1.7 m (representing the neck level for a standing person). Figure 12 shows the location of measurements in the representative office room.

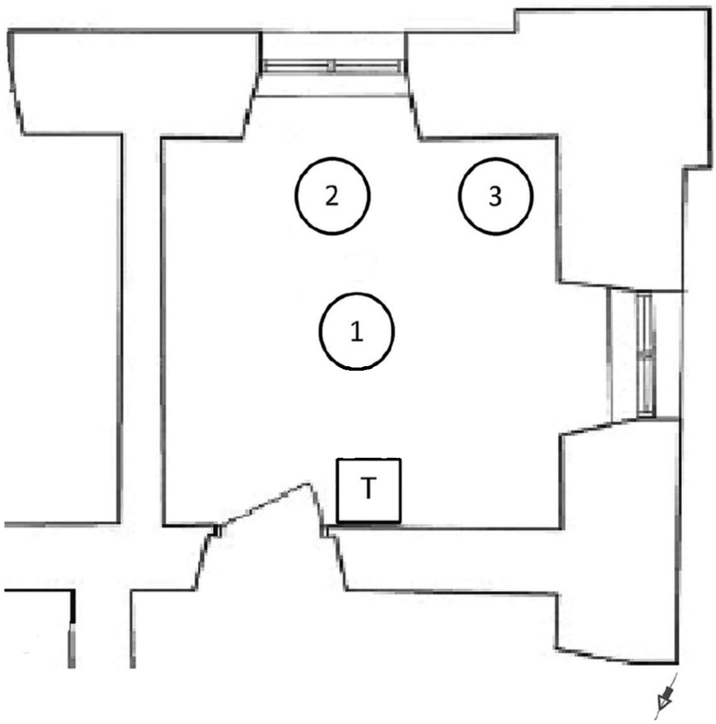


Figure 12. Measurement locations in the representative room. The arrow points to the north. NOTE: T represents the BMS room thermostat.

For locations 2 and 3, the measurements were carried out 0.6 m away from wall surfaces, based on recommendations from ISO 7730 standard [51].

The short-term measurements were performed at one-second time intervals during both winter (over ten-minute periods on a cloudy day with negligible contribution of direct solar radiation) and summer (over five-minute periods on a sunny day). The long-term measurements were carried out during winter, only at the corner of the office room, at the height of 1.1 m, at 15-minute time intervals and over a one-week period.

Thermal comfort indices were calculated by the thermal comfort data logger using the equations proposed by the ISO 7730 standard [51] and based on average values during the measurement periods. Predicted Mean Vote (*PMV*) and Predicted Percentage Dissatisfied (*PPD*) were calculated for the heights of 0.6 and 1.1 m to illustrate thermal state of the body as a whole for a seated and a standing person respectively [52].

The desired thermal environment for a space maybe selected from among the three categories A, B, and C according to Table 3.

Table 3. Categories of desired thermal environment [51]

Category	Thermal state of the body as a whole		Local discomfort	
	PPD (%)	*PMV*	Draught Rate (*DR*) (%)	Vertical air temperature difference[a] (˚C)
A	< 6	-0.2 < *PMV*< 0.2	< 10	< 2
B	< 10	-0.5 < *PMV*< 0.5	< 20	< 3
C	< 15	-0.7 < *PMV*< 0.7	< 30	< 4

[a] between head and ankles

3.1.3. Data logging on BMS

Room air temperatures were logged on BMS in different offices during summer (August 2016) and in one unoccupied office room during May 2018 (for the model calibration purpose) at ten-minute time intervals. The BMS thermostats in office rooms are ZS 102 series [50] and are mounted on internal walls, 1.7 m above the floor. The temperature sensor in the BMS thermostat has the accuracy of ±0.3℃ at the range 0 - 35℃ [50]. The thermostat is shown in Figure 13.

Figure 13. The BMS thermostat in the office room

3.2. Proposing ventilation strategy

When thermal comfort issues were identified, NV strategy was proposed to improve thermal comfort and reduce energy use for cooling in the building, since it is non-intrusive. Since upgrading the historic building's envelope, which risks changing the building's external characteristics and appearance, is not allowed according to the Swedish National Heritage Board [47], the measure to improve thermal comfort was focused on improving control strategies of the ventilation system. For the purpose of investigating NV, modelling and simulations with a BES-program were chosen.

3.2.1. Parametric study using BES modelling

A BES model of a representative floor level of the historic office building was created on the IDA-ICE 4.8 simulation program based on the information about building technologies from the time period of this historic building's erection [53]. IDA-ICE has been tested and validated according to various international and standard tests [52-56]. Except for office rooms, which were modelled individually, other spaces were merged and formed three corridors and one entrance hall. In case of merged spaces, the internal walls were compensated by defining internal mass in the zones. The model of the representative floor level on IDA-ICE is presented in Figure 14.

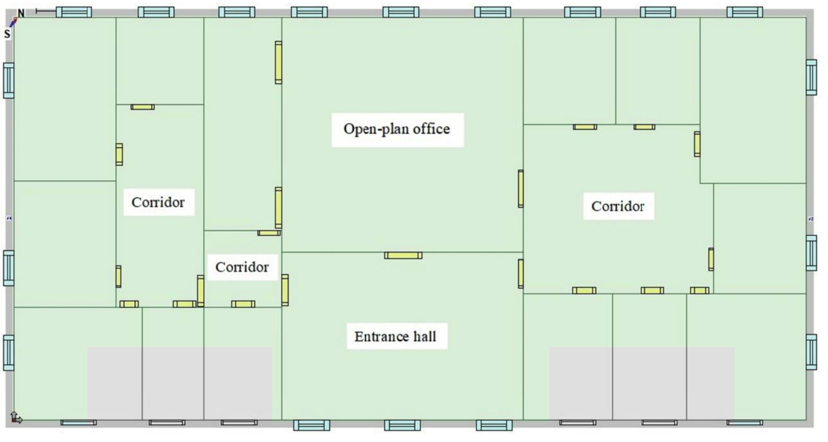


Figure 14. The model of the representative floor level on IDA-ICE 4.8. (unlabeled zones are offices)

The IDA-ICE simulation program supports only one-dimensional heat transfer, while the windows have niches which are two-dimensional thermal bridges. The niches were modelled as equivalent walls with one-dimensional heat transfers and the equivalent thicknesses were calculated using COMSOL Multiphysics (CM) simulation program version 5.3. The modeled building in IDA-ICE is oriented with 40° clockwise from north which was measured on-site. The shading effects of neighboring buildings were modelled by non-transparent bars (shading building) based on estimated heights and distances to the building of the City Hall using on-site observation.

In order to get the materials and the thermal performance of the structures reasonably accurate, a BES model of an unoccupied office room with mechanical ventilation turned off was calibrated. The calibration was done based on the heating demand of the office during a certain period in May 2018. For the purpose of calibration, the room's air and surface temperatures as well as the power of an electrical radiator, used for heating the room, were measured during the mentioned period. A manually tuned iterative process of simulation runs aiming at reducing discrepancies between simulated and measured data was used for calibrating the model of the selected office room. The iterative process was performed by calculating two principal uncertainty indices at each runtime including Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CV (RMSE)) [59]. Detailed information about model calibration can be seen in sections 3.1 to 3.4 in Paper II.

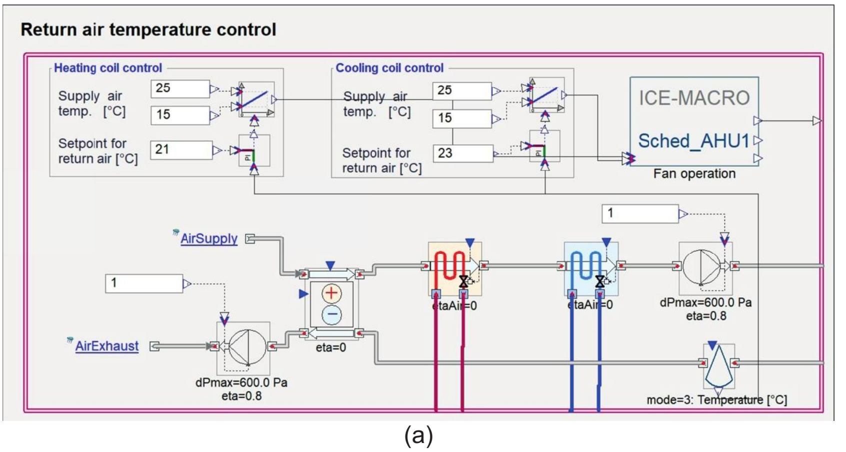
Input data about the mechanical ventilation system (including the NV strategy) and internal gains (occupancy, lighting and equipment) were collected in different ways: field measurements, logging on BMS, operation documents (BMS documentation), standards and guidelines, and on-site observations. Schedules on the model were defined based on the operational schedule of the mechanical ventilation system and the normal office working schedules. It was assumed that only one person worked in each single office with their desk placed in the middle of the office. The design ventilation rate was measured as 1.66 ACH in the case study building.

Predefined supply and return air ventilation unit with a constant air volume (CAV) type was applied. The unit included a predefined control macro for modeling NV strategy (ICE-MACRO in Figure 14 (a)). The related schematics are illustrated in Figure 15.

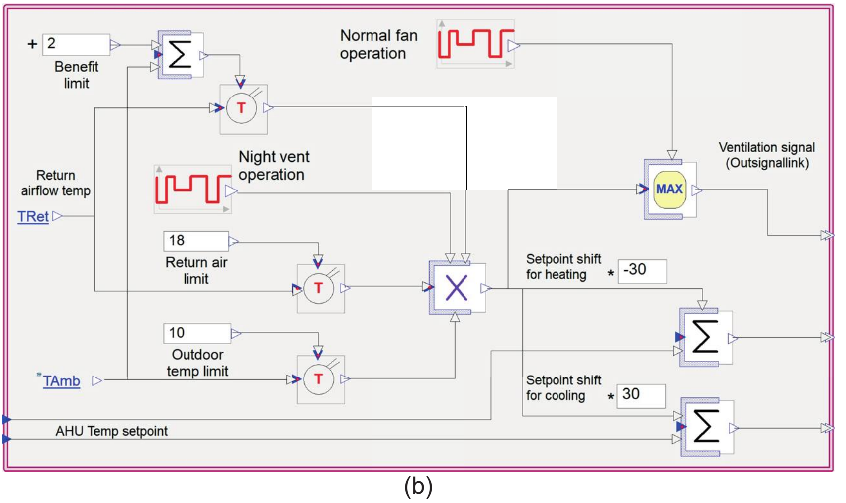
For NV strategy, the ventilation unit's return air and ambient temperature limit were set to 18 and 10 °C, respectively, and the benefit limit (i.e., the difference between ambient and return air temperatures) was defined as +2 °C. It means that the NV starts if all the following conditions are fulfilled and stops if any of them is missed:

(1) The time is during the period defined for NV schedule;
(2) The ventilation unit's return air temperature is over 18℃;
(3) The ambient temperature is over 10℃;
(4) The ambient temperature is at least 2℃ lower than the return air temperature.

The active cooling was modelled using local ideal coolers in the modelled office rooms with proportional controller with the P-band corresponding to 1℃ (i.e., setpoint temperature ± 0.5℃). Accordingly, the heating and cooling coils as well as the heat exchanger on the predefined ventilation unit were deactivated. In each modelled office room, the design ventilation rate was defined. Only one ventilation output signal (with value between or including 0 and 1) from the NV control macro to the air terminals of the office rooms was modelled in order to simulate the desired ventilation rate in office rooms during each simulation time step. The default output signals from the NV control macro to the supply and return fans were disconnected and the fans were modelled with unlimited performance; the fans' ventilation rates being equal to the total ventilation rate in office rooms during each simulation time step.



(a)



(b)

Figure 15. The schematic of (a) the predefined ventilation unit (b) the predefined detailed model of NV strategy (the detailed configuration of the ICE-MACRO on the ventilation unit).

The BES model of the representative floor was used to evaluate the impact of NV strategy on improving thermal comfort and reducing electricity use for cooling in the building. In the thermal comfort analysis section, the active cooling was deactivated and design ventilation rate was applied for both daytime ventilation and NV. In the energy use analysis section, the active cooling was activated during working hours with the minimum required ventilation rate (i.e., 0.35 l/s·m^2 + 7 l/s person) [60], keeping the NVR at the design value. The parametric study was carried out for two climatic conditions, a typical summer and the extraordinarily hot summer of 2018. The influence of different office door schemes on reducing the offices' operative temperatures by NV was also assessed. The cases are presented in Table 4. Open or closed represents status of doors to the office rooms, to capture air exchange between zones.

Table 4. Different schemes of open or closed doors with/without NV with NVR= 1.66 ACH (cases are without active cooling)

Cases	NV	Southern offices' doors[1]	Northern offices' doors[2]
1	No	Always closed	Always closed
2	No	Open during working hours	Always closed
3	Yes	Always closed	Always closed
4	Yes	Open during working hours	Always closed
5	No	Always open	Always closed
6	Yes	Always open	Always closed
7	No	Always open	Always open
8	Yes	Always open	Always open

[1] representing offices with southeast orientation with higher internal solar gains compared to other offices [2] representing all other offices excluding the open-plan office

The effect of four measures on further improvement of thermal comfort for the selected optimum case was also evaluated. The improvement measures included:

(1) Decreasing the minimum ambient temperature limit (ATL) of NV strategy from 10℃ to 5℃
(2) Doubling the daytime ventilation rate (DVR)
(3) Doubling the NV rate (NVR) while decreasing the NV period (NVP) from 20:00-06:00 to 20:00-04:00
(4) Tripling the NV rate (NVR) while decreasing the NV period (NVP) from 20:00-06:00 to 20:00-04:00

The total electricity use for cooling comprises two main parts: the electricity use in cooling machine and the electricity use in the ventilation unit's fans. The parametric study included different cooling setpoints and different cooling machine's COP values (as the affecting parameters on the first part) as well as different NV rates and various SFP models (as the influencing parameters on the second part). The SFP= 1.5 kW/ (m^3/s) was applied as a common value at the design flow rate, which is recommended for new air handling systems for the supply and return fans in ventilation units with heat recovery [60]. The design ventilation rate in the case study building is 1.66 ACH. The parametric study included different multiples of the current design flow rate as different NV rates to evaluate their impact on the electricity use in the fans. In this regard, three SFP models were defined. In SFP model 1, the same SFP value was defined for all NV rates. In SFP models 2 and 3, the SFP value was defined at the NV rates of 1.66 ACH and 3 × 1.66 ACH respectively. SFP values for ventilation rates below the design flow rate were calculated based on data of part-load performance for VAV fan systems according to ASHRAE standard 90.1 [61]. The assessed SFP models are presented in Table 5.

Table 5. The SFP values of the fans for different NVRs (kW / (m^3/s))

NVR	0 ACH	0.5 × 1.66 ACH	1.66 ACH	2 × 1.66 ACH	3 × 1.66 ACH
SFP model 1	1.5	1.5	1.5	1.5	1.5
SFP model 2	0.3	0.6	1.5	5.4[1]	11.7[1]
SFP model 3	0.1	0.1	0.2	0.7	1.5

[1] calculated by extrapolation on data of part-load performance for VAV fan systems based on ASHRAE standard 90.1 [61] for the assumed NV rate

4. Results and Discussion

Section 4.1 presents the thermal comfort issues in a historic office building and results connected to RQ1. Section 4.2 presents the effects of different office door schemes on thermal comfort and results related to RQ2. Section 4.3 presents the results connected to RQ3 and describes how NV strategy can resolve thermal comfort issues without increasing energy use.

4.1. Results linked to RQ1 – Thermal comfort issues

In section 4.1.1, the results based on the replies to the MM- questionnaire and in section 4.1.2, the results of measurements with thermal comfort equipment are presented. Detailed results of logged data on BMS can be seen in section 3 in Paper I.

4.1.1. Results of the standardized questionnaire survey

Detailed results based on the replies to the MM- questionnaire can be seen in section 3 in Paper I. The prevailing environmental disturbing factors in the offices compared to references 1 and 2 during summer and winter are presented in Figure 16. The percentages of dissatisfaction were calculated based on the number of "yes, often" responses.

During summer, complaints about six environmental disturbing factors were higher than the accepted limits proposed by reference 2, related to typical Swedish office buildings. These factors, in order, include: stuffy air, unpleasant odor, too high room temperature, noise, lighting problems, and varying room temperature.

During winter, complaints about three environmental disturbing factors were higher than the accepted limits proposed by reference 2 including noise, lighting problems, and varying room temperature, in order.

As the responses to MM- questionnaires illustrate, it is interesting that the building has more thermal comfort problems during summer compared to winter although the building is located in a cold climate. Even though the building's envelope has poor thermal performance (a common characteristic in historic compared to modern buildings), it is interesting that poor indoor environmental quality during winter was mainly due to environmental disturbing factors which were not related to thermal comfort (i.e., complaints about noise and poor lighting).

4.1.2. Results of measurements with thermal comfort equipment

Detailed results of measurements with thermal comfort equipment can be seen in section 3 in Paper I. The calculated *PMV* and *PPD* in the representative room during winter and summer are presented in Table 6 and Table 7. Based on the short-time measurements, during winter, for all three locations for both a seated and a standing person, *PMV* and *PPD* were in the acceptable ranges according to ISO 7730 (see Table 3). During summer, only for a seated person in the middle of the room, the criteria proposed by ISO 7730 were fulfilled.

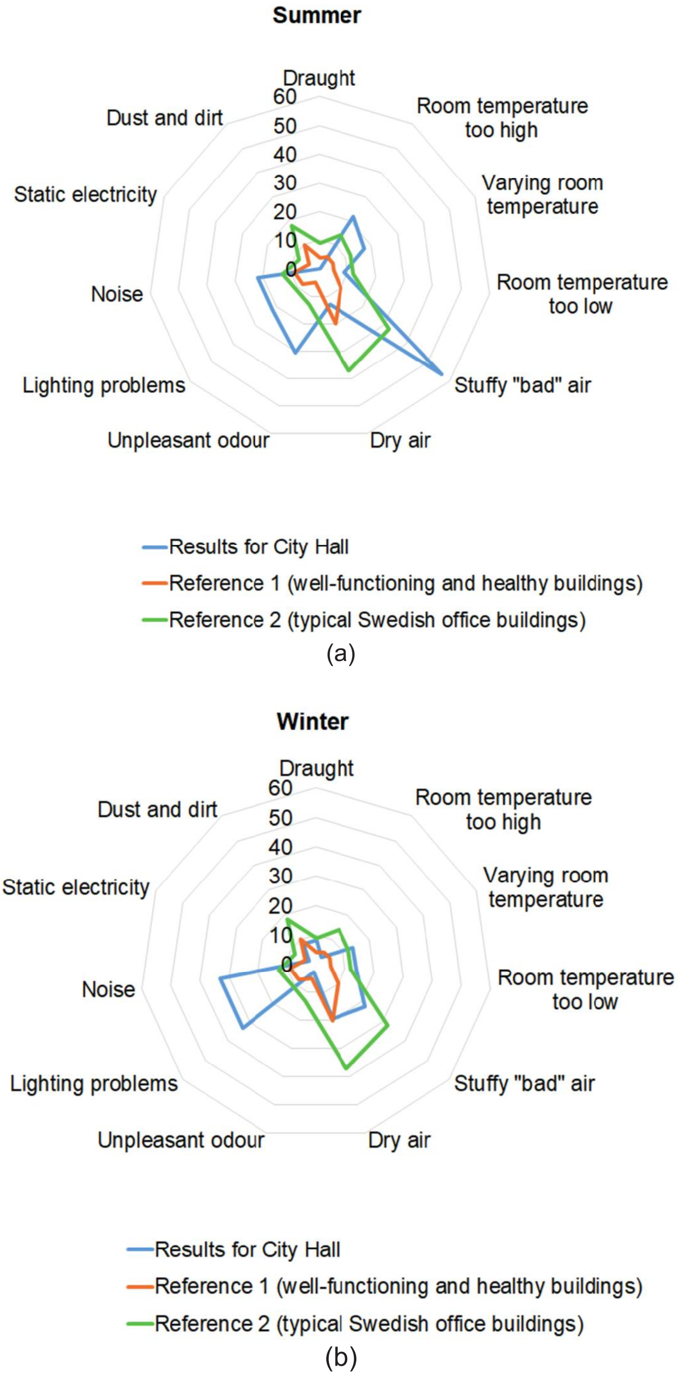


Figure 16. Environmental disturbing factors based on the responses to the MM- questionnaires during (a) summer (b) winter.

