

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

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Gävle University Press

Dissertation for the Degree of Licentiate in Energy Systems to be publicly defended on Thursday 12 November 2020 at 10:00 in 33:203, University of Gävle.

External reviewer: Associate Professor Patrik Rohdin, Linköping University

*This thesis is based on work conducted within the industrial post-graduate school Reesbe- Resource-Efficient Energy Systems in the Built Environment. The projects in Reesbe are aimed at key issues in the interface between the business responsibilities of different actors in order to find common solutions for improving energy efficiency that are resource-efficient in terms of primary energy and low environmental impact.*



The research groups that participate are Energy Systems at the University of Gävle, Energy and Environmental Technology at Mälardalen University, and Energy and Environmental Technology at the Dalarna University. Reesbe is an effort in close co-operation with the industry in the three regions of Gävleborg, Dalarna, and Mälardalen, and is funded by the Knowledge Foundation (KK-stiftelsen).

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Cover illustration: The studied historic office building / Abolfazl Hayati

Gävle University Press

ISBN 978-91-88145-54-3

ISBN 978-91-88145-55-0 (pdf)

urn:nbn:se:hig:diva-33941

Distribution:

University of Gävle

Faculty of Engineering and Sustainable Development

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SE-801 76 Gävle, Sweden

+46 26 64 85 00

[www.hig.se](http://www.hig.se)

 Svanenmärkt trycksak, 3041 0736 Kph Trycksaksbolaget 2020

*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.

## **Acknowledgements**

I would like to express my sincerest gratitude to my supervisors Doc. Mathias Cehlin, Dr. Jan Akander and Dr. Abolfazl Hayati for their continuous advice and support and their patience, motivation and immense knowledge throughout the research process. Without your support, this research would not have been possible.

This research has been carried out under the auspices of the industrial post-graduate school Reesbe, which is financed by the Knowledge Foundation (KK-stiftelsen) and the participating companies. I am very grateful to be a part of Reesbe and thankful for the courses, seminars and the opportunities to get to know new friends and colleagues. I appreciate the contribution of the Knowledge Foundation to Reesbe and their financial support for this research.

I would like to thank Gavlefastigheter AB for enabling and supporting this research study and all my colleagues there for their support. I am specifically grateful to my company manager Mrs. Emma Björkenstam for her patient support, advice and motivation during the work on this research project. I would also like to thank all my friends and colleagues at the University of Gävle, especially Elisabeth Linden for all her technical supports for the measurements.

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. 4<sup>th</sup> 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 <sub>2</sub>	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<sub>2</sub> 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].

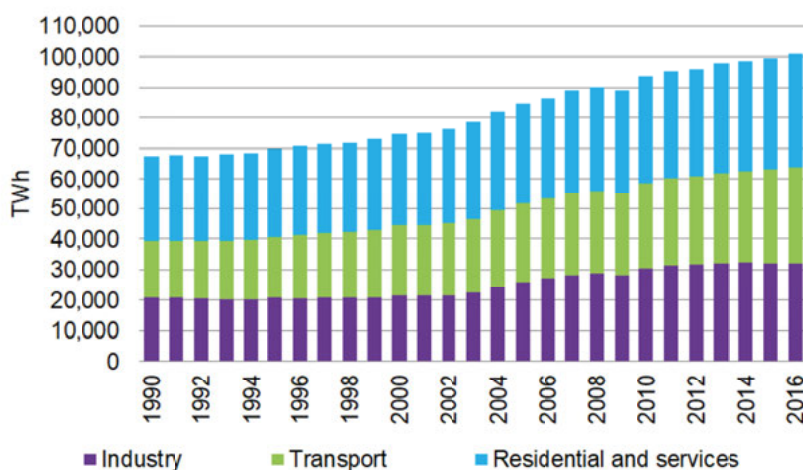


Figure 1. Final energy use in different sectors in the world during the period 1990-2016 [10]