The calculated *PMV* and *PPD* and *DR* at the neck level for a seated person were in the acceptable ranges according to ISO 7730 for the long-term measurements during winter. Regarding local thermal comfort, the vertical air temperature difference between head and ankles and *DR* at both ankle and neck levels for a seated person were all in the acceptable range according to ISO 7730 in all locations during both summer and winter.

Table 6. The calculated PMV and PPD in the representative room for short-term measurements during winter

Measurement location	Winter			
	0.6 m[a]		1.1 m[b]	
	PMV	*PPD* (%)	*PMV*	*PPD* (%)
In the middle of the room	-0.3	6.6	-0.2	6.1
In front of the window	-0.3	6.3	-0.4	7.7
At the corner of the room	-0.4	8.7	-0.3	6.8

[a] the values represent *PMV*/*PPD* for the body as a whole for a seated person
[b] the values represent *PMV*/*PPD* for the body as whole for a standing person

Table 7. The calculated PMV and PPD in the representative room for short-term measurements during summer

Measurement location	Summer			
	0.6 m[a]		1.1 m[b]	
	PMV	*PPD* (%)	*PMV*	*PPD* (%)
In the middle of the room	0.5	9.9	0.6	11.8
In front of the window	0.6	13.3	0.6	13.5
At the corner of the room	0.6	11.9	0.6	12.8

[a] the values represent *PMV*/*PPD* for the body as a whole for a seated person
[b] the values represent *PMV*/*PPD* for the body as whole for a standing person

4.1.3. Results of logged data on BMS

Detailed results of logged offices' air temperatures on BMS can be seen in section 3 in Paper I.

The results of these three methods are generally comparable to each other. The results of measurements with thermal comfort equipment illustrate a good correspondence with the responses to MM- questionnaires. Both point to the fact that thermal comfort issues occur mainly during summer period and that winter thermal comfort is satisfactory – but not exceptionally good. A comparison between offices with different orientations of the façades based on the questionnaire responses illustrates more dissatisfaction with too high room temperature during summer in the offices facing southeast compared to the ones facing northwest, possibly related to receiving more solar radiation on the southeast façade. Logged room temperatures on BMS show similarly that offices facing southeast experience higher temperatures during summer than the ones facing northwest.

4.2. Results linked to RQ2 – Office door schemes

In order to show how different office door schemes (i.e. closed or open office doors) affect the average operative temperature (T_{op}) of office rooms with different orientations, the simulation results during the hot summer of 2018 for the cases with NV (NVR = 1.66 ACH) were applied. The detailed results are shown in Figure 6 in section 4.1 in Paper II. Southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices and northern offices represent all other offices excluding the open-plan office.

For cases with all doors always closed with NV (case 3), except for short periods, the average T_{op} of northern offices is always lower than those of southern offices and corridors. The average T_{op} of southern offices is lower than that of corridors during a large proportion of working hours during June and August and during a very short proportion of working hours during July.

All offices are influenced by NV. As long as the northern offices' doors are always closed, the southern offices' doors are open during working hours in case 4 and during the whole 24-hour period in case 6. During these periods and when corridors are cooler than southern offices, these offices could be slightly cooled down. When northern offices' doors are also opened during the whole 24-hour period in case 8, southern offices are further cooled down, while northern offices are warmed up. In all cases, only direct airflow between zones via open doors affect different zones' average T_{op}. The influence of heat transfer between different zones through internal walls and closed doors is negligible. The number of working hours with the average operative temperature over 26℃ in offices or corridors is called exceedance hours (He) [62]. Figure 17 shows the percentage of exceedance hours in offices and corridors during July as a sample in the hot summer for both cases with and without NV. The information for other months during the hot summer of 2018 can be seen in Figure 8 in section 4.1 in Paper II.

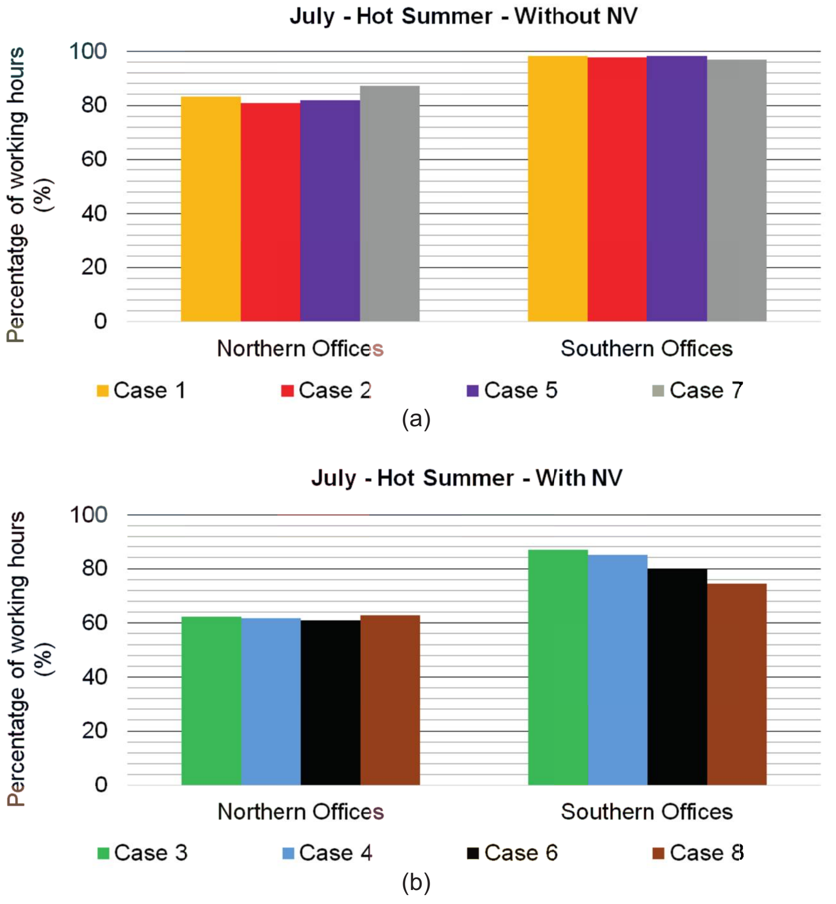


Figure 17. The percentage of exceedance hours in offices during July 2018 (a) without NV (b) with NV. Cases 1 & 3: All doors always closed, Cases 2 & 4: Northern offices' doors always closed / Southern offices' doors open during working hours, Cases 5 & 6: Northern offices' doors always closed / Southern offices' doors always open, Cases 7 & 8: All doors always open; Southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices, Northern offices represent all other offices excluding the open-plan office.

Based on the results for all months during the hot summer for both cases with and without NV, the cases with all doors always open (case 7 without NV and case 8 with NV) result in the lowest and highest H_e amongst all cases in southern and northern offices respectively. Table 8 illustrates the amount of decrease and increase in H_e for cases 7 and 8 compared to cases 1 and 3 in southern and northern offices respectively.

Table 8. The amount of decrease (negative values) and increase (positive values) in H_e (in %) in offices through shift between cases during the hot summer of 2018.

Shift between cases	Southern offices[c]			Northern offices[d]		
	June	July	August	June	July	August
case 1[a] to case 7[b]	-10.5	-1.4	-3.0	+5.7	+4.1	+1.3
case 3[a] to case 8[b]	-5.7	-12.3	-5.2	+1.0	+0.5	+2.2

[a] cases 1 & 3: all doors always closed [b] cases 7 & 8: all doors always open [c] southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices [d] northern offices represent all other offices excluding the open-plan office

Table 8 shows that, except for cases without NV during July, the amount of decrease in H_e in southern offices always outweighs the amount of increase in H_e in northern offices. This happens thanks to considerably lower average operative temperature in northern offices during some periods, while the southern offices' average operative temperature is slightly over 26℃ during the same periods. Therefore, the cases with all office doors always open (case 7 without NV and case 8 with NV) are optimum cases for the overall thermal comfort status in the representative floor level. The exceptional case during July does not contradict the optimum cases since the staff are mostly on holidays during July in Sweden.

4.3. Results linked to RQ3 – Effects of NV strategy

In section 4.3.1, the effect of NV as the non-intrusive technique for improving thermal comfort during summer in the historic office building is presented. Section 4.3.2 presents the influence of NV strategy on reducing the total electricity use for cooling during summer in the historic office building.

4.3.1. Thermal comfort improvement by NV strategy

Detailed information about the influence of NV strategy on thermal comfort improvement can be seen in Figure 8 and in section 4.1 in Paper II. During the extraordinarily hot summer of 2018, NV could contribute to indoor temperature reduction during working hours in offices for all cases during the whole period June-August. H_e in offices is reduced by the range of 7.1-28.6% as a result of applying NV.

Compared to the case with all office doors always closed without NV (case 1, referred to as base case), the mechanical NV strategy is capable of reducing the percentage of exceedance hours by up to 33% and 28% during a typical and a hot summer, respectively. This amount of reduction is achievable thanks to NVR = 1.66 ACH (design ventilation rate for the case study building) for the optimum case with all office doors always open (case 8).

In order to further improve the thermal comfort, the NV performance was improved with higher NV rates and lower ATL. Figure 18 illustrates the amount of decrease in the exceedance hours in northern and southern offices during June and July in the hot summer of 2018 as a result of applying the improving measures on NV performance for the optimum case.

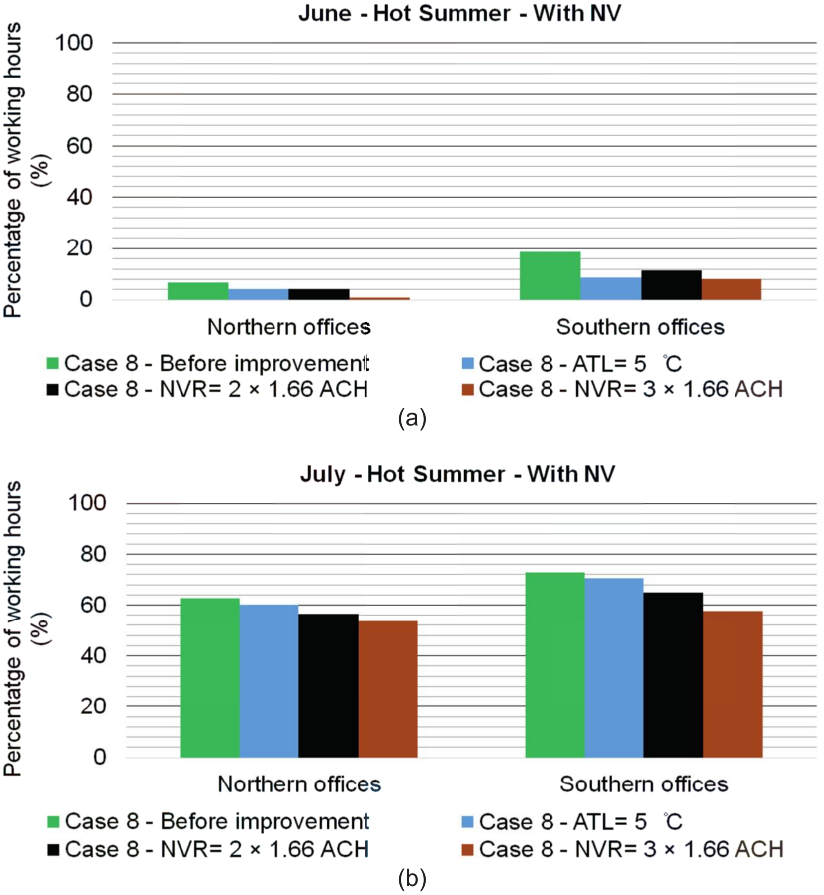


Figure 18. Percentage of exceedance hours in offices for thermal comfort improving measures for (a) case 7 and (b) case 8 during the hot summer of 2018.

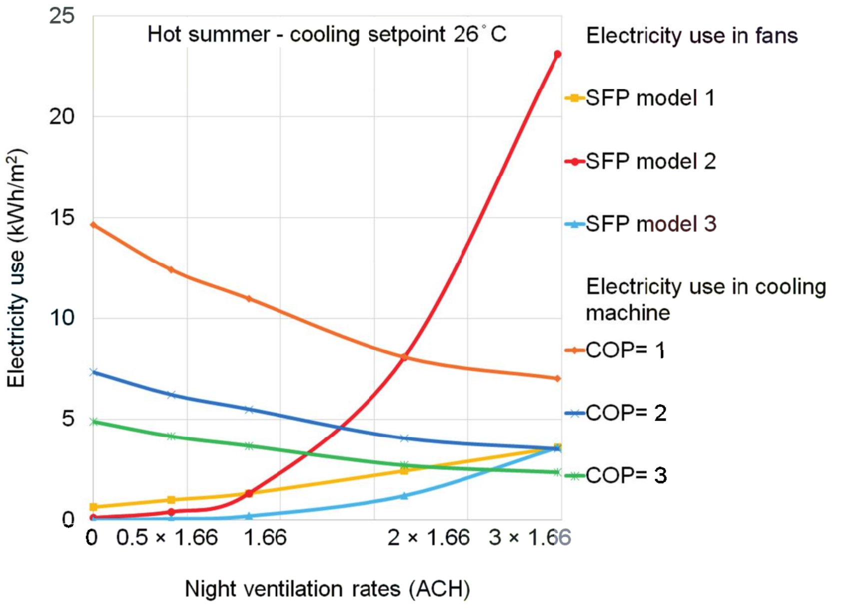
The information for other months during the hot summer can be seen in Figure 9 and section 4.2 in Paper II. By doubling the NVR, H_e is decreased by the ranges 2.4-6.5% in northern offices and by the range 7.1-7.8% in southern offices. Tripling the NVR leads to decrease in H_e by the ranges 5.7-12.2% in northern offices and 10.5-16.1% in southern offices. A finding is that the amount of decrease in H_e during June as a result of decreasing the ATL of NV strategy from 10℃ to 5℃ is more than and equal to the one caused by doubling the NVR in southern and northern offices respectively. It is because the ambient temperature during NV periods is lower than 10℃ for longer periods during June compared to July and August. There is, however, the risk of condensation on the surfaces with low ATL.

4.3.2. Reducing the total electricity use for cooling during summer by NV strategy

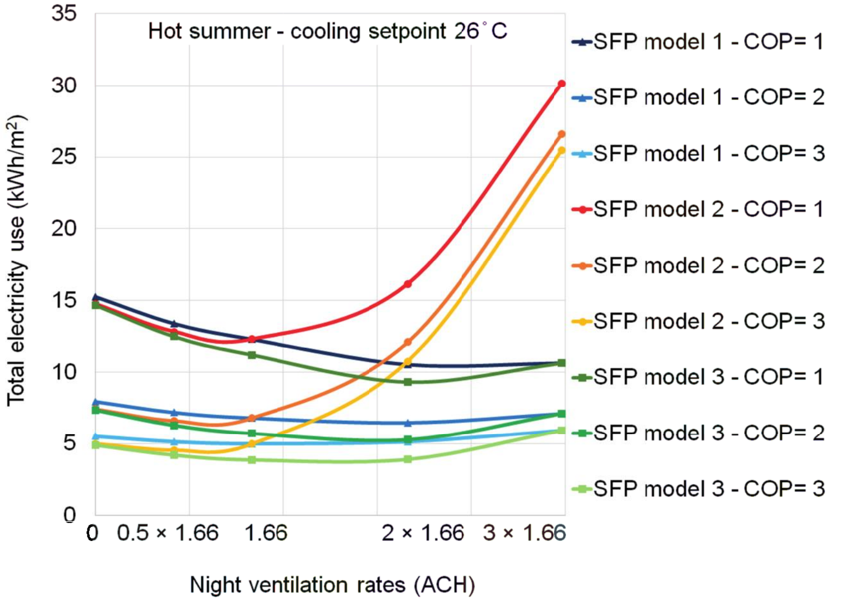
Figures 19 and 20 show the individual electricity use in the ventilation unit's fans as well as in the cooling machine and total electricity use for cooling during the hot summer of 2018. According to these figures, as the NV rate increases, the electricity use in cooling machine decreases, while the electricity use in the ventilation unit's fans rises. There is an optimum NV rate over which the amount of increase in electricity use in fans outweighs the amount of decrease in electricity use in the cooling machine. As a result, increasing the NV rate over the optimum rate leads to increase in total electricity use for cooling during summer.

For the same building and the same ambient air temperature, the optimum NV rate depends on the cooling machine's COP value and the SFP model. The optimum NV rate is higher for lower COP values. SFP is defined at the fans' design (maximum) ventilation rate. Therefore, the optimal SFP model is the one in which a low SFP is obtained for a high NV rate.

Compared to the base case (case 1), the mechanical NV strategy is capable of saving 1.5 kWh/m^2 (40%) and 0.4 kWh/m^2 (7%) of the electricity use for cooling during a typical and a hot summer, respectively. This amount of reduction is achievable thanks to the optimum NVR = 0.83 ACH (0.5 × 1.66 ACH), cooling machine's COP = 3, for the optimum case with all office doors always open (case 8), and at temperature setpoint of 26℃. For the same situation, decreasing the temperature setpoint from 26℃ to 24℃ leads to increase in the electricity use for cooling by 2.1 kWh/m^2 during the hot summer of 2018.



(a)



(b)

Figure 19. (a) individual electricity use; electricity use in fans and electricity use in cooling machine (b) total electricity use for cooling (electricity use in fans + electricity use in cooling machine); during the hot summer of 2018 for operative temperature cooling setpoint of 26 ℃.

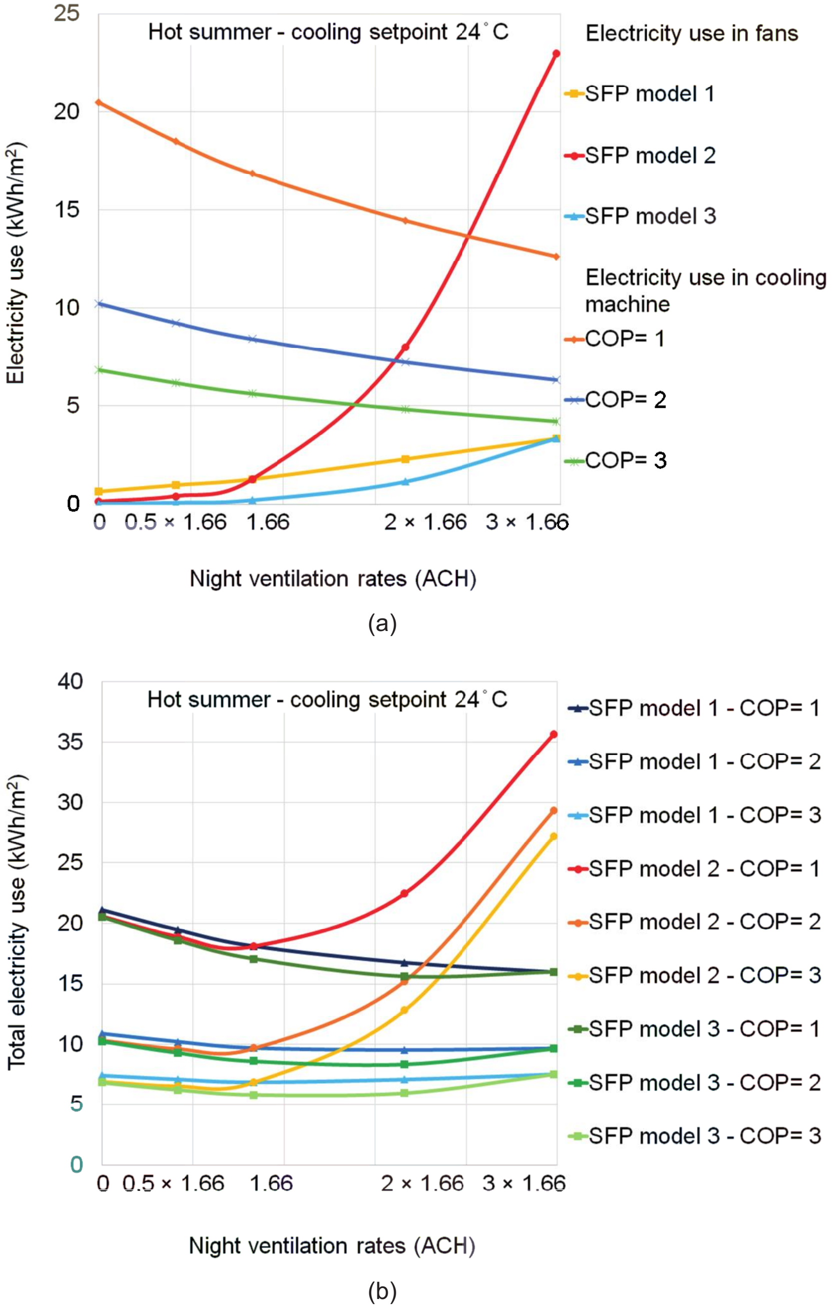


Figure 20. (a) individual electricity use; electricity use in fans and electricity use in cooling machine (b) total electricity use for cooling (electricity use in fans + electricity use in cooling machine); during the hot summer of 2018 for operative temperature cooling setpoint of 24 ℃.

5. Conclusion

The methods in this thesis were developed for the case study on a historic office building located in Sweden. These methods, however, can entirely or partly be generalized and used in other BES modelling case studies.

RQ1 was: *Which thermal comfort issues can be expected in a historic office building with mechanical ventilation?*

It is concluded that the indoor environment in the historic office building in this case study is unsatisfactory in comparison with well-functioning and healthy Swedish office buildings. Stuffy air, too high, too low and varying room temperatures, lighting problems and noise are constant issues during both summer and winter compared to both well-functioning and healthy as well as typical Swedish office buildings. It is revealed that the historic building thermal comfort issues have not completely been resolved even though the building has been equipped with a mechanical ventilation system. This also implies that it is possible to further improve thermal comfort by improving the HVAC system's control strategies. This improvement measure is proposed since upgrading the building envelope, which risks changing the building's external characteristics and appearance, is not allowed in historic buildings with heritage values according to the Swedish National Heritage Board.

It is also concluded that the summer period has the most dissatisfied occupants, while winter thermal comfort is satisfactory – but not exceptionally good, according to both questionnaire and measurement results. HVAC systems in cold climates may improve the conditions caused by "traditional" winter problems in historic buildings, but still have summer problems. It is due to the fact that in a cold climate, retrofitting of historic building design focuses on the trade-off point between energy use and thermal comfort during the heating season. However, summer issues concerning large window areas, absence and prohibiting of shading devices (building code restrictions), and high ambient summer temperatures might not have been foreseen as a problem, since the building is located in a cold climate. Future research should in these cases focus on making HVAC systems more efficient and investigate how both heating and cooling loads could be reduced.

RQ2 was: *What is the effect of different office door schemes on thermal comfort?*

Cases with all office doors always open, both with and without NV, are the optimum cases for the overall thermal comfort status in the representative floor level. As a result of opening all office doors during the whole 24-hour period, the amount of decrease in the percentage of exceedance hours in southern offices always outweighs the amount of increase in this parameter in northern offices, only except for during July without NV when staff are mostly on holidays in Sweden.

RQ3 was: *How can NV strategy resolve thermal comfort issues without increasing energy use?*

As the historic building in this case study has thermal comfort issues mainly during summer, natural heat sinks could be used in the form of NV in order to improve thermal comfort in the building, specifically considering the rising cooling demand worldwide resulting from climate change. For the historic building equipped with mechanical ventilation, NV strategy has the potential to both improve thermal comfort and reduce the total electricity use for cooling (i.e., electricity use in the cooling machine and the electricity use in the ventilation unit's fans). The optimum (maximum) NV rate (i.e., the potential of NV strategy) is dependent on the thermal mass capacity of the building, the available NV cooling potential (dependent on the ambient air temperature), COP value of the cooling machine, the SFP model of the fans (low SFP value for high NV rate is optimal), and the office door scheme (open or closed doors). For the optimum door scheme (all doors always open), NV strategy is capable of decreasing the percentage of exceedance hours in offices by up to 33% and reducing the total electricity use for cooling by up to 40%.

6. Future Work

In future research, the BES model of the whole building will be created on IDA-ICE 4.8 and further measures for improving thermal comfort and reducing energy use in the building for both cooling and heating seasons will be analyzed. The improvement measures could include night set-back strategy, identifying the optimal temperature setpoints and deadbands, applying energy-efficient HVAC scheduling techniques and applying occupancy-control ventilation strategy (such as using CO_2 sensors). A general framework could also be proposed in which the influences of different ranges of building weights (different time constants), fans with different SFP values, and cooling machines with various COP values on the potential of NV strategy are illustrated.

Moreover, the impact of future climates on the potential of thermal comfort improvement and energy efficiency measures could be assessed. Furthermore, the research can be extended to include the cost and environmental effects of the improvement measures from an overall energy system perspective and through performing life cycle analysis and life cycle cost.

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Appendix

The MM questionnaires for offices

WORK ENVIRONMENT

Have you been **bothered** during **the last three months** by any of the following factors **at your work place**? (Answer every question even if you have not been bothered!)

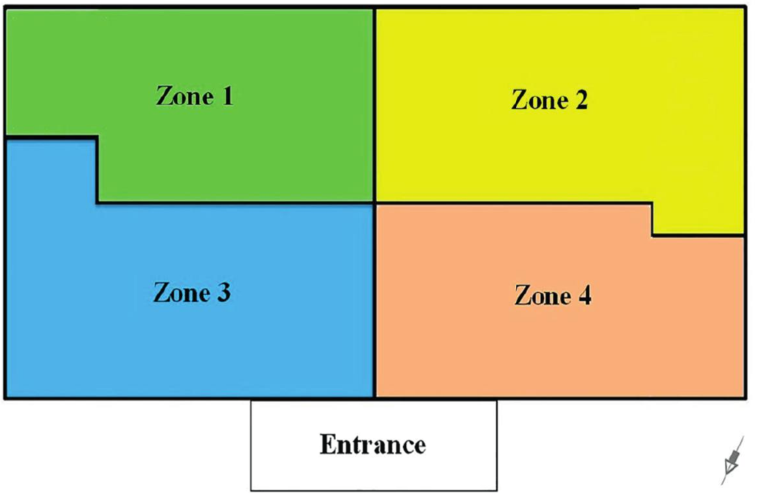
	Yes, often (every week) (1)	Yes, sometimes (2)	No, never (3)
Draught	☐	☐	☐
Room temperature too high	☐	☐	☐
Varying room temperature	☐	☐	☐
Room temperature too low	☐	☐	☐
Stuffy "bad" air	☐	☐	☐
Dry air	☐	☐	☐
Unpleasant odour	☐	☐	☐
Static electricity, often causing shocks	☐	☐	☐
Passive smoking	☐	☐	☐
Noise	☐	☐	☐
Light that is dim or causes glare and/or reflections	☐	☐	☐
Dust and dirt	☐	☐	☐

PRESENT SYMPTOMS

During the **last three months**, have you had any of the following symptoms?
(Answer every question even if you have not had any symptoms!)

	Yes, often (every week) (1)	Yes, sometimes (2)	No, never (3)
Fatigue	☐	☐	☐
Feeling heavy-headed	☐	☐	☐
Headache	☐	☐	☐
Nausea/dizziness	☐	☐	☐
Difficulties concentrating	☐	☐	☐
Itching, burning or irritation of the eyes	☐	☐	☐
Irritated, stuffy or runny nose	☐	☐	☐
Nose-bleeding	☐	☐	☐
Hoarse, dry throat	☐	☐	☐
Cough	☐	☐	☐
Dry or flushed facial skin	☐	☐	☐
Scaling/itching scalp or ears	☐	☐	☐
Hand dry, itching, redskin	☐	☐	☐
Suffering from stress	☐	☐	☐
Easily irritated about small matters	☐	☐	☐
Difficulties to sleep	☐	☐	☐
Other	☐	☐	☐

On which floor and zone your office room is located? (Please select the zone based on the following plan of the building. The arrow points to the north)



Paper I

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Evaluation of thermal comfort in a historic building refurbished to an office building with modernized HVAC systems

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ABSTRACT

Envelopes with low thermal performance are common characteristics in European historic buildings, causing higher energy demand and insufficient thermal comfort. This paper presents the results of a study on indoor environmental quality (IEQ), with special focus on thermal comfort, in the historic City Hall of Gävle, Sweden, now used as an office building. There are two modern heat recovery ventilation systems with displacement ventilation supply devices. The district heating network heats the building via pre-heat supply air and radiators. Summer cooling comes from electric heat pump ejecting heat into the exhaust ventilation air. A building management system (BMS) controls the heating, ventilation and air-conditioning (HVAC) equipment. The methodology included on-site measurements, BMS data logging and evaluating the occupants' perception of a summer and a winter period indoor environment using a standardized questionnaire. In conclusion, indoor environmental quality in this historic building is unsatisfactory. Stuffy air, too high, too low and varying room temperatures, lighting problems and noise are constant issues. Although it is equipped with modern ventilation systems, there are still possibilities for improving thermal comfort by improved control strategies, since upgrading the building's envelope is not allowed according to the Swedish Building Regulations in historic buildings with heritage value.

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KEYWORDS
Historic buildings; on-site measurements; standardized questionnaire; thermal comfort

1. Introduction

Total primary energy use has doubled during the last 40 years globally (Rohdin, Dalewski, & Moshfegh, 2012). In order to break down the resulting global warming mechanisms, achieving energy efficiency is an important goal. In Europe, the building sector accounts for almost 40% of total energy use (Morelli et al., 2012) and over 25% of buildings are historic (Moran, Blight, Natarajan, & Shea, 2014). This illustrates the important role of these types of buildings in reaching the mentioned aim. Achieving energy efficiency should not compromise and, if possible, should actually improve indoor environmental quality in the building sector. Accordingly, studies related to improving energy efficiency are

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normally accompanied by investigations of indoor environmental quality in the built environment.

1.1. Thermal comfort in office buildings

Several field studies on the concept of indoor environmental quality (IEQ) (specifically including thermal comfort) have been carried out on office buildings with different objectives, methods, and in different climates which have been assessed through some main review papers. Meir, Garb, Jiao, and Cicelsky (2009) reviewed scientific articles on post-occupancy evaluation (POE) for thermal comfort investigations divided into two main categories including lateral studies (limited number of parameters/large number of case studies) and in-depth studies (all possible parameters/a single case study). Lateral studies included Roulet, Foradini, Cox, Maroni, and de Oliveira Fernandez (2005) in which the indoor environmental quality was investigated in a number of office and apartment buildings, mainly using interviews and questionnaire surveys. Around 75% of the buildings had been designed to be energy efficient and 50% of them proved to be so. They proposed a series of recommendations for improving the performance of those buildings: (1) changing the layout from open to cellular offices and improving the acoustical ambiance of the occupants for resolving the noise problem; (2) improving thermal comfort using passive ways such as passive solar gains in winter, passive cooling in summer, and pre-heating or cooling air using heat recovery or underground heat exchanger; and (3) efficient daylighting and artificial lighting design. Zagreus, Huizenga, Arens, and Lehrer (2004) performed the same type of investigation using both questionnaires and measurements of influential physical parameters on thermal comfort in several office buildings in the USA, Canada and Europe. In one of the field studies in the USA, per-occupancy (prior to the move to the new building, called baseline) and POE of occupant comfort in a new large office building containing underfloor air distribution (UFAD) technology were conducted. According to the responses to the questionnaires, air quality satisfaction improved significantly and light satisfaction was significantly lower in the new building compared to the baseline. Survey comments indicated that the low light satisfaction was mainly related to inadequate illumination from task lighting. Morhayim and Meir (2008) presents an in-depth study in which the Sick Building Syndrome (SBS) phenomenon was investigated using POE on a university building including offices and laboratories. The POE included questionnaires, spot measurements of influential physical parameters on thermal comfort, and also walk-through. The results depicted the main reasons for complaints about some environmental disturbing factors. It was revealed that poor indoor air quality (IAQ) was likely caused by (1) visible mould concentration on HVAC outlets and return air openings; (2) moisture-caused patches on acoustic ceilings; and (3) condensation-induced mould on aluminum window frames. Lack of adequate individual control on the central HVAC system resulted in overheated building, causing both redundant energy use and relative discomfort in most spaces. Low relative humidity (around 20%) may have led to complaints about eye, nose, throat and skin irritation, as well as headaches. Finally, high levels of odour were observed in the laboratory spaces due to malfunctioning ventilation system and wrong-positioned exhaust chimneys on the roof.

Humphreys, Fergus Nicol, and Raja (2007) reviewed the main databases of field studies which are the experimental basis of the adaptive approach to thermal comfort. One of the databases was created by de Dear and Brager (1998) in which the collected datasets were categorized into three main classes. In research studies in class III, questionnaire studies were accompanied by simple measurements of temperatures alone and, possibly, relative humidity at only one height level above the floor. This class included field studies such as Humphreys (1976, 1978, 1981) and Auliciems (1981), which resulted in the early adaptive thermal comfort models. Class II included field experiments in which all physical environmental variables required for PMV/PPD calculations were measured at one arbitrary height at the same time and area as the thermal comfort questionnaires. However, field studies in Class I, applied the same combination of questionnaire surveys and field measurements as in Class II, but introduced measuring at the recommended heights (0.1, 0.6 and 1.1 m) above floor level for the field measurements according to ASHRAE standard 55 and ISO standard 7730. Class I included studies carried out by e.g. Schiller et al. (1988), de Dear and Fountain (1994), and Donnini et al. (1996).

Two literature reviews of thermal comfort studies done by Rupp, Vásquez, and Lamberts (2015) and Wang et al. (2018) include more recent scientific articles on field studies in office buildings in several climates, all applying a combination of questionnaires and measurements of indoor variables. A variety of thermal comfort field studies using both questionnaires and physical thermal comfort measurements have been carried out on office buildings located in different climates, most of which are equipped with modern HVAC systems (e.g. Choi & Moon, 2017; Deuble & de Dear, 2014; Indraganti, Ooka, & Rijal, 2013; Luo, Cao, Damiens, Lin, & Zhu, 2014). However, these office buildings do not include old historic buildings.

One of the specific research areas for thermal comfort field studies is historic buildings. Martínez-Molina, Tort-Ausina, Cho, and Vivancos (2016) presented a review on energy efficiency and thermal comfort in historic buildings. These studies were categorized based on types of applications including historic buildings for residential, religious, academic and palace, museum, library and theatre uses as well as historic buildings in urban areas. Several studies related the poor indoor climate due to poor thermal resistance of the building envelope, lack of ventilation system with heat recovery, and negative effects of thermal bridges and air leakage (e.g. Alev et al., 2014; Buvik, Andersen, & Tangen, 2014). Moreover stratification and insufficient lighting and in several cases poor acoustics and poor performing heating system are common (e.g. Balocco & Calzolari, 2008; Li, You, Chen, & Yang, 2013; Varas-Muriel, Martínez-Garrido, & Fort, 2014).

Rohdin et al. (2012) studied indoor climate during winter in a town hall in Sweden that provided space for offices as well as city archives. The studied building was reported having high complaints about too low temperature, draught and varying temperature. These problems were connected to infiltration and cold surface temperatures.

As shown, various thermal comfort field studies have been carried out on historic buildings located in different climates. However, studies including old historic buildings used as office buildings are very limited. All in all, a knowledge gap is recognized in the field of thermal comfort field studies on old historic buildings refurbished as office buildings and moreover have been equipped with modern heating, ventilation and air-conditioning (HVAC) systems. Such buildings have unique architectures mainly characterized by thicker walls than modern buildings and by higher heat losses through the building envelope, which could affect occupants' perceived thermal comfort in a different way compared to modern buildings situated in a colder climate. Therefore, the current paper aims to primarily investigate thermal comfort, but also, to a certain extent, other environmental variables in City Hall in Gävle in Sweden using a questionnaire survey study combined with on-site measurements and BMS logged data. The aim of this case-study is to investigate if a modern HVAC system is capable of resolving all the typical thermal comfort issues in this old office historic building.

1.2. Building description

The City Hall in Gävle is a historic building built in 1784–1790; historic meaning that the building envelope is not allowed to be changed, especially the external appearance. It is currently used as an office building for municipal staff. Situated in Gävle, the annual mean temperature is 5.5°C with winter temperatures plummeting to about −22°C. The building consists of three floors with 37 offices and a basement and attic. The total usable area is around 2100 m^2 and the average floor to ceiling height is 4 m. The building itself and the plan of the building's first floor are shown in Figure 1. All four façades of the building have double-glazed windows with wooden frames. The windows installed on the longer façades face northwest and southeast and the ones on the shorter façades face northeast and southwest. The building is connected to the local district heating network, which provides heat to the hydronic radiators (below the windows) in the rooms, to the domestic hot water preparation heat exchanger as well as to the heating coils in the air handling units. Supply temperature set point of the radiator circuit is calculated based on the supply temperature curve and a night set-back control strategy. The schedule for night set back is set for the whole weekend, 10:00_24:00 on Mondays, and 00:00_04:00 as well as 10:00_24:00 on other weekdays. The circulation pump in the radiators circuit is shut off during the summer period. During the winter period, the pump stops and the related heating valve is closed when the ambient temperature exceeds 15°C. The excess heat is calculated five times per day and when the exceeded outdoor temperature over the mentioned boundary value reaches the margin of + 0.5°C, the pump starts and the heating valve opens again.

Room thermostat controls temperature by adjusting the air flow. In each ventilation unit (totally two units), the set point of the supply air temperature to the related rooms is calculated based on the mean of room temperatures of the zones ventilated by the unit in question. The set point is 21°C with 2°C dead band between heating and cooling, i.e. the supply air temperature in each unit is regulated between 15°C and 25°C in order to keep the related rooms' temperatures at 21°C during winter, and cooling is supplied when the mentioned average room temperature exceeds 23°C. The circulation pump in the heating battery in each ventilation unit is in operation if two circumstances are fulfilled: The period is October_April (winter period) or as long as the ambient temperature is lower than 10°C and when the heating valve in the heating battery opens. The heating valve operates according to a heating curve which defines to which extent it needs to be opened based on the ambient temperature. It is totally closed and 50% opened when the ambient temperature is 10°C and −15°C respectively. Supply and exhaust fans in each ventilation unit are in operation 06:00_18:00 during week days. At start-up of the ventilation unit, the exhaust fan starts operating first. The heat recovery heat exchanger is regulated to recover heat at the maximum capacity. After one minute, the supply fan starts operating and the outdoor air damper is opened and normal regulation is continued. At ventilation

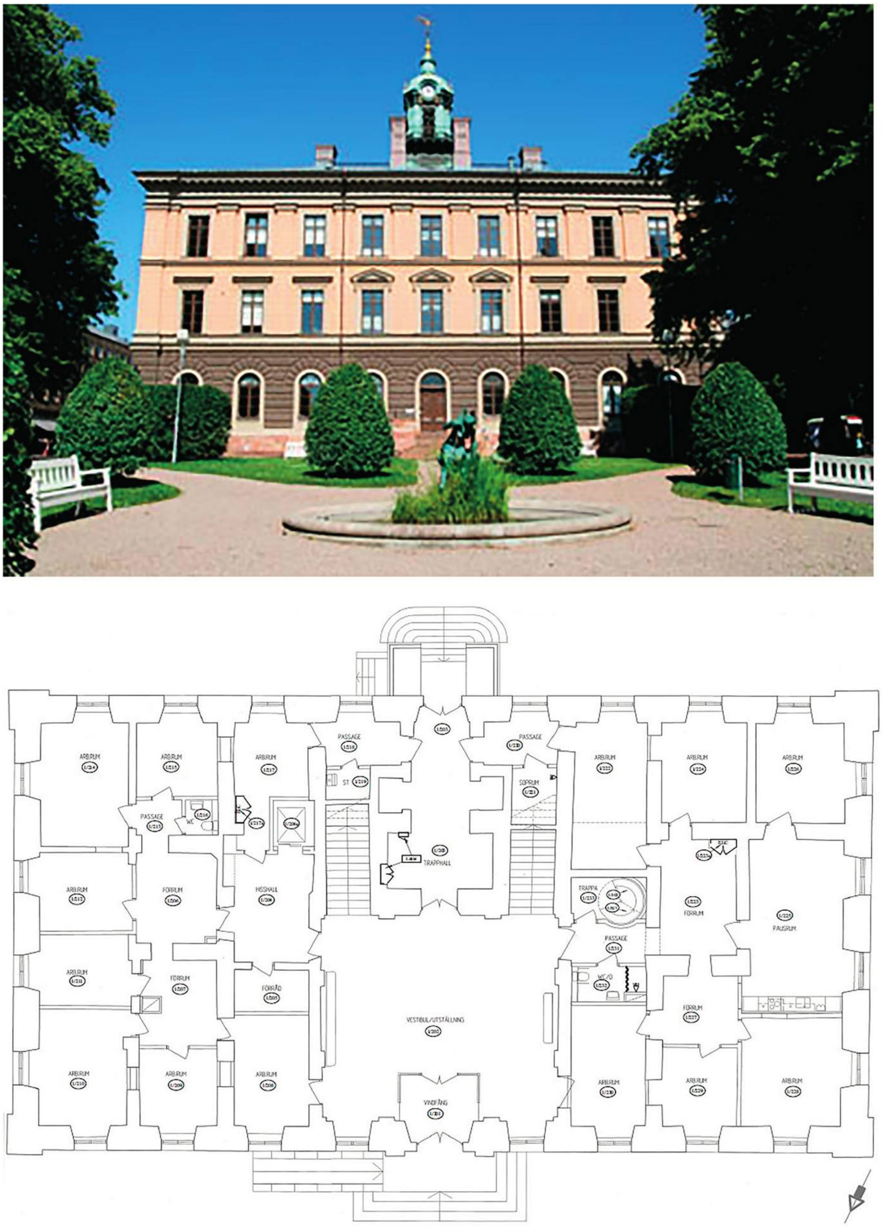

Figure 1. City Hall in Gävle (upper), first floor plan (lower). The arrow points to the north.

unit shut off, the outdoor air damper is closed. It is also possible to start the ventilation unit by the pushbutton timer. In such case, the ventilation unit is stopped after 120 min or by pushing the pushbutton timer again. Night cooling starts if certain circumstances happen together: (1) indoor temperature exceeds 23°C; (2) the ambient temperature is at least 2°C lower than the indoor temperature; (3) the ambient temperature is over 12°C; (4) the ventilation unit is not in ordinary operation; and (5) the time schedule of night cooling is active. The time schedule for night cooling is 01:00_05:00 during weekdays.