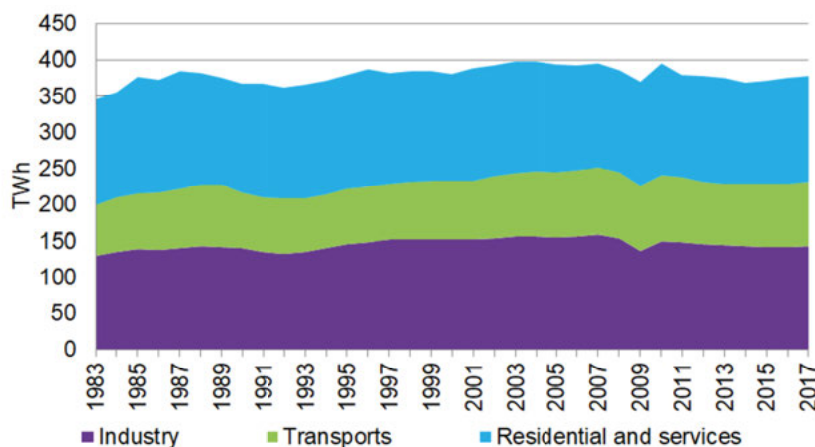


Figure 2. Final energy use in different sectors in Sweden during the period 1983-2017 [10]

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.

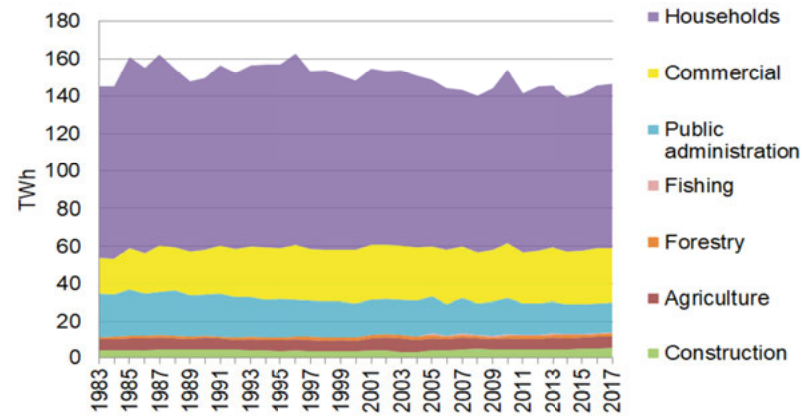


Figure 3. Final energy use in different subsectors of the residential and services sectors in Sweden during the period 1983-2017. [10]

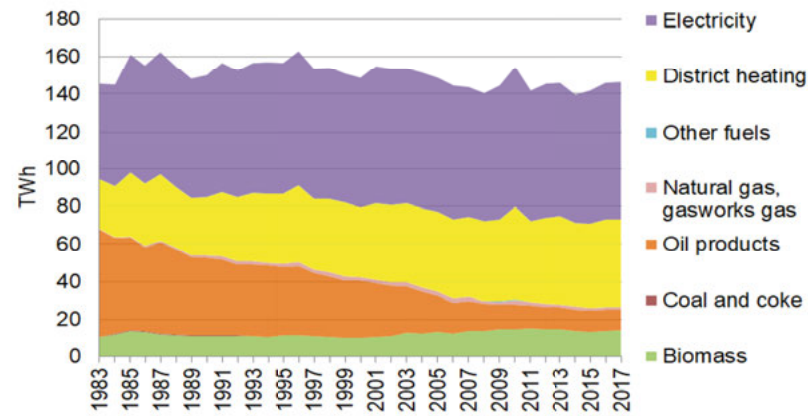


Figure 4. Final energy use by different energy carriers in the residential and services sectors during the period 1983-2017 [10]

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 <sup>1</sup>
Share of space cooling in total final electricity use in buildings	13%	18.5%

<sup>1</sup> 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].

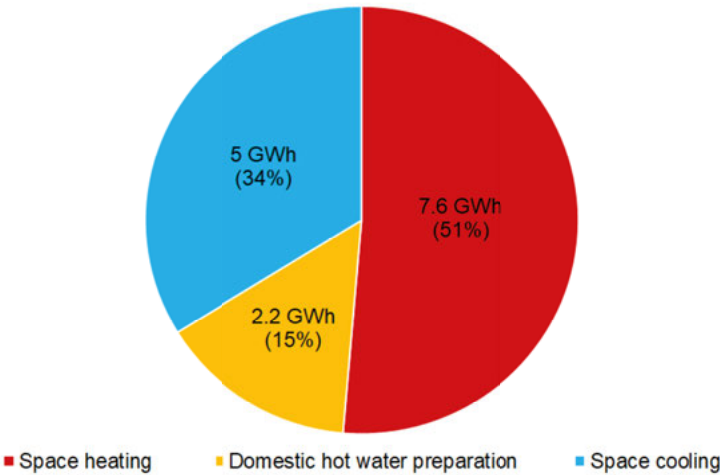


Figure 5. Final energy use for space heating, space cooling and domestic hot water preparation in Swedish office buildings in 2009 [13]

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].