There are also thermostatic radiator valves (TRVs) on the radiators, with the setting 3–4 which usually corresponds to 20_23°C. Summer cooling comes from an electric heat pump that ejects heat into the exhaust ventilation air.

2. Method

Questionnaire surveys, on-site measurements as well as data logging were performed. All physical environmental variables required for calculating PMV/PPD indices were measured at all four heights (0.1, 0.6, 1.1 and 1.7 m) above the floor level according to ISO standard 7730 in a critical room located at the southeast-southwest corner on the first floor, hence categorized as Class I according to de Dear and Brager (1998).

2.1. Standardized questionnaire

In order to investigate the occupants' perception of indoor environment in a building, an epidemiological survey using a standardized questionnaire can be used (Rohdin et al., 2012). There are several types of standardized questionnaires in the literature, such as the Royal Society of Health (RSH) questionnaire developed by the British Building Research Establishment, which focuses on office buildings (Rohdin et al., 2012), the standardized questionnaires described in ANSI/ASHRAE Standard 55 and in NS/EN 15251 (Berge & Matisen, 2016), and Miljö Medicinsk (MM) questionnaire (The MM Questionnaires, 2014). The MM questionnaire for offices (MM 040 NA Office) was applied in this study since it is well-established and often used in Nordic countries in studies focused on investigating perceptions and experiences related to indoor climate. It carries out a retrospective assessment of thermal evaluation, in contrast to the questionnaires described in ANSI/ASHRAE Standard 55 and NS/EN 1521 in which the assessment of thermal sensation is done instantaneously based on a seven-point comfort scale (Berge & Matisen, 2016). The aim was to investigate the occupants' perception of indoor environment during two periods including summer 2016 and winter 2016 to spring 2017.

2.2. MM questionnaire

The first version of the MM-questionnaire for non-industrial workplaces was released in 1989 by the Department of Occupational and Environmental Medicine at Örebro University Hospital in Sweden (Andersson et al. 1993) after three years of being intensely tested regarding its validity, reliability and its practical application (Andersson 1998. Several versions exist for different environments such as schools, day care centres, offices, hospitals and residential buildings (Andersson 1998). The MM-questionnaire for offices (MM 040 NA Office) includes a total of ten categories of questions about:

(1) Background factors such as the location of the workplace, the position of the staff, working hours, etc.
(2) Disturbing factors in the work environment such as draught, too high room temperature, etc.

(3) Work conditions such as work load, support from fellow-workers, etc.
(4) Present symptoms in the work environment such as fatigue, headache, etc.
(5) Physical and psychological work environment such as being on sick-leave, etc.
(6) Temperature conditions such as too cold in winter, too warm in summer, etc.
(7) Cleaning situation in the work environment
(8) Noise in the work environment such as disturbing noise from ventilation, noise from outside, etc.
(9) Air quality like problems such as odours, problems in different periods of the day, etc.
(10) Other background factors such as date of birth, gender, education level, etc.

The questionnaire in this study only included multiple-choice questions about disturbing factors and symptoms present in the work environment followed by an open question where respondents were asked if they had experienced any other symptoms and/or environmental factors linked to indoor environment. The questions about the background of the respondent (the categories No. 1 & 10) were not included to ensure the anonymity of the respondents and also because they did not provide useful information for analysis of IEQ in the scope of this study. Additionally, a plan of the building was appended to the questionnaire in which the building was divided into four main zones for all floors and two more questions were added asking the respondents on which floor and in which zone their offices are located. Such division provided the opportunity to analyse the responses considering the different influences of solar radiation on indoor environment in various zones according to their orientation and height from the ground surface. This plan is shown in Figure 2.

Each zone contained several offices (at least three persons worked in each zone) and, in this way, the anonymity of the respondents was assured. The multiple choice answer alternatives included 'yes, often', 'yes, sometimes' and 'no, never'. Web-based questionnaire was sent to staff twice via email: in the middle of September 2016 and February 2017. The respondents had three weeks to answer the questions online and two reminder emails were sent. A total of 23 and 36 responses were collected for summer and winter cases which led to response rates of 76% and 65% respectively. The majority of employees worked at single or two-person offices, while a few had their workplaces located in open-

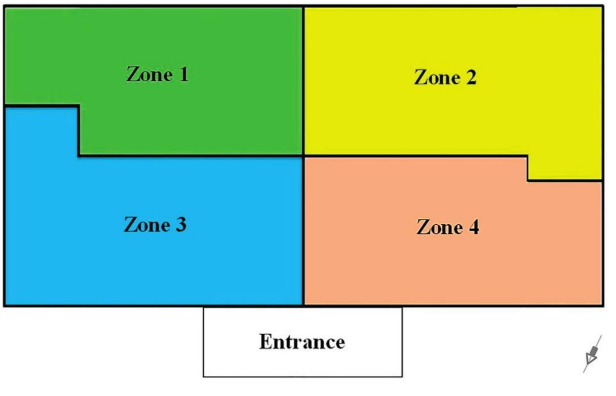

Figure 2. Building plan divided into four zones per floor. The arrow points to the north.

space offices. To analyse the responses, these were compared with two reference materials of the MM-questionnaire. Reference 1 is representative of well-functioning and healthy buildings, i.e. the buildings without known indoor climate problems. The reference data was created in 1989 based on the results of a study of seven offices and two schools which were considered healthy. Reference 2 represents typical Swedish office buildings created from 91 office buildings dispersed all over Sweden, in some cases with indoor climate problems (The MM Questionnaires Manual Work Environment, 2014).

2.3. Data logging on the building management system (BMS)

Room air temperatures in different offices were logged on the building management system during summer (August 2016) at ten-minute time intervals. The BMS temperature sensors in offices are attached to the wall 1.7 m above the floor.

2.4. On-site measurements

According to literature, there are two different approaches regarding studies on thermal comfort: climate-chamber and field-study approaches, which have led to steady-state models and standards (like ASHRAE 55-1992 and ISO7730) and adaptive thermal comfort models and standards (like ASHRAE 55-2010 and EN15251), respectively. In the former, the personal parameters (metabolic rate and clothing insulation) are determined by the task and assumed to be constant and the environmental parameters are measured. In the latter, thermal comfort is studied in the real world while subjects continue their daily routine in the place. In most cases, clothing insulation and metabolic rate are recorded. Cultural and psychological parameters could also affect the studies (Taleghani, Tenpierik, Kurvers, & Dobbelsteen, 2013). The steady-state model based on standard ISO 7730 (ISO, 7730, 2005) was used to perform thermal comfort measurements in this study. This standard was developed for evaluation of moderate thermal environment and Swedish national standards organizations are bound to implement it. Thermal comfort measurements were done using the thermal comfort data logger in one of the office rooms. The equipment consisted of four transducers for measuring operative temperature, air humidity, air velocity, and air temperature, which were attached to a vertical rod at the same height. It was possible to adjust their height through the length of the rod. A logger time stamped and saved the transducers measured values and calculated the thermal comfort indices. According to ISO 7730, metabolic rate was set at 1.2 met corresponding to sedentary activity in the office and clothing insulation was determined as 0.5 clo during summer and as 1.0 clo during winter (1 met = 58.2 W/m^2 and 1 clo = 0.155 $m^2.K/W$). The technical specifications of the thermal comfort data logger as well as the transducers are presented in Table 1.

During winter, two sets of measurements were carried out. Short-term measurements with negligible contribution of direct solar radiation were done on 22 February 2017 on a cloudy day in three different locations in the room (in the middle of the room, in front of the window, at the corner of the room) at four heights (0.1 m, 0.6 m, 1.1 m, 1.7 m) and at one-second time intervals over 10 min. The different heights correspond to ankle level (0.1 m), the middle of the body while seated (0.6 m), neck level while seated as well as the middle of the body while standing (1.1 m) and neck level while standing (1.7 m).

Table 1. Technical specifications of thermal comfort data logger – 1221.

Manufacturer	INNOVA (Air teck instruments)		
Model	Thermal comfort data logger – 1221		
Transducers	Model	Measurement range	Accuracy
Air temperature	MM0034	−20°C to + 50°C	5°C to 40°C range: ±0.2°C −20°C to 50°C range: ±0.5°C
Air velocity	MM0038	0–10 m/s	$V_a < 1$ m/s: $\pm(0.05\ V_a + 0.05)$m/s[a] $1 < V_a < 10$ m/s: typically better than $\pm 0.1\ V_a^b$ and $\pm 0.25\ V_a^c$ 2% drop in displayed reading[d]
Air humidity	MM0037	$T_a - T_d < 25$°C[e]	$T_a - T_d < 10$K: ±0.5 K or ± 0.05 kPa $10\ K < T_a - T_d < 25$K: ±1.0 K or ± 0.1 kPa
Dry heat loss[f]	MM0057	−20°C to + 50°C	5°C to 40°C range: ±0.5°C −20°C to 50°C range: ±1.0°C

[a]For any flow direction greater than 15̊ from rear of transducer axis.
[b]For flow directions perpendicular to transducer axis.
[c]For flow directions more than 15̊ from rear of transducer axis.
[d]Displayed reading will drop 2% when a standard 6 m extension cable is used.
[e]Dew-point range: Ta is the air temperature and Td is the dew-point temperature.
[f]Used also for measuring operative temperature.
Sources: LUMASENSE TECHNOLOGIES (2007) and INNOVA _ Air Teck Instruments (2007).

Figure 3 shows the three locations of measurements in the mentioned room. For locations 2 and 3, according to ISO 7730, measurements were performed 0.6 m away from wall surfaces. Long-term measurements were continuously carried out only at the corner of the room and at the height of 1.1 m at 15-minute time intervals for one week from 22 February to 1 March 2017.

During summer, measurements were performed in the same locations and heights in the same office room on a sunny day on 11 August 2017 at one-second time intervals over 5 min. Due to time shortage, the measurements in the middle of the room were

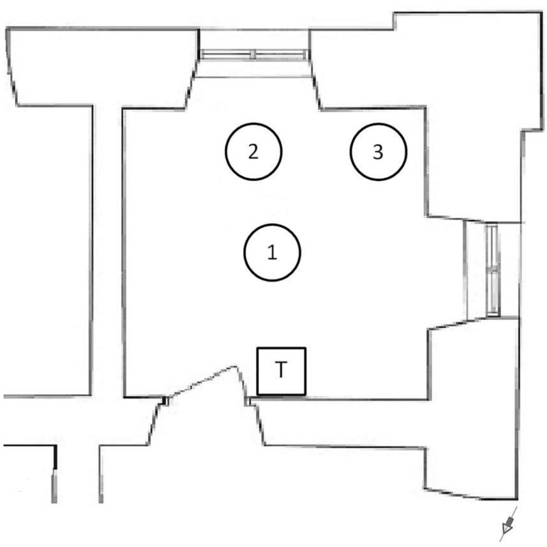

Figure 3. Measurement locations in the representative room. The arrow points to the north.
Note: T represents the room thermostat.

performed on another sunny day on 14 August. To capture the difference between the operative temperature in front of the window with no internal shading (location 2 in Figure 3) and in front of the room thermostat (T in Figure 3), measurements in these two locations in that room were carried out on a sunny day on 24 May 2017. The same measurements were also done in another office room with internal shading on 11 August 2017. Finally, to investigate the difference in operative temperatures in front of the window with no internal shading (location 2 in Figure 3) in the mentioned room in two cases of sunny and cloudy weather, measurements were done in this location on a partly cloudy day on 6 June 2017.

Thermal comfort indices were calculated by thermal comfort data logger using the equations which are available in the ISO 7730 standard. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) were calculated for the heights of 0.6 and 1.1 m to illustrate thermal state of the body as a whole for a seated and a standing person respectively (ANSI/ASHRAE Standard 55, 2013).

3. Results and discussion

Based on the replies to the MM-questionnaire, the prevailing environmental disturbing factors and symptoms caused by inappropriate indoor environment in the offices compared to references 1 and 2 during summer and winter are presented in Figures 4 and 5. The dissatisfaction percentages were calculated based on the number of 'yes, often' responses.

Analysis showed that complaints about stuffy 'bad' air, unpleasant odour and too high room temperature were reported extremely more frequently compared to reference 1 during summer. Complaints about lighting problems, noise, varying room temperature (variation over time) and too low room temperature were also respectively higher than data from reference 1. During winter, the highest percentage of complaints was about lighting problems and noise. Dissatisfaction with stuffy 'bad' air, varying room temperature, too low room temperature and draught were also respectively higher than data from reference 1. Regarding the present symptoms, feeling heavy headed and irritation of the eyes during summer and feeling heavy headed during winter accounted for the highest dissatisfaction percentage. Except for dry or flushed facial skin during summer and irritated, stuffy, runny nose and cough during winter, complaints about all other symptoms were higher than data from reference 1 for both periods. In comparison with typical Swedish office buildings (reference 2), the situation was similar to when comparing to reference 1 with only some differences. Percentage of complaints about too low room temperature and fatigue during summer and about draught, stuffy 'bad' air, fatigue, headache and dry throat during winter were acceptable by reference 2.

Complaints about unpleasant odour decreased drastically in winter to an acceptable level based on reference 1. The main reason could be water leakage in the basement during summer which was resolved before winter. One staff member also mentioned this problem in their response. Dissatisfaction with symptoms like irritated eyes, irritated/stuffy/runny nose, dry throat and cough (which are typical in winter) was surprisingly higher in summer. One reason could be that the respondents were informed about the mould problem caused by water leakage in the basement while the questionnaire related to summer period was available online and this might have affected their

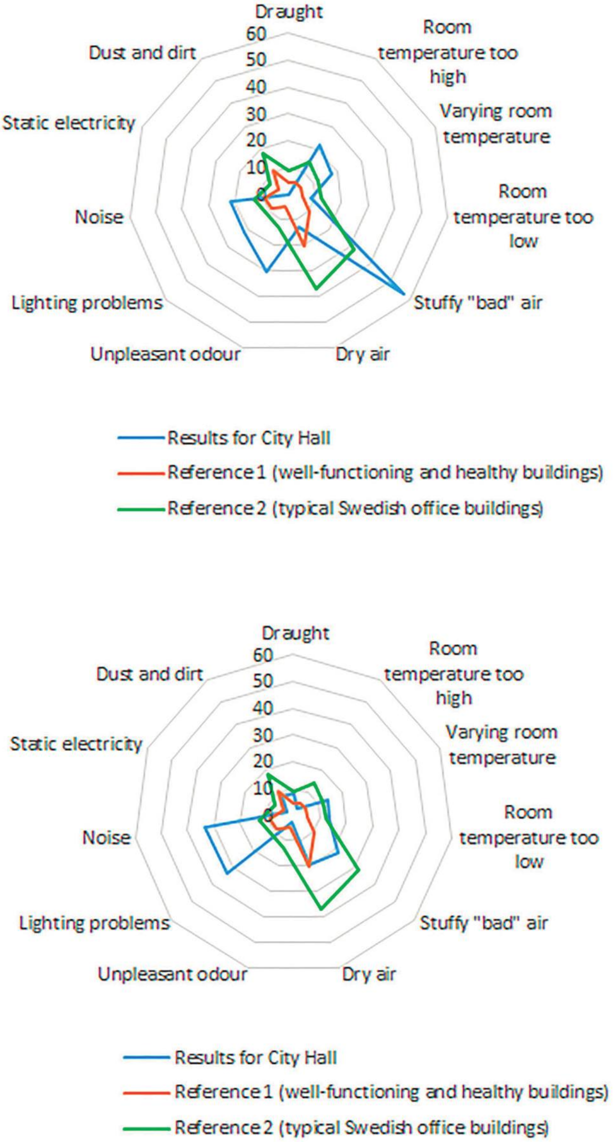

Figure 4. Environmental disturbing factors during summer (upper) and winter (lower)

replies. Regarding the reasons for some symptoms, one respondent blamed the unpleasant odour and stuffy air as the cause of stuffy nose and headache during summer. Some others mentioned noise as the cause of fatigue and heavy- headed feeling and lighting problems as the reason for concentration difficulties and fatigue during winter.

In January 2017, more employees moved from another building with fairly calm surroundings to City Hall, which is affected by more noise caused by traffic. This could be one reason why complaints about noise were higher during winter. Some respondents

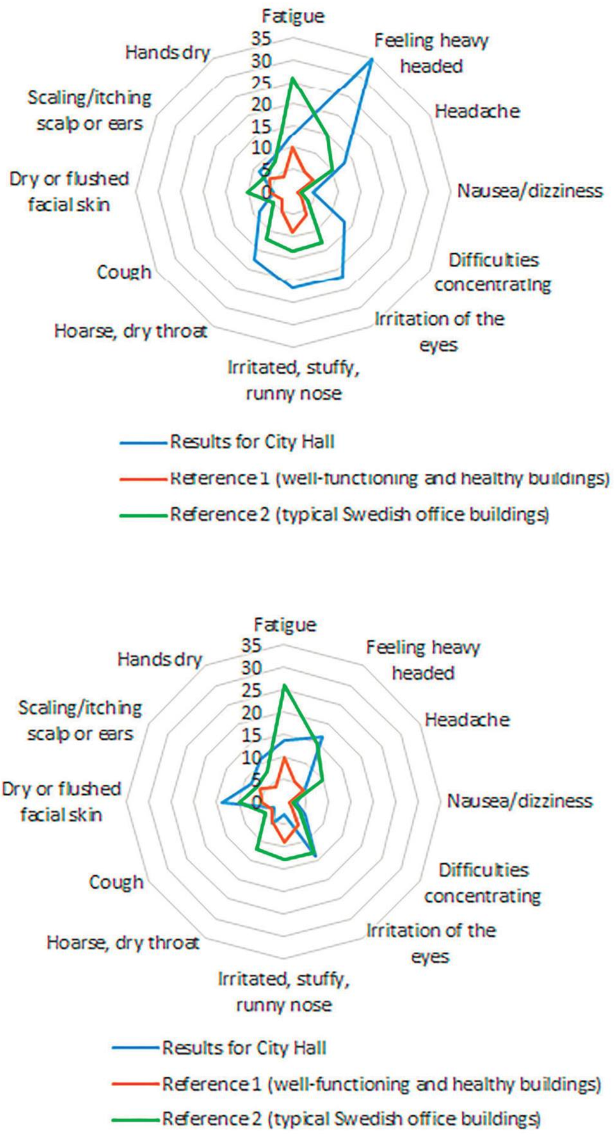

Figure 5. Symptoms caused by inappropriate indoor environment during summer (upper) and winter (lower).

also connected the noise problem to the fact that more than one employee works in one room in some offices. A cause for too high room temperature during summer could be that the cooling system was out of order. A main problem which was revealed through inspection of the building and also through a short interview with one staff member was that room thermostats did not work. One reason could be that the cooling system malfunctioned, but the dampers of the ventilation system also did not seem to work in all offices, most likely due to control strategy problems.

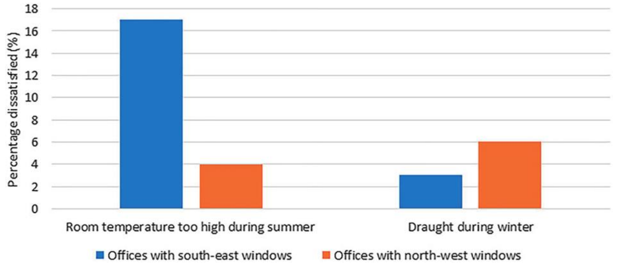

Figure 6. Comparison between offices with different façades based on questionnaire responses.

An analysis was also done for different offices. Figure 6 illustrates the results of this analysis. There was more dissatisfaction with draught during winter in offices facing north-west and with too high room temperature during summer in the ones facing southeast. This could be related to receiving more solar radiation on the southeast façade. The ranges of logged temperatures in different zones during August 2016 are shown in Figure 7. It is shown that zones 1 and 2 experience higher room temperatures than zones 3 and 4. This confirms the results of the analysis done for various zones based on questionnaire responses.

According to Figure 7, air temperatures logged on BMS could reach over 25°C during some periods in some zones while it was often between 22 and 23°C in zones 1 and 2 and between 21 and 22°C in zones 3 and 4. In addition, according to thermal comfort measurement results (on-site measurements) in sunny weather in the mentioned room, operative temperature in front of the window with no internal shading was 1.3°C higher than in front of the room thermostat, while in another office with internal shading (roll screens) in sunny weather, there was almost no difference in operative temperature between these two locations. Therefore, on-site measurement results and BMS logged data do not clearly illustrate the disturbing factor of 'Too high room temperature'. Considering that northeast windows do not have internal shading in four offices in the building, one could only argue that either office air temperatures higher than the prevailing ones in the zones (according to Figure 7) could be perceived as too high by some employees or some personnel could suffer from local too high operative temperatures as a result of solar radiation.

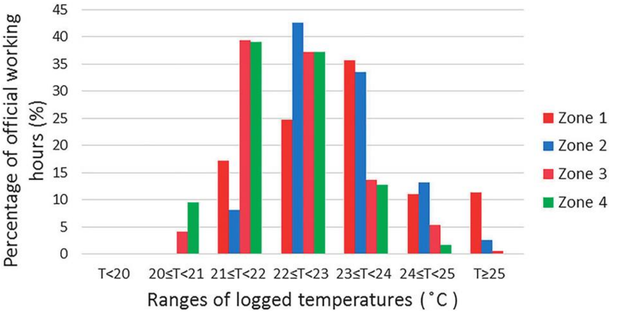

Figure 7. Ranges of logged air temperatures in different zones on BMS during August 2016.

On-site thermal comfort measurements during the partly cloudy day in the selected room showed that operative temperature in front of the window with no shading was 1.2°C higher during sunny compared to cloudy weather. This could be a reason for complaints about varying room temperature.

BMS-Logged air temperatures of some selected rooms on 1 August 2016 between 06:00_18:00 are presented in Figure 8(a–f). These are the rooms with southeast, southwest and northeast windows which tend to receive more solar radiation during summer in comparison with other rooms, leading to higher room air temperatures. The selected rooms experienced higher air temperatures on the first day of August compared to other days of the month, which is why logged data for this date are presented. The time period 06:00_18:00 was selected based on the ventilation units' schedules according to operation description documents.

As shown in Figure 8(a–f), the rooms located on the left half of the building at the southeast-southwest corners tend to have higher air temperatures in the afternoons and close to end of working hours compared to other rooms with northwest windows, due to more solar gain through southwest windows. On the third (last) floor (probably due to less shading effect from surrounding buildings as well as the impact of stratified air temperature in the building), the air temperature in the southeast-southwest corner room goes up to nearly 28°C at the end of the day. It could also be another argument for complaints about too high and varying room temperatures during summer.

According to Figure 8(a), (c) and (e), rooms with only northeast windows have relatively high room air temperatures at the beginning of the day due to early morning solar gain through the window and also the fact that there is no ventilation turned on before 06:00. These air temperatures are higher in such rooms on higher floors for the same reason as mentioned previously. The air temperature in the room with only one northeast window on the second floor is surprisingly very high at the beginning of the day. It could be due to direct solar radiation hitting the room thermostat. However, following the apparent movement of the sun in the sky, the room air temperature drops quickly (after around one hour) and does not change dramatically during the day.

On the other hand, as Figures 8(a–f) depict, rooms with only southeast or southwest windows have very similar (relatively low) air temperatures at the beginning of the day due to the lack of solar gain through the window, while they rise during the day as the building's southeast and southwest façades receive solar radiation. Air temperatures in rooms with southeast windows start to rise earlier and in the rooms with southwest windows rise fast in the late afternoon. According to Figure 8, probably due to stronger shading effect from the surrounding buildings, this causes more changes in the air temperature of the room with only one southeast window on the first floor. This could also be a probable reason for complaints about varying room temperatures. It goes without saying that, additionally, changes in internal loads in the rooms could also cause (especially random) changes in the room air temperatures.

The average ambient temperatures during the periods when thermal comfort measurements were carried out are presented in Table 2. The calculated PMV and PPD in the selected room for the summer period are shown in Table 3. Except for a seated person in the middle of the room, for all other cases PMV > +0.5 and PPD > 10%. Draught rate (DR) was zero in all locations for both ankle level and neck level for a seated person. Vertical air temperature differences between head and ankles are presented in Table 4.

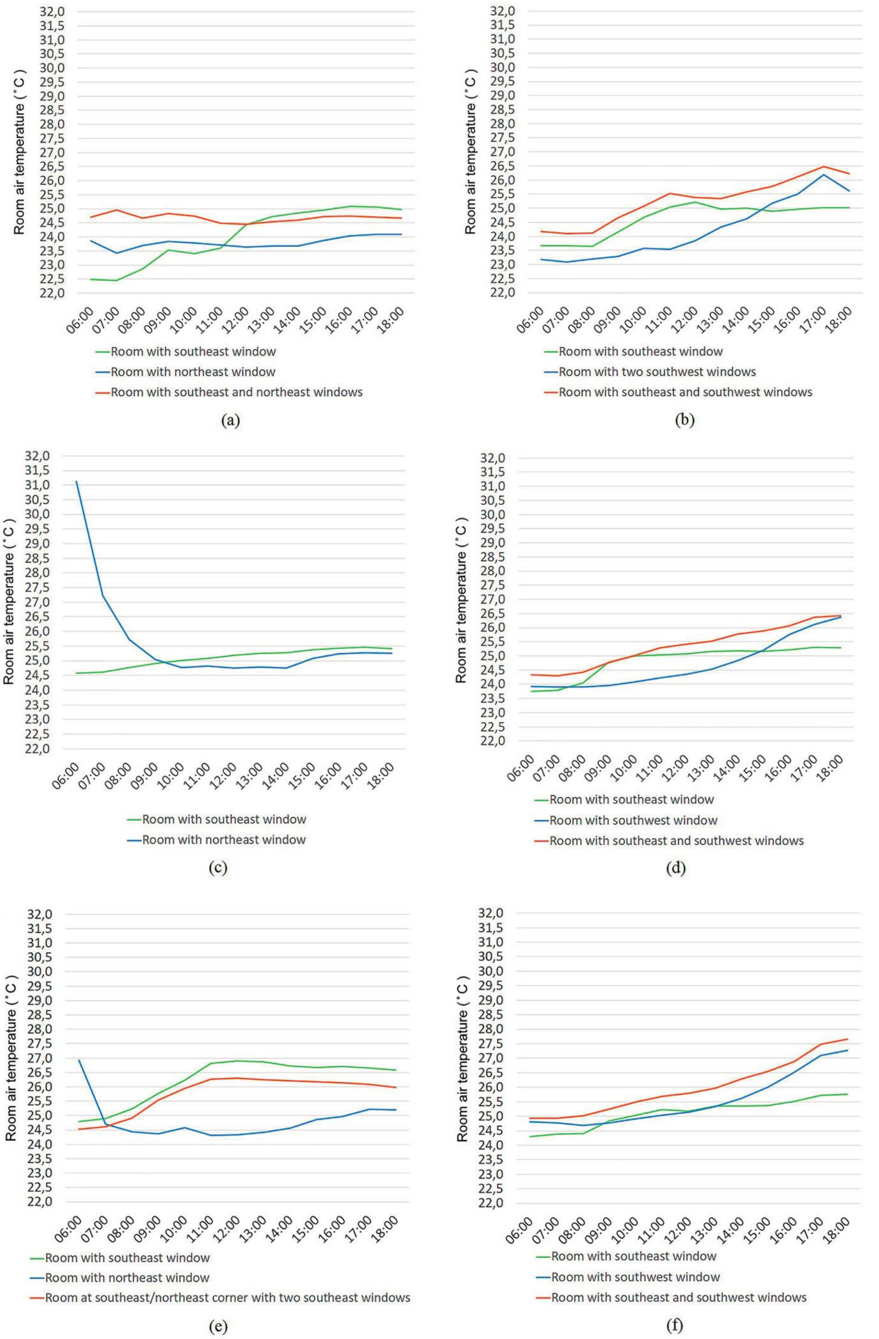

Figure 8. Logged air temperatures of selected rooms on BMS on 1 August 2016 in (a) and (b) 1st floor, (c) and (d) 2nd floor, (e) and (f) 3rd floor. ** Data is not logged on the building management system (BMS) for the room with both southeast and northeast windows in the right half of the building on the second floor (8 c).

Table 2. Average ambient temperatures during thermal comfort measurement periods[a].

Measurement period	Average ambient temperature (°C)
22 February	0.5
24 May	14.2
11 August	24.9
14 August	21.4

[a]Ambient temperature for June 6th failed to be logged on the building management system.

Table 3. The calculated PMV and PPD in the representative room during summer.

	0.6 (m)[a]		1.1 (m)[b]	
	PMV	PPD (%)	PMV	PPD (%)
In the middle of the room	0.5	9.9	0.6	11.8
In front of the window	0.6	13.3	0.6	13.5
At the corner of the room	0.6	11.9	0.6	12.8

[a]The values represent PMV/PPD for the body as a whole for seated person.
[b]The values represent PMV/PPD for the body as a whole for standing person.

Table 4. Vertical air temperature differences in the representative room during summer

	Vertical air temperature difference (°C)
In the middle of the room	0.9
In front of the window	1.3
At the corner of the room	1.1

The calculated PMV and PPD in the mentioned room for winter period are shown in Table 5. In all three locations for both a seated and a standing person, PMV > −0.5 and PPD < 10%. Draught rate (DR) at the neck level for a seated person in front of the window is 19.3% and for all other cases is zero. Vertical air temperature differences between head and ankles are presented in Table 6. The calculated PMV and PPD in the selected room for winter period during the one-week period are shown in Table 7. For a standing person at the corner of the room, PMV > −0.5 and PPD < 10. Draught rate (DR) at the neck level for the seated person at the corner of the room is zero.

ISO 7730 describes the desired thermal environment for a space as presented in Table 8. Accordingly, during summer, thermal comfort for the body as a whole is only achieved for a

Table 5. The calculated PMV and PPD in the representative room during winter.

	0.6 (m)[a]		1.1 (m)[b]	
	PMV	PPD (%)	PMV	PPD (%)
In the middle of the room	−0.3	6.6	−0.2	6.1
In front of the window	−0.3	6.3	−0.4	7.7
At the corner of the room	−0.4	8.7	−0.3	6.8

[a]The values represent PMV/PPD for the body as a whole for seated person.
[b]The values represent PMV/PPD for the body as a whole for standing person.

Table 6. Vertical air temperature differences in the representative room during winter.

	Vertical air temperature difference (°C)
In the middle of the room	1.2
In front of the window	1.8
At the corner of the room	0.9

Table 7. The calculated PMV and PPD in the representative room during winter for one week.

	1.1 (m)[a]	
	PMV	PPD (%)
At the corner of the room	−0.3	7.3

[a]The values represent PMV/PPD for the body as a whole for standing person

Table 8. The desired thermal environment for a space based on ISO 7730.

Acceptable ranges of thermal comfort indices
−0.5 < PMV < +0.5
PPD < 10%
DR < 20%
Vertical air temperature difference < 3°C

seated person in the middle of the room. However, there is no local discomfort in any of the three locations. During winter, thermal comfort for the body as a whole with no local discomfort is achieved for both a seated and a standing person in all three locations.

The environment is thermally comfortable in the selected office room during winter. However, draught rate at neck level for a seated person in front of the window had a narrow margin with the maximum acceptable draught rate (20% according to ISO 7730). Moreover, the measurements were done 1.5 m away from the window surface and seven employees worked in their offices close to the window (about 1.3 m away from the window surface). This may cause a feeling of draught for these persons. Staff might experience the same problem if they sit close to the ventilation supply devices. All in all, it is in agreement with results derived from questionnaire responses showing that only a few people complained about draught during winter.

To sum it up, the questionnaire results primarily indicate that thermal comfort problems appear during the summer season, whereas both questionnaire and measurement results point to that winter thermal comfort is satisfactory – but not exceptionally good. In a cold climate, retrofitting of historic building design focuses on the trade-off point between energy use and thermal comfort during the heating season. However, summer issues concerning large window areas, absence and prohibiting of shading devices (building code restrictions), high ambient summer temperatures might not have been foreseen as a problem, since the building is situated in a cold climate. Future research should in these cases focus on making HVAC systems more efficient and investigate how both heating and cooling loads can be reduced, independently of hot or cold climate.

Finally, a short interview with one of the employees who explained the indoor climate during summer 2017 in zones 2 and 4 on the second floor shed light on some probable reasons for some of the disturbing factors in these zones. She gave these comments:

> 'In my office, the window is not properly acoustically insulated but the level of noise with the closed window is still tolerable. The main issue is the stuffy air which forces one to open the window which, in turn, exacerbates the disturbing noise from outside. Attempts to decrease the room temperature to overcome the stuffy air problem fail since adjusting the room thermostat has no effect. In the other office with two windows facing southeast and southwest, the staff suffers from too high temperature during the day even with internal shading. Due to high ceilings, proper lighting is not provided in the corridor of the zone. Finally, the City Hall in Gävle is a really beautiful historic building but with problems for the staff's comfort!

4. Conclusion

The indoor environment in the historic City Hall in Gävle is unsatisfactory compared to well-functioning and healthy reference Swedish office buildings (according to questionnaire results). Stuffy air, too high, too low and varying room temperatures, lighting problems and noise are constant issues during both summer and winter. Though this building has been equipped with a modern mechanical ventilation system, it illustrates that the typical historic building thermal comfort issues have not completely been resolved. This also indicates that there should be possibilities for further improving thermal comfort by improved control strategies, since upgrading the building's envelope, which risks changing the buildings external characteristics and appearance, is not permitted according to the Swedish Building Regulations in historic buildings with heritage value. The results presented particularly pertain to the summer/non-heating period, since thermal comfort during the winter period is not a problem as pointed out in both measurements and questionnaire results. This indicates that modern HVAC systems in cold climates may improve conditions concerning 'traditional' historic building winter problems but have summer problems since there often are no design requirements and focus on design issues during summer conditions in cold climates.

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Paper II

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Article

On the Performance of Night Ventilation in a Historic Office Building in Nordic Climate

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Abstract: The effect of mechanical night ventilation on thermal comfort and electricity use for cooling of a typical historic office building in north-central Sweden was assessed. IDA-ICE simulation program was used to model the potential for improving thermal comfort and electricity savings by applying night ventilation cooling. Parametric study comprised different outdoor climates, flow rates, cooling machine's coefficient of performance and ventilation units' specific fan power values. Additionally, the effect of different door schemes (open or closed) on thermal comfort in offices was investigated. It was shown that night ventilation cannot meet the building's total cooling demand and auxiliary active cooling is required, although the building is located in a cold climate. Night ventilation had the potential in decreasing the percentage of exceedance hours in offices by up to 33% and decreasing the total electricity use for cooling by up to 40%. More electricity is saved with higher night ventilation rates. There is, however, a maximum beneficial ventilation rate above which the increase in electricity use in fans outweighs the decrease in electricity use in cooling machine. It depends on thermal mass capacity of the building, cooling machine´s coefficient of performance, design ventilation rate, and available night ventilation cooling potential (ambient air temperature).

Keywords: night ventilation; historic buildings; office buildings; building energy simulation; IDA-ICE; Nordic climate

1. Introduction

The European Union (EU) has set an objective to be climate neutral by 2050. This implies that 80–95% reduction in greenhouse gas (GHG) emissions, compared to the 1990 levels, needs to be achieved through pursuing the most energy efficient and economically feasible measures. It is estimated that the EU building sector accounts for about 36% of CO_2 emissions and 40% of used energy [1] and over 25% of buildings are historic [2]. Therefore, one of the main measures to achieve these goals is to focus on improving energy efficiency in the building sector, including historic buildings.

One part of energy use in buildings, especially for office and commercial buildings, is cooling demand. Night ventilation (NV) is one of the promising techniques which has shown to significantly reduce buildings' cooling demand and improve thermal comfort [3], specifically when applied to massive/heavy buildings [4]. This is an indirect way of cooling in which the building is ventilated with colder ambient air during nighttime to cool down its structural elements. The cool fabric can then absorb the heat flows the following day and provide comfort by reducing both the indoor air and wall temperature rises.

The efficiency of NV is strongly dependent on some main parameters: (1) daily amplitude of the ambient temperature (higher effectiveness with higher amplitude; specifically with lower minimum ambient temperature), (2) the difference between indoor and ambient temperatures mainly during night period, (3) the NV rate, (4) the NV operation period and duration, (5) the thermal capacity of the building, and (6) efficient coupling of air flow and thermal mass (an example of inefficient coupling is short circuit air flow through the windows) [5].

Some studies have evaluated the effect of climatic situations (including the ambient temperature) on the potential of NV strategy. Artman et al. [6] showed that Northern European climates (including the British Isles) offer a significant potential for cooling by NV, while in Central, Eastern and even some regions of Southern Europe, additional cooling systems are required to fulfill thermal comfort during a series of warmer nights at some locations. It was depicted that in southern Spain, Italy and Greece, NV might be promising for hybrid systems. Another study by Artmann et al. [7] assessed the influence of the future climate warming on NV potential and showed that by 2071–2100, the decrease in mean cooling potential will be in the range of 12.5–37.5 W/m^2, depending on season, location and the emission scenarios. Jimenez-Bescos [8] simulated the effect of the future climate scenarios on the required NV rates with the help of thermal mass for reducing overheating in the buildings located in London Islington. It was shown that while NV rates over eight air changes per hour (ACH) could provide significant overheating reductions in the short term, in the long term, the 2080s, NV rates less than 10 ACH have very low influence for this purpose, less than 3% and 8% for high and medium emissions scenarios, respectively. Kolokotroni et al. [9] simulated how urban heat island phenomenon can increase the building summer cooling demand and deplete the NV potential. They showed that, during a typical hot week and in the same location, the rural reference office has 84% of the cooling demand of the urban one. It also depicted that a rural optimized office, unlike an urban one, could maintain temperatures below 24 °C without artificial cooling and would need 42% of the cooling required for an urban optimized office.

Several parametric studies using Building Energy Simulation (BES), pointed out the important influence of different building design and operational parameters including thermal mass of the building [10], NV rate [11,12] and NV period and duration [12] on the effectiveness of NV strategy in different climatic conditions. The results of some studies have shown more than 60% cooling load reduction by increasing building time constant between 400–1000 h [13], up to 3 °C reduction in peak indoor air temperature for high thermal mass [5,14], 2–3 °C reduction in indoor temperatures by doubling the building mass (800 kg/m^3 to 1600 kg/m^3) [15], and 3–6 °C indoor temperature decrease depending on the amount of thermal mass, the rate of NV, and the temperature swing of the site between day and night [16].

The higher the NV rate, the higher the effectiveness of the strategy; there may exist some thresholds, however. The results of some parametric studies using BES have depicted the achievable reduction of the peak indoor temperature up to 1 °C as well as attained comfort criteria with NV rates lower than 10 ACH for Spanish climates (further increases produced marginal improvements) [17] and for maritime Irish climate [15]. Some studies have shown reduction in the mean radiant temperature of building's indoor surface up to 3.9 °C at 8:00 am with NV rate of 10 ACH for the Northern Chinese climate [4], and a 39–96% decrease in the overheating hours (with natural NV) and 48–94% energy reduction (with air conditioning systems) with the NV rates of 10–30 ACH for the Greek climate (Athens) [5].

Different suggestions have been proposed regarding the influence of NV runtime (including the start point and the duration) on the effectiveness of NV strategy. They include, among others, NV duration with 5 a.m. in the middle of the period (such as 4 a.m. to 6 a.m.) [18] and longer NV duration and closer NV period to the active cooling period [4,12,19,20].