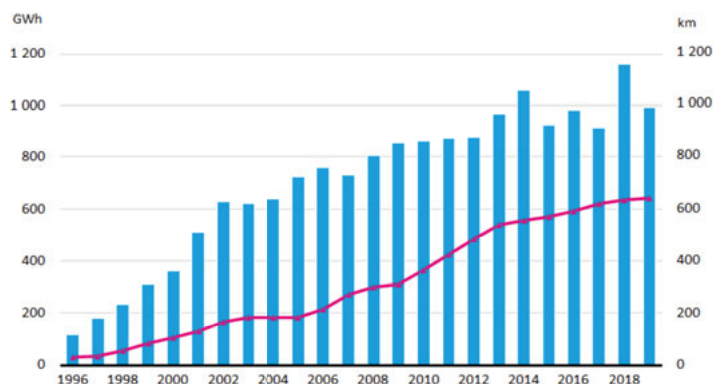


Figure 6. District cooling (DC) supply in GWh (blue bars) and network length in km (red trend line) in Sweden during the period 1996-2019 [14]

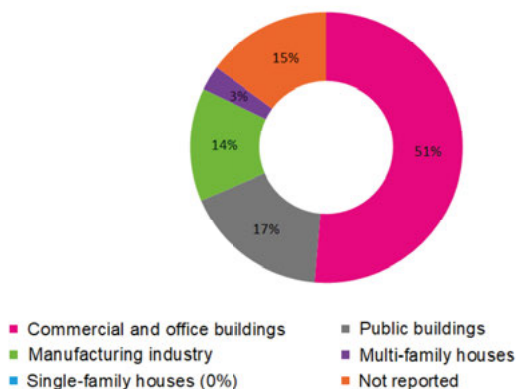


Figure 7. Distribution of district cooling (DC) supply in different sectors in Sweden in 2019 [14]

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.