Many parametric studies, using BES, investigated the influence of NV strategy on both improvement of thermal comfort and reduction of energy use for active cooling in office buildings. Some studies have shown the potential of NV in the form of determining the optimal NV flow rate over which further increase in ventilation rate, produces marginal improvements in thermal comfort in the building; dependent on the thermal mass capacity of the building [4,5,17]. These studies, afterward, calculated the amount of saved energy for active cooling based on this maximum beneficial ventilation rate. However, for mechanically driven NV, the electricity use in ventilation unit's fans needs also to be taken into account. In other words, the maximum beneficial NV rate is the ventilation rate which results in the minimum total energy use which consists of energy use for active cooling plus electricity use in ventilation unit's fans. For NV rates above this maximum limit, the amount of increase in electricity use in fans outweighs the amount of decrease in energy use for active cooling and, therefore, the total energy use starts increasing.

Lain and Hensen [21] performed a parametric study on the optimization of mechanical NV system in an office building, including two NV rates and the mechanical cooling system's coefficient of performance (COP) 2.5. They illustrated that due to the relatively high COP value, the electrical energy use in the fans can outweigh even the large cooling energy savings by NV. However, they did not evaluate the potential of NV for other COP values. In fact, cooling systems with lower performance, lower COP values, might result in higher potential of NV for cooling energy savings. The evaluation of NV potential for cooling energy savings for various cooling system's COP values has not been widely covered in the literature and a research gap is recognized in this area.

Guo et al. [22] evaluated the influence of the key design parameters on NV performance indicators using a holistic approach integrating sensitivity and parametric simulation analyses. They concluded that the window-wall ratio, internal convective heat transfer coefficient, internal thermal mass level, and NV rate are the most important parameters. Percentage outside the range (POR), from the thermal comfort improvement category, ventilative cooling advantage (ADV), from the energy efficiency category, and cooling requirements reduction (CRR), from the ability to reduce cooling energy use category, were recommended to evaluate the NV performance.

In the present study, the effect of mechanical NV strategy on both thermal comfort and electricity use for cooling of a typical historic office building in north-central Sweden was assessed. The NV performance indicators from thermal comfort improvement and energy efficiency categories were used in the assessment. In the former, POR was applied and, in the latter, the total electricity use for cooling, comprising the electricity use in cooling machine plus the electricity use in ventilation system, was compared in different cases. The IDA indoor climate and energy (IDA-ICE) simulation program was used to model the potential for improving thermal comfort and electricity savings by applying NV cooling. The parametric study comprised different outdoor climate conditions, flow rates, cooling machine´s COP and ventilation unit's specific fan power (SFP) values. In addition, the effect of different door schemes (i.e., open doors or closed doors) on thermal comfort in the offices was investigated.

2. Case Study

This study is based on the design and structure of the City Hall of Gävle in Sweden. The City Hall is a typical historic building, refurbished to an office, with the usable floor area of around 2100 m^2. A detailed description of the building was presented in the previous published paper by Bakhtiari et al. [23]. The building consists mainly of 66 spaces: small office rooms, corridors, open-plan offices/seminar rooms, stairwells/entrance halls, with heavyweight construction and large windows. The height of each floor level is around 4 m, except for the open-plan offices/seminar rooms (around 5 m). The parametric study has been performed based on the third floor of the four-story building, which is a representative floor level. The building of the City Hall of Gävle is shown in Figure 1.

Figure 1. The building of the City Hall of Gävle (photo: Abolfazl Hayati).

3. Materials and Methods

Methods used in this study include on-site measurements, including logging on the building management system (BMS), and applying a BES tool. An overview of the methods is shown in Figure 2, and it can be divided into five main steps. In the first step, the input and calibration data were collected from on-site measurements and BMS logging, and the initial BES model of a non-occupied zone was created. In the second step, the BES model of the zone was calibrated. The final calibrated BES model included the construction materials normally used at the time the City Hall was constructed [24]. In the third step, the BES model of a representative floor level was created with the same construction materials as the second step. In the fourth and fifth steps, using the floor-level BES model, the thermal comfort and energy use analyses were carried out.

3.1. Calibration

The numerical analyses were carried out using the dynamic simulation software IDA-ICE version 4.8. IDA-ICE has been tested and validated according to various international and standard tests [25–29].

The aim was to simulate a floor plan of the building for the parametric study. In order to get the materials and the thermal performance of the structures reasonably accurate, a simulation model of a non-occupied office room was calibrated. The IDA-ICE simulation program supports only one-dimensional heat transfer, while the windows have niches which are two-dimensional thermal bridges. The niches were modelled as equivalent walls with one-dimensional heat transfers and the equivalent thicknesses were calculated using COMSOL Multiphysics (CM) simulation program version 5.3.

The modeled building in IDA-ICE is oriented with 40° clockwise from north which was measured on site. The shading effects of neighboring buildings were modelled by non-transparent bars (shading building) based on estimated heights and distances to the building of the City Hall using on-site observation.

3.2. Calibration of One Zone

In order for BES models to be used with any degree of confidence, it is necessary that the model closely characterizes the actual behavior of the building. The purpose of model calibration is to decrease the discrepancies between BES and measured building performance.

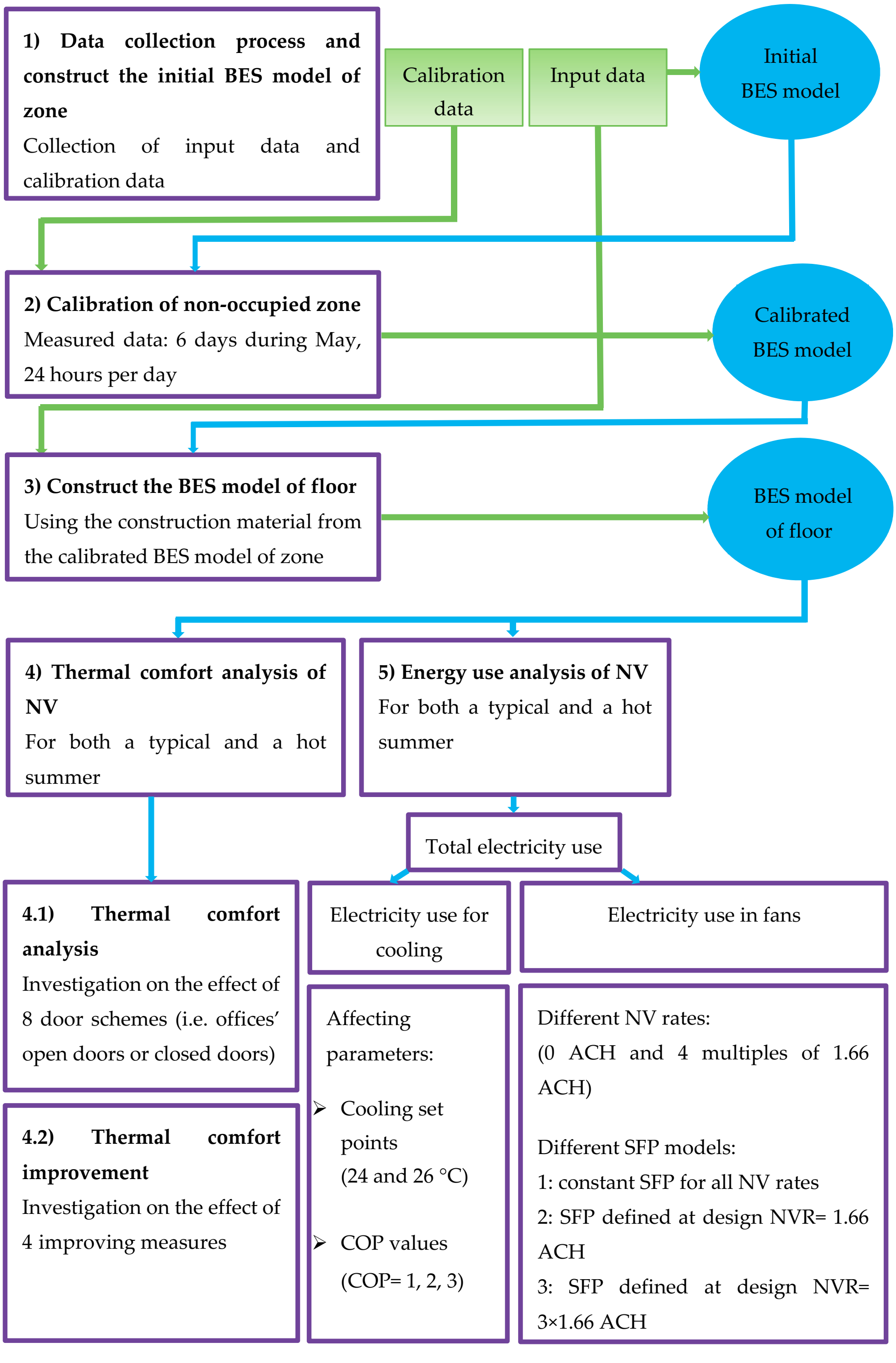


Figure 2. Overview of the research process.

With the aim of calibrating the BES model, a set of detailed measurements were done in a non-occupied office room in the building, with mechanical ventilation turned off. The room was situated on the last floor facing northwest with the minimum solar radiation during the day. The room size was 4 × 3.2 m and the floor–ceiling height was 2.9 m. The window size was 1.3 (width) × 2.6 m (height) and without internal shading.

The calibration of the office's BES model was done based on the heating demand of the office during the measurement period. An electrical radiator in which the operative temperature was controlled by the thermostat was applied in the model.

A manually tuned iterative process of simulation runs aiming at reducing discrepancies between simulated and measured data was used for calibrating the model of the selected office room. The iterative process was performed by calculating two principal uncertainty indices at each runtime including Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) [30].

The calibration indices were calculated as follows:

$$NMBE = \frac{1}{\overline{m}} \cdot \frac{\sum_{i=1}^{n} (m_i - s_i)}{n - p} \times 100\ (\%) \tag{1}$$

$$CV\ (RMSE) = \frac{1}{\overline{m}} \sqrt{\frac{\sum_{i=1}^{n} (m_i - s_i)^2}{n - p}} \times 100\ (\%) \tag{2}$$

where m_i is the measured value, s_i is the simulated value, n is the number of measured data points, and $\overline{m}$ is the mean of the measured values. P is the number of adjustable model parameters which, for calibration purpose, is suggested to be zero in Equation (1) and to be one in Equation (2) [31,32]. Table 1 shows the calibration criteria proposed by ASHRAE Guideline 14 [33].

Table 1. The calibration criteria proposed by ASHRAE Guideline 14 [33].

Calibration Criteria (%)	Index	ASHRAE Guideline 14
Monthly criteria	NMBE	±5
	CV (RMSE)	15
Hourly criteria	NMBE	±10
	CV (RMSE)	30

After the first set of simulation runs, the heat transmission through the internal walls as well as the construction materials were identified as the influencing parameters on the difference between the simulated and measured data. In the final calibrated model, the temperature profiles of the adjacent zones (based on BMS logged data) as well as the typical constructions used in buildings at the time when City Hall was built [24] were taken into account. Thermal bridges along different joints were also implemented.

3.3. Measurements Used for Calibration

An electrical radiator, on/off controlled by thermostat, was used to heat up the room during the period 12th–17th May 2018. During this period, the hydronic radiator was shut off, the ventilation supply and return devices were completely sealed, and the room's closed door was taped to ensure that only the electrical radiator heated up the room.

The electrical power measurements were done at one-minute intervals using an energy logger. Room air and surface temperatures were measured at five-minute intervals using thermistor sensors for temperature which were connected to a data logger. A vertical rod with attached thermistor sensors for temperatures at four different heights was placed in the middle of the room to measure room air temperature. Room air temperature was calculated as the average of measured values at the four different heights. Temperatures of all available internal surfaces in the room were measured, including the surface of internal walls, external wall, floor, ceiling, door and window. A weather station installed on the roof of a nearby building was used to measure ambient air temperature, relative humidity, and wind direction. The climate file used for the simulation part of the calibration process was created based on the measured data on the weather station plus the solar radiation data from the Swedish meteoroidal institute [34]. The measurement tools and equipment are illustrated in Figure 3. The technical data of measurement equipment are presented in Table 2.

Figure 3. (**a**) The vertical rod for the office room's air temperature measurement, (**b**) The electrical radiator connected to the energy logger, (**c**) Temperature thermistor sensors attached to the surfaces of internal wall and door, and (**d**) Temperature thermistor sensors attached to the inner surface of the external wall and window.

Table 2. Measurement equipment and accuracy.

Measurement	Equipment	Accuracy
Electrical radiator power	Tinytag Energy logger	Inaccuracy of ± 0.2% [35]
Room air and surface temperatures	Thermistor sensor for temperature	Inaccuracy of ± 0.3 °C [36]

3.4. Model Calibration

Table 3 illustrates the construction materials and infiltration rate used in the IDA-ICE model of the selected room for the calibration purpose. Table 4 shows the calculated linear heat loss coefficients for thermal bridges for different types of joints.

Table 3. Construction materials [24] and infiltration rate used in the IDA-ICE model of the selected room for the calibration purpose.

Construction Part.	Construction Material	Thickness (m)	U-Value (W/m^2·K)
External wall—below the window	Brick + light insulation	0.43	0.44
External wall—other parts	Brick	0.66	0.72
Internal wall towards corridor	Glass mineral wool + wood studs	0.15	0.34
Other internal walls	Brick	0.35	1.25
Floor and ceiling	Wood + sand	0.39	0.47
Window	Double-glazed with clear glass	0.03	2.83 [1]
Door	Wood	0.04	2.07
Infiltration rate [2]	2.285 ACH (at pressure difference of 50 Pa)		

[1] Glazing U-value. [2] Measured on-site in a representative zone.

Table 4. The linear heat loss coefficient for thermal bridges (W/K·m) for different types of joints in the building.

Type of Joints	External Wall/Internal Slab	External Wall/Internal Wall	External Wall/External Wall	External Window's Perimeter
Thermal bridges (W/K·m)	0.73	0.23	0.26	0.04

The calibration indices were calculated on an hourly basis for office room's air temperature and different surface temperatures. Since the electrical radiator was an on/off radiator and due to low seasonal heating demand, it turned on during very short periods (maximum ten-minute periods). The thermostat of the modelled radiator could not model the on/off performance, rather than on P-control. Therefore, the use of hourly calibration indices for the power of the electrical radiator did not give the possibility for correct comparison between measured and simulated data for this parameter. Thus, the calibration indices for this parameter were calculated based on a daily basis. The calculated indices are shown in Table 5.

Table 5. The calculated calibration indices for the office room's air temperature and the office room's different surface temperatures (on an hourly basis) and for the power of the electrical radiator (on a daily basis).

	Air Temperature in Office Room	Power of Electrical Radiator	External Wall	Internal Wall with Lunch Saloon	Internal Wall with Corridor
NMBE (%)	−0.9	−6.4	−4.0	−1.3	−2.0
CV (RMSE) (%)	2.1	9.1	4.2	1.8	3.1
	Internal Wall with Seminar Room	**Floor**	**Ceiling**	**Door**	**Window**
NMBE (%)	−2.1	−3.4	−3.5	−1.7	−3.8
CV (RMSE) (%)	3.5	3.8	3.8	2.2	6.9

As Table 5 illustrates, the hourly calibration indices for the office room's air temperature and different surface temperatures are in the acceptable range based on ASHRAE Guideline 14 according to Table 1. This guideline does not present any daily criteria. However, considering the daily criteria as an average between hourly and monthly criteria, the acceptable daily criteria for NMBE and CV (RMSE) could be proposed as ±7.5% and 22.5%, respectively. Considering these daily criteria, the daily calibration indices for the power of the electrical radiator are in the acceptable range base on ASHRAE Guideline 14.

Figure 4 shows the office room's air temperature and the power of the electrical radiator during the measurement period based on both measurement and simulation results. Note the influence of late afternoon sun on the increase in room temperature. Simulations tend to over-estimate the air temperature during insolation (which could be due to window niches which are not possible to fully model in IDA-ICE).

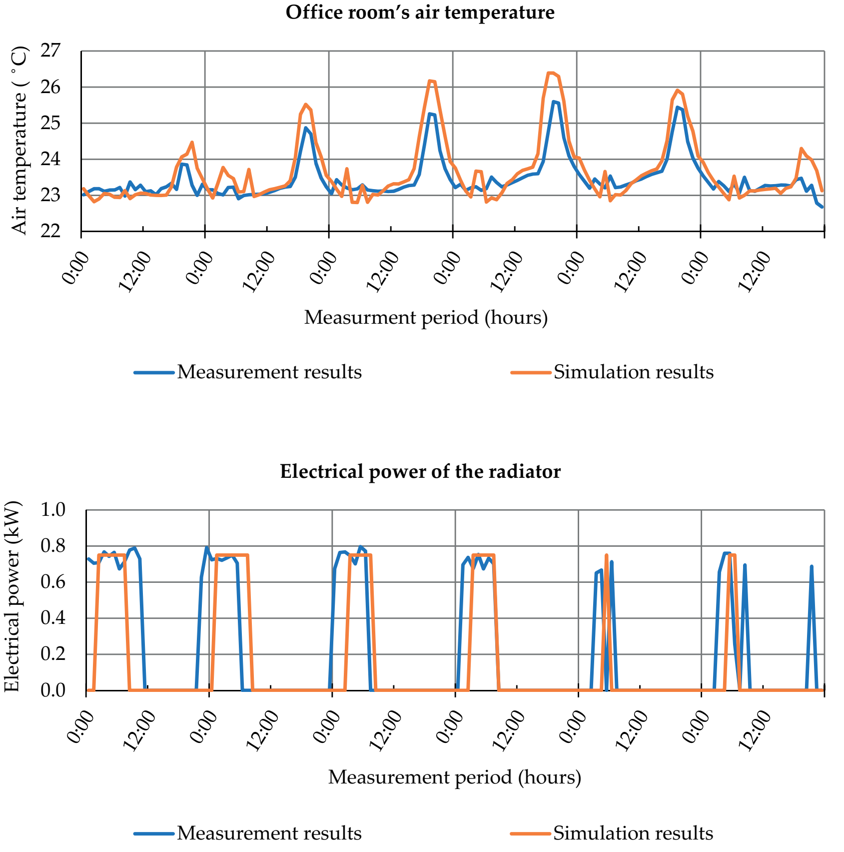


Figure 4. Office room's air temperature (°C) and electrical power of the radiator (kW) during the measurements period (12th–17th May) based on both measurement and simulation results.

3.5. *Simulation of NV*

In thermal comfort analysis, in the first step, the influence of totally eight different cases on the operative temperatures of office rooms was assessed and the optimum case was determined. The cases included with and without NV strategy as well as different schemes of offices' doors (i.e., closed or open doors). The cases are presented in Table 6.

Next, the effect of four different improving measures was evaluated on the optimum case determined in the previous step. In the building's energy use analysis section, the variation of total electricity use for cooling (i.e., electricity use in cooling machine plus electricity use in fans) was evaluated for different cooling machine's COP values and various SFP models for ventilation unit's fans.

Table 6. Different schemes of open or closed doors with/without NV with NVR = 1.66 ACH (cases are without active cooling).

Cases	NV	Southern Offices' Doors [1]	Northern Offices' Doors [2]
1	No	Always closed	Always closed
2	No	Open during working hours	Always closed
3	Yes	Always closed	Always closed
4	Yes	Open during working hours	Always closed
5	No	Always open	Always closed
6	Yes	Always open	Always closed
7	No	Always open	Always open
8	Yes	Always open	Always open

[1] Representing offices with southeast orientation with higher internal solar gains compared to other offices.
[2] Representing all other offices excluding the open-plan office.

The corridors and the entrance hall on the representative floor level were modelled as integrated zones and the existing internal walls located inside them were defined as internal masses in these zones. The model of the representative floor level on IDA-ICE is shown in Figure 5.

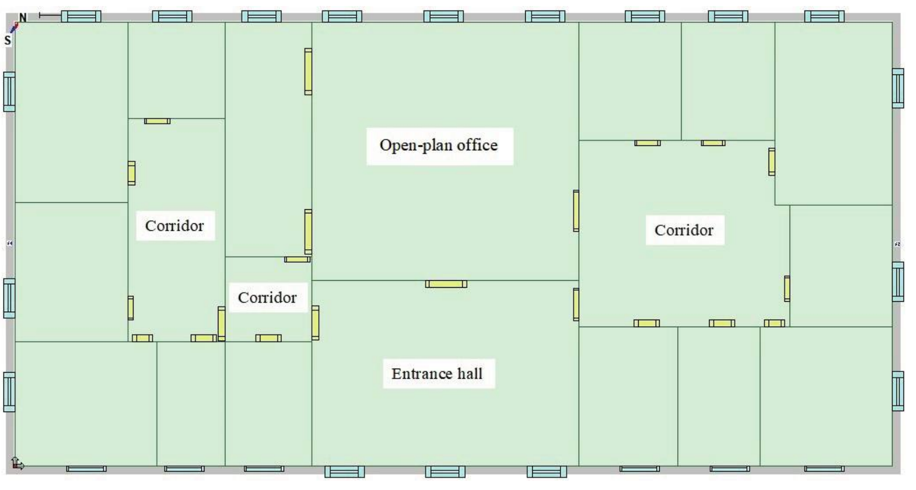


Figure 5. The model of the representative floor level (unlabeled zones are offices).

Internal gains from equipment and lighting were defined according to common assumptions for office buildings [37]. The default value of 0.1 m/s was specified for the air velocity in offices during summer. The occupants' clothing insulation was defined as 0.8 ± 0.2 clo for summer in order to represent normal office clothing plus, when needed, an extra sweater [38]. The activity level was specified to be 1.1 met to represent the average of common office activities including seated quiet resting, seated reading, typing as well as standing relaxed rest [38]. It was assumed that only one person worked in each single office with their desk placed in the middle of the office. The period 08:00–17:00 (normal working hours) was defined as the schedule for all internal gains. The defined internal gains in different zones on the floor are shown in Table 7.

Predefined supply and return air ventilation unit with a constant air volume (CAV) type was applied. The unit included a predefined control macro for NV strategy which also included the schedule of the daytime ventilation. The ventilation rate was measured as 1.66 ACH in one of the offices in the building which corresponded to the design ventilation rate. Considering the same design ventilation rate in all offices, the ventilation unit's total design ventilation rate was defined as 1.66 ACH of the total volume of the connected office rooms. The schedule for daytime ventilation and NV were defined as 06:00–18:00 and 20:00–06:00, respectively. For improving measures on NV by doubled and tripled NV rates (see thermal comfort analysis section), the NV schedule was shortened to 20:00–04:00.

Table 7. The internal gains from different sources in different zones of the modelled floor.

Zones	Occupants (W/Zone)	Equipment (W/m^2)	Lighting (W/m^2)
Offices	115.2 [1]	13	9
Open-plan office [2]	115.2 [1]	13	9
The smallest corridor	0	0	9
Other corridors [3]	0	7.5	9
Entrance hall	0	0	9

[1] Corresponding to internal gains from one person with the activity level of 1.1 met. [2] The same internal gins as offices were defined for the open-plan office. [3] The values are presented for each of these corridors.

For thermal comfort analysis, without active cooling (AC) during day, the total design ventilation rate was set for both daytime- and NV rates. For energy use analysis, when local ideal coolers were applied in offices as active cooling, the minimum required ventilation rate (corresponding to 0.35 l/s·m^2 + 7 l/s·person) [39] was set for the daytime ventilation keeping the night ventilation rate at the total design value. This means that the ventilation unit acted as a CAV system with two different constant ventilation rates with different working schedules (daytime ventilation and NV) plus the off mode. The proportional controller with the P-band corresponding to 1 °C (i.e., set point temperature ±0.5 °C) was defined for each local ideal cooler.

For NV strategy, the ventilation unit's return air and ambient temperature limit were set to 18 and 10 °C, respectively, and the benefit limit (i.e., the difference between ambient and return air temperatures) was defined as +2 °C. It means that the NV starts if all the following conditions are fulfilled and stops if any of them is missed:

(1) The time is during the period defined for NV schedule;
(2) The ventilation unit's return air temperature is over 18 °C;
(3) The ambient temperature is over 10 °C;
(4) The ambient temperature is at least 2 °C lower than the return air temperature.

3.6. Thermal Comfort Analysis

In order to evaluate thermal comfort in this study through comparing with standards' recommendations, operative temperature (T_{op}) was used as an indicator. The maximum acceptable T_{op} during summer for activity level around 1.2 met and clothing insulation around 0.5 clo in single (cellular) offices is 26 °C [40]. T_{op} of office rooms with different orientations were compared with each other for the eight different cases presented in Table 6. Simulations were carried out for two summer climates for the city of Gävle in Sweden: (1) Typical summer (representative of the average climate condition for a 30-year period of 1981–2010), and (2) the unusually hot summer of 2018. The cases which resulted in the lowest possible T_{op} in the offices were determined. The mean and average diurnal variation of ambient temperature for both typical and hot summer are presented in Table 8.

Table 8. The mean and average diurnal variation of ambient temperature.

Climate	Mean Ambient Temperature (°C)			Average Diurnal Variation [1] (°C)		
	June	July	August	June	July	August
Typical summer	13.3	17.7	14.4	9.9	10.3	9.2
Hot summer	15.2	20.4	16.8	9.6	10.0	9.6

[1] Average difference between daily maximum and minimum temperatures.

In order to further decrease the T_{op} in offices for the determined cases, four improving measures were proposed:

(1) Decreasing the minimum ambient temperature limit (ATL) of NV strategy from 10 to 5 °C;
(2) Doubling the daytime ventilation rate (DVR);
(3) Doubling the NV rate (NVR) while decreasing the NV period (NVP) from 20:00–06:00 to 20:00–04:00;
(4) Tripling the NV rate (NVR) while decreasing the NV period (NVP) from 20:00–06:00 to 20:00–04:00.

3.7. Energy Use Analysis

In the first step, the active cooling was added to four different cases with NV in the "Thermal comfort analysis" section (i.e., cases 3, 4, 6, and 8 in Table 6) and simulations were run for both typical and hot summers in order to show the difference in building's total electricity use for cooling between these cases.

In the second step, the parametric study was carried out on the effect of different NV rates on the building's total electricity use for cooling during the hot summer conditions of 2018. The total electricity use for cooling in the building consisted of (1) electricity use in cooling machine plus (2) the electricity use in ventilation unit's fans. Considering the former, three cooling machines with COP values of 1, 2 and 3 as well as two cooling set points for T_{op} including 26 and 24 °C were taken into account in the parametric study. COP = 1 represents a cooling machine in which the amount of electricity use equals the amount of heat extracted equivalent to the cooling demand. Considering the latter part, five different NV rates including 0 ACH (i.e., without NV) and four multiples of 1.66 ACH as well as three various SFP models were considered. The VR during daytime was the minimum required value. In the first model, a constant SFP was defined for all NV rates. In the second and third models, the NV rates of 1.66 ACH and 3 × 1.66 ACH were considered as the design ventilation rates, respectively, and the SFP value was defined at these design ventilation rates. The SFP = 1.5 kW/(m^3/s) was applied as a common value for each design flow rate, which is recommended for new air-handling systems for the supply and return fans in ventilation units with heat recovery [39]. SFP values for ventilation rates below the design flow rate were calculated based on data of part-load performance for VAV fan systems according to ASHRAE standard 90.1 [41]. Table 9 shows the SFP values in different NV rates in the three mentioned models.

Table 9. The SFP values of ventilation unit's fans (supply and return fans) for different NV rates in three various models (kW/(m^3/s)).

NVR	0 ACH [1]	0.5 × 1.66 ACH	1.66 ACH	2 × 1.66 ACH	3 × 1.66 ACH
SFP model 1	1.5	1.5	1.5	1.5	1.5
SFP model 2	0.3	0.6	1.5	5.4 [2]	11.7 [2]
SFP model 3	0.1	0.1	0.2	0.7	1.5

[1] For the first case with NVR = 0, the SFP value is defined for the daytime ventilation rate (corresponding to the minimum requirement of 0.35 l/s·m^2 + 7 l/s·person). [2] Calculated by extrapolation on data of part-load performance for VAV fan systems based on ASHRAE standard 90.1 [41] for the assumed NV rate.

4. Results and Discussion

4.1. Thermal Comfort Analysis

In order to show how different schemes of offices' doors (i.e., closed or open doors) affect the average T_{op} of offices and corridors, the simulation results during the hot summer for the cases with NV (NVR = 1.66 ACH) were applied. According to Figure 6, for cases with all doors always closed with NV (case 3), except for short periods, the average T_{op} of northern offices is always lower than those of southern offices and corridors. The average T_{op} of southern offices is lower than that of corridors during a large proportion of working hours during June and August and during a very short proportion of working hours during July.

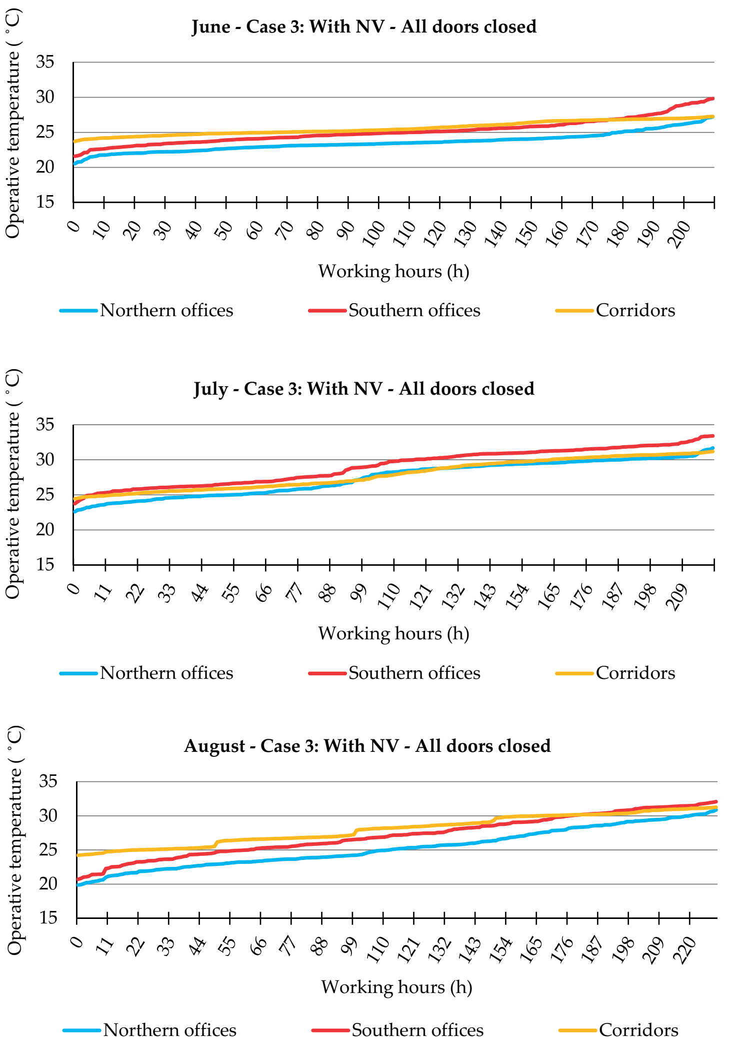


Figure 6. The average operative temperatures of the northern and southern offices and the corridors for the case with NV with all doors always closed (case 3) during the hot summer of 2018. Southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices. Northern offices represent all other offices excluding the open-plan office.

In case 4, the southern offices' doors are open only during working hours. Compared to case 3, this helps southern offices' average T_{op} drop during periods of working hours when corridors are cooler than southern offices (mainly during July). During the night, only southern offices are cooled down by NV. In case 6, the southern offices' doors are open during the whole period (24 h). Thus, corridors are also cooled down by NV during night, influenced by the southern offices' air. Therefore, compared to case 4, corridors' average T_{op} drops during working hours. When northern offices' doors are also opened (for 24 h), case 8, both corridors' and southern offices' average T_{op} decrease and northern offices' average T_{op} increases. In all cases, only direct connection between zones via open doors affect different zones' average T_{op}. The influence of heat transfer between different zones through internal walls and closed doors is negligible.

Figure 7 illustrates the percentage of working hours with the average T_{op} over 26 °C, the percentage of exceedance hours (H_e) [42], in offices for cases without NV for both typical and hot summers. Figure 7 clearly shows that for the hot summer, northern and southern offices' average T_{op} are over 26 °C during longer periods of working hours compared to the typical summer. The differences are specifically significant during June and August. This shows the significance of hot as opposed to typical summer weather.

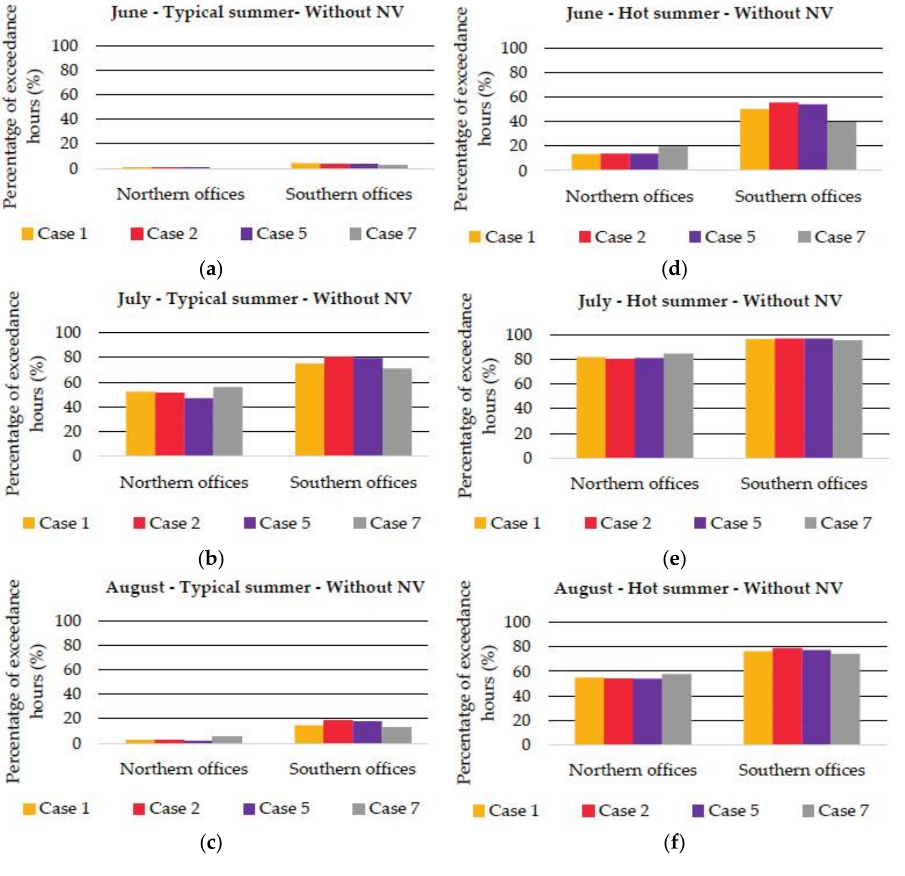


Figure 7. Percentage of exceedance hours in offices for cases without NV during June, July and August during (**a**–**c**) the typical summer and (**d**–**f**) the hot summer of 2018. Case 1: All doors always closed, Case 2: Northern offices' doors always closed/Southern offices' doors open during working hours, Case 5: Northern offices' doors always closed/Southern offices' doors always open, Case 7: All doors always open. Southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices. Northern offices represent all other offices excluding the open-plan office.

Figure 8 shows the exceedance hours in offices for the hot summer both with and without NV. According to Figure 8, NV helps reducing the offices' indoor temperatures during working hours during the whole period June-August and for all cases. H_e in offices is decreased by the range 7.1–28.6% as a result of NV application.

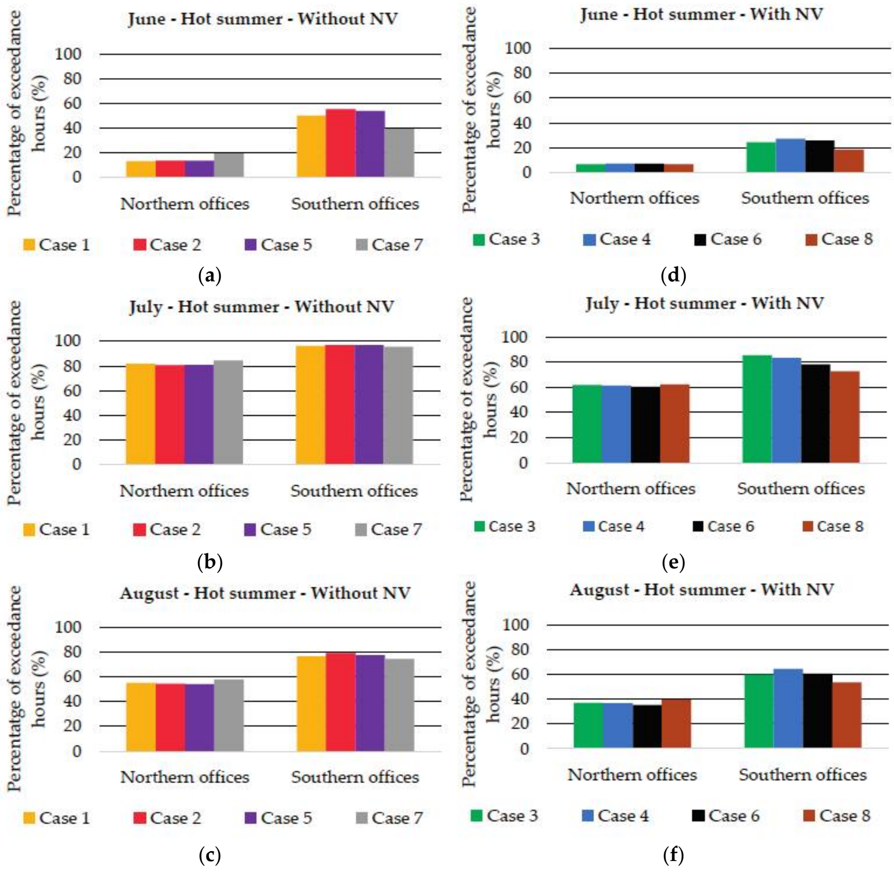


Figure 8. Percentage of exceedance hours in offices during the hot summer of 2018 (**a**–**c**) without NV and (**d**–**f**) with NV. Cases 1 and 3: All doors always closed, Cases 2 and 4: Northern offices' doors always closed/Southern offices' doors open during working hours, Cases 5 and 6: Northern offices' doors always closed/Southern offices' doors always open, Cases 7 and 8: All doors always open. Southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices. Northern offices represent all other offices excluding the open-plan office.

As Figure 8 shows, in southern offices and for both cases with and without NV during the whole period June-August, the cases with all doors always open (cases 7 and 8) lead to lower average T_{op} compared to other cases. For the cases without NV, H_e in southern offices is decreased by the range 1.4–10.5% in the shift from case 1 to 7. For the cases with NV, H_e in southern offices is decreased by 5.2–12.3% in the shift from case 3 to 8. On the other hand, cases 7 and 8 result in the higher H_e in northern offices compared to other cases. For the cases without NV, H_e in northern offices is increased by the range 1.3–5.7% in the shift from case 1 to case 7. For the cases with NV, H_e in northern offices is increased by the range 0.5–2.2% in the shift from case 3 to 8.

Generally, it is shown that the amount of decrease in H_e in southern offices outweighs the amount of increase in H_e in northern offices. This happens thanks to the considerably lower average T_{op} in northern offices during some periods, while southern offices' average T_{op} is over 26 °C during the same periods. There is only one exception for the cases without NV during July when H_e is increased by 4.1% in northern offices, while it is decreased only by 1.4% in southern offices. All in all, it is shown that cases with all offices' doors always open (i.e., case 7 without NV and case 8 with NV) result in the best possible condition for all offices among the available cases regarding offices' operative temperatures (optimum cases).

4.2. Thermal Comfort Improvement

In this section, the effect of higher flow rates for both daytime ventilation and NV on improving thermal comfort in offices was studied. Figure 9 illustrates the amount of decrease in the exceedance hours in northern and southern offices as a result of applying the thermal comfort improving measures.

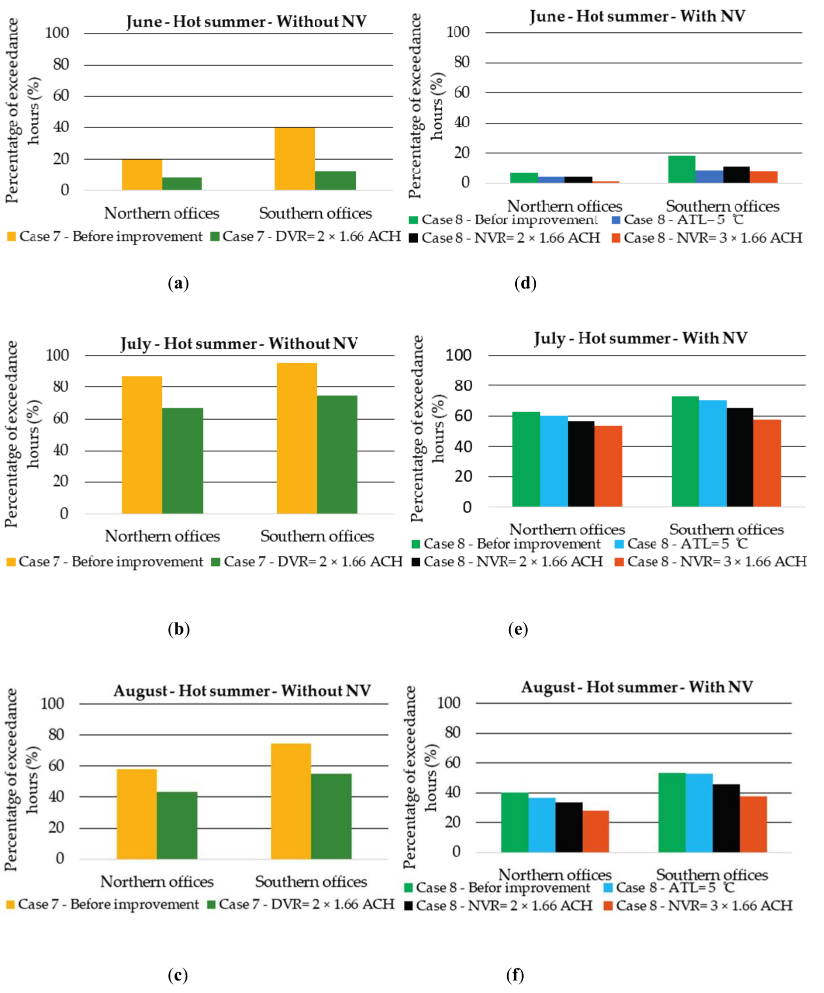


Figure 9. Percentage of exceedance hours in offices for thermal comfort improving measures for (**a**–**c**) case 7 and (**d**–**f**) case 8 during the hot summer of 2018. Cases 7 and 8: All doors always open. Southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices. Northern offices represent all other offices excluding the open-plan office. DVR: Daytime Ventilation rate, NVR: NV Rate, ATL: Ambient Temperature Limit.

According to Figure 9a–c, by doubling DVR, H_e is decreased by the range 19.1–27.1% in southern offices and by the range 11.4–20.5% in northern offices. It is understood that the ambient temperature is lower than the offices' indoor temperatures during a considerably long period. According to Figure 9d–f, by doubling the NVR while shortening the NV period to 20:00–04:00, H_e is decreased by the ranges 2.4–6.5% in northern offices and by the range 7.1–7.8% in southern offices. Tripling the NVR leads to decrease in H_e by the ranges 5.7–12.2% in northern offices and 10.5–16.1% in southern offices.

A finding is that the amount of decrease in H_e during June as a result of decreasing the ATL of NV strategy from 10 to 5 °C is more than and equal to the one caused by doubling the NVR in southern and northern offices, respectively. It is because the ambient temperature during NV periods is lower than 10 °C for longer periods during June compared to July and August. There is, however, the risk of condensation on the surfaces with low ATL.

4.3. Energy Use Analysis

Table 10 illustrates the total electricity use for cooling (kWh/m^2) during summer season in cases with different schemes of offices' doors with NV plus active cooling for both typical and hot summer conditions.

Table 10. The total electricity use for cooling (kWh/m^2) during summer season in cases with different schemes of offices' doors with NV plus active cooling for COP = 3 and the maximum beneficial NVR = 0.5 × 1.66 (ACH).

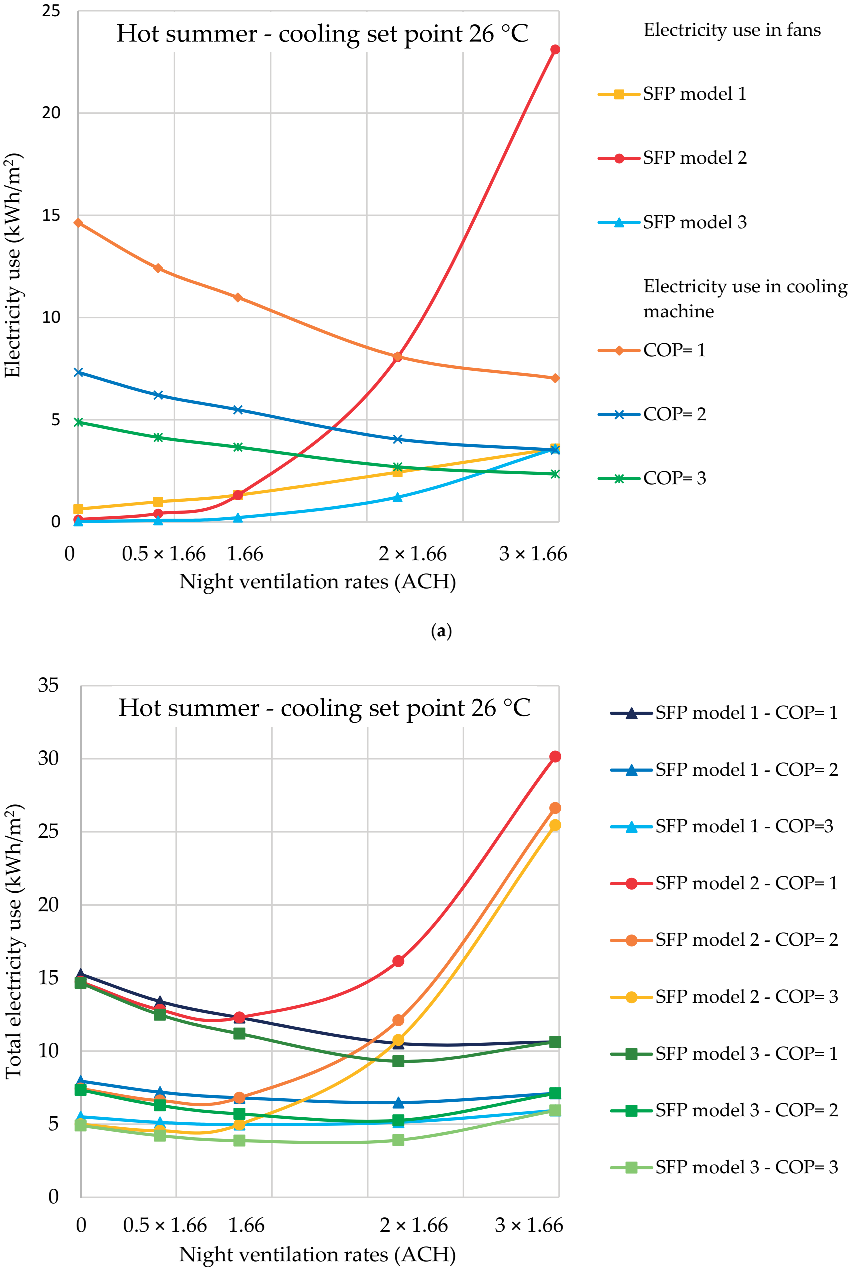
Cases	**Total Electricity Use for Cooling during Summer Season (kWh/m^2)**	
	Typical Summer	**Hot Summer of 2018**
B.C	3.8	5.9
Case 3	3.3	5.8
Case 4	4.1	6.3
Case 6	5.1	6.2
Case 8	2.3	5.5

B.C: Base case, i.e., all doors always closed without NV. Case 3: All doors always closed. Case 4: Northern offices' doors always closed/Southern offices' doors open during working hours. Case 6: Northern offices' doors always closed/Southern offices' doors always open. Case 8: All doors always open.

According to Table 10, total electricity use for cooling is the lowest in case 8 compared to other cases during both typical and hot summers. This, along with the results of thermal comfort analysis, confirms that the case with all doors always open is the optimum case resulting in the best possible condition for all offices. Figures 10 and 11 show the individual electricity uses in fans as well as for active cooling and total electricity use for cooling for the hot summer of 2018.

According to Table 11, the following findings for all SFP models are presented:

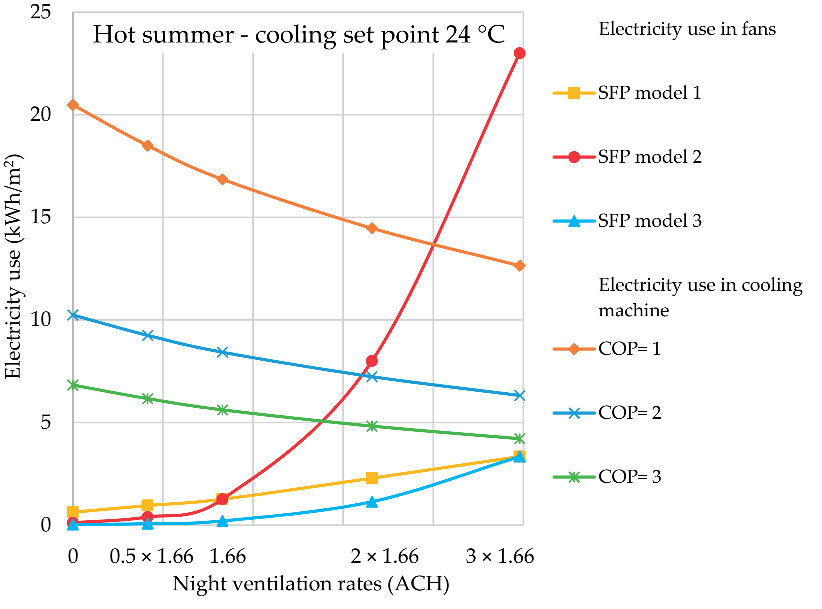
(1) The influence of increasing NV rate on decreasing the total electricity use for cooling is more significant for lower COP values;
(2) The influence of decreasing operative temperature cooling set point on increasing the total electricity use for cooling is more significant for lower COP values;
(3) For all different NV rates, the influence of increasing COP on decreasing the total electricity use for cooling is more significant for the lower operative temperature cooling set point (i.e., 24 °C).



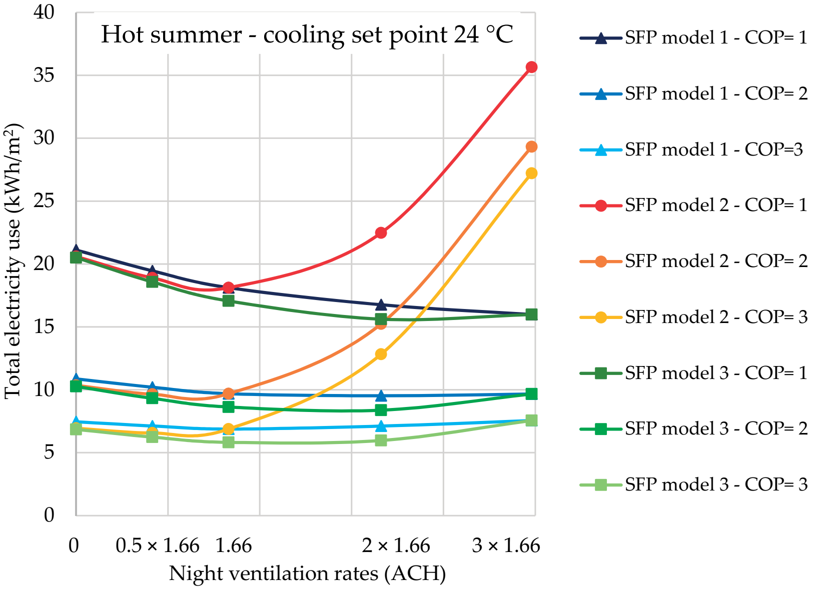
(**a**)

(**b**)

Figure 10. (**a**) individual electricity uses; electricity use in fans and electricity use in cooling machine (**b**) total electricity use for cooling (i.e., electricity use in fans + electricity use in cooling machine); during the hot summer of 2018 for operative temperature cooling set point of 26 °C.



(**a**)



(**b**)

Figure 11. (**a**) individual electricity uses; electricity use in fans and electricity use in cooling machine (**b**) total electricity use for cooling (i.e., electricity use in fans + electricity use in cooling machine); during the hot summer of 2018 for operative temperature cooling set point of 24 °C.

Table 11. The ranges of decrease or increase in total electricity use for cooling (kWh/m^2) during summer season through different perspectives of investigation in the three defined SFP models.

Perspective of Investigation	Corresponding COP or Cooling Set Point (SP)	Absolute Change in Total Electricity Use for Cooling (kWh/m^2)		
		SFP Model 1	SFP Model 2	SFP Model 3
Decrease in total electricity use through increase in NVR	COP = 1 COP = 3	2.0–5.1 0.3–0.6	2.0–2.4 0.4–0.5	2.3–5.3 0.7–1.0
Increase in total electricity use through decrease in SP (from 26 to 24 °C)	COP = 1 COP = 3	5.4–6.2 1.6–2.1	4.0–5.8 0.3–2.1	5.4–6.3 1.6–2.1
Decrease in total electricity use through increase in COP	SP = 26 °C SP = 24 °C	3.5–9.8 6.3–13.7	5.5–9.8 8.4–13.7	3.5–9.8 6.3–13.7

Based on the data in Figures 10 and 11, Table 12 shows the NV rates at which the minimum total electricity use for cooling occurs (optimal NV rates) for different COP values and SFP models for both operative temperature cooling set points of 26 and 24 °C. Table 13 shows the amount of total electricity use for cooling which is saved due to applying NV strategy with the maximum beneficial NV rate in each case (i.e., the NV rates presented in Table 12) compared to the case without NV.

Table 12. The NV rates (ACH) at which the minimum total electricity use for cooling during the hot summer of 2018 occurs for different COP values for operative temperature cooling set points of 26 and 24 °C.

SFP Models	Cooling Set Point	Optimal NVR (ACH)		
		COP = 1	COP = 2	COP = 3
SFP model 1	26 °C 24 °C	2 × 1.66 3 × 1.66	2 × 1.66 2 × 1.66	0.5 × 1.66 1.66
SFP model 2	26 °C 24 °C	1.66 1.66	0.5 × 1.66 0.5 × 1.66	0.5 × 1.66 0.5 × 1.66
SFP model 3	26 °C 24 °C	2 × 1.66 2 × 1.66	2 × 1.66 2 × 1.66	1.66 1.66

Table 13. The amount of saving in total electricity use for cooling during the hot summer of 2018 both in (kWh/m^2) and (%) as a result of applying NV strategy with the maximum beneficial NV rate (compared to the case without NV).

SFP Models	Cooling Set Point	Electricity Saving (kWh/m^2)		
		COP = 1	COP = 2	COP = 3
SFP model 1	26 °C 24 °C	4 (27%) 5 (24%)	2 (19%) 1 (12%)	1 (10%) 1 (8%)
SFP model 2	26 °C 24 °C	2 (16%) 2 (11%)	1 (13%) 1 (8%)	1 (10%) 0.5 (6%)
SFP model 3	26 °C 24 °C	5 (36%) 5 (24%)	2 (28%) 2 (18%)	1 (21%) 1 (15%)

According to to Table 12, for higher COP values, the minimum total electricity use for cooling occurs at lower NV rates. In the first SFP model, the high NVR = 3 × 1.66 ACH and 2 × 1.66 ACH are still beneficial for the cases with COP = 1 and COP = 2, while for COP = 3, NV rates over 0.5 × 1.66 ACH (for cooling set point = 26 °C) or over 1.66 ACH (for cooling set point = 24 °C) result in increase in the total electricity use for cooling. In the second SFP model, NVR= 1.66 ACH still results in a decrease in the total electricity use for cooling for the case with COP = 1, whereas NV rates over 0.5 × 1.66 ACH lead to increase in the total electricity use in the cases with COP = 2 and COP = 3. Finally, in the third SFP model, while NVR = 2 × 1.66 ACH still decreases the total electricity use in the cases with

COP = 1 and COP = 2, NV rates over 1.66 ACH cause increase in the total electricity use in the case with COP = 3.

5. Summarized Discussion

(1) The typical summer climate (based on average climate data during the period 1980–2010) does not represent an extraordinary warm summer which may be more common in the future. Applying this typical summer climate for energy simulation in buildings could lead to underestimation of the offices' indoor temperatures and, consequently, of the building's cooling need.

(2) Amongst all the proposed schemes of open/closed offices' doors, the case with all offices' doors always open was recognized as the overall optimum case. The case with all offices' doors always closed was considered as the base case, given that offices should be locked for security reasons when unoccupied. The simulation results were presented for the cases with NV and during the hot summer of 2018. In comparison with the base case, the optimum case led to decrease in percentage of working hours with the offices' average operative temperature over 26 °C, the percentage of exceedance hours, H_e [42], in southern offices by the range of 1.3–5.7%, while it resulted in increase in H_e in northern offices only by the range 0.5–2.2%. Thus, the optimum case improves thermal comfort in offices in overall.

(3) The mechanically driven NV strategy has the potential to improve thermal comfort in offices and to save the total electricity use for cooling in the building. Compared to the base case, the NV strategy is capable of reducing H_e by up to 33% and 28% during the typical and the hot summer, respectively. This amount of reduction is achievable thanks to NVR = 1.66 ACH (design DVR for the present building) for the optimum case with all offices' doors always open. For the same scheme of offices' doors, with the maximum beneficial NVR = 0.8 ACH (0.5 × 1.66 ACH) and cooling machine's COP = 3, the NV strategy is capable of saving 1.5 kWh/(m^2·year) (40%) and 0.4 kWh/(m^2·year) (7%) of the electricity use for cooling during the typical and the hot summer, respectively. These results are in line with the findings by Artmann et al. [7] and Jimenez-Bescos [8] predicting decrease in NV potential in future climates.

(4) Four proposed improving measures on daytime and NV (both without active cooling) showed potential in improving thermal comfort in offices. Doubling daytime ventilation rate had the potential in decreasing the percentage of exceedance hours in southern and northern offices by up to 27.1% and 20.5%, respectively. Increasing the NVR was capable of decreasing the percentage of exceedance hours by up to 6.5% and 7.8% for the doubled NVR and by 12.2% and 16.1% for the tripled NVR in northern and southern offices, respectively. Decreasing the ambient temperature limit of the NV strategy from 10 to 5 °C had the potential to decrease the percentage of exceedance hours in southern and northern offices by up to 10% and 4%, respectively. During June, compared to July and August, when the ambient temperature was below 10 °C for longer periods during the NV period, decreasing the ambient temperature limit of the NV strategy led to more improvement in thermal comfort in southern offices and the same improvement in northern offices in comparison with doubling the NV rate.

(5) With higher NV rates, thermal comfort in offices is improved further and more savings are achieved in electricity use in cooling machine in the building. There is, however, a maximum beneficial NV rate over which the total electricity use for cooling starts increasing since the amount of increase in the electricity use in fans outweighs the amount of saved electricity use in cooling machine. This maximum beneficial ventilation rate depends on the thermal mass capacity of the building's construction, the coefficient of performance (COP) value of the cooling machine, the design (maximum) ventilation rate, and available NV cooling potential (ambient air temperature). SFP is defined at the design (maximum) ventilation rate. Therefore, the optimum case is important in the design of the ventilation for new building projects, so that a low SPF is obtained for high NVR (this will require large size ventilation ducts). It is more difficult to achieve in buildings with an already installed duct system.

6. Conclusions

The potential of NV for cooling of a typical historic office building in north-central Sweden was evaluated by parametric study using building energy simulation (BES). Although the building is located in a cold climate, it was shown that NV alone is not capable of meeting the total cooling demand of the building and an auxiliary active cooling is required. NV with mechanical system, however, showed a potential in reducing the total electricity use for cooling, comprising the electricity use in cooling machine plus the electricity use in ventilation unit's fans, thanks to the building's heavy construction. The effect of NV on reducing the building's total electricity use for cooling increases with higher NV rates. However, there is a maximum beneficial ventilation rate above which further increase in the NV rate results in increase in the building's total electricity use for cooling. This maximum NV rate depends on the thermal mass capacity of the building, the COP value of the cooling machine, design (maximum) ventilation rate, and available NV cooling potential (ambient air temperature). For buildings with equal weight (same time constant), for the ones equipped with cooling machines with higher COP values, lower NV rates are recommended. This work also suggests that open doors in all zones of the building overall result in the best thermal comfort and reduced electricity use for cooling purposes. For this door scheme, the NV is capable of reducing the percentage of exceedance hours in offices by up to 33% and decreasing the total electricity use for cooling by up to 40%.

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