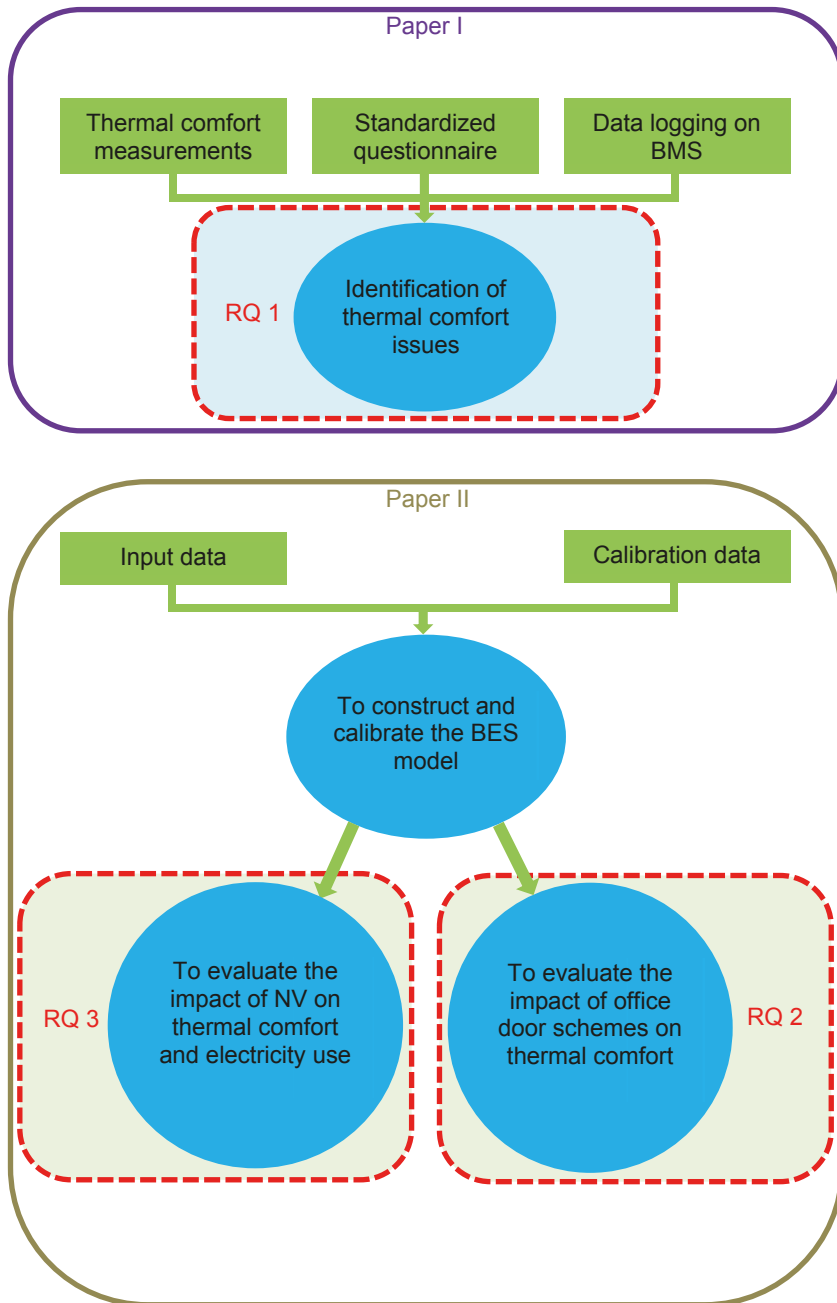


Figure 8. An overview of the research process including the connection between thesis RQs and Papers I and II.

## 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<sup>2</sup>. 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°C with winter temperature plummeting to about -22°C 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.

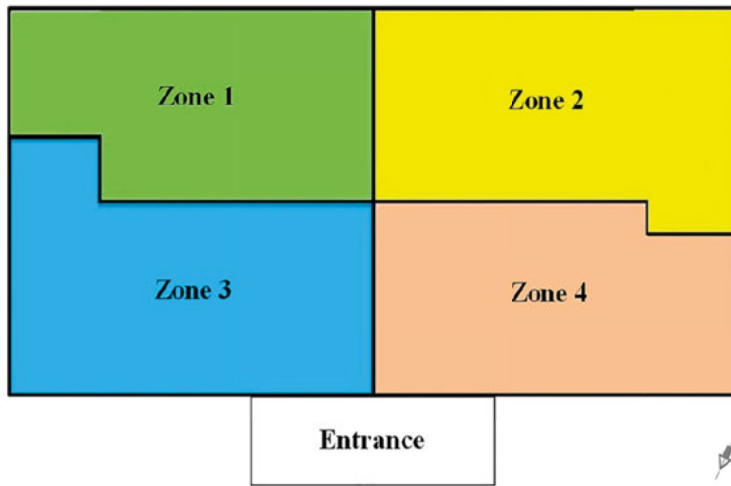


Figure 10. Building plan divided into four zones per floor. The arrow points to the north.

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.

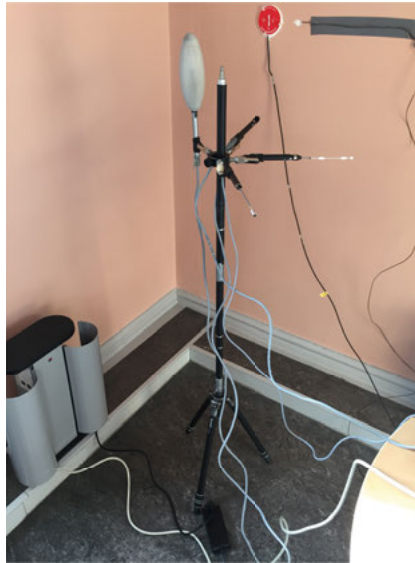


Figure 11. Transducers used for thermal comfort measurements

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 °C to +50 °C	$\pm 0.2\text{ °C}$ for 5 °C to 40 °C $\pm 0.5\text{ °C}$ for -20 °C to 50 °C
Air velocity	MM0038	0-10 m/s	$V_a < 1\text{ m/s}$ : $\pm(0.05 V_a + 0.05)\text{m/s}^a$ $1 < V_a < 10\text{ m/s}$ : typically better than $\pm 0.1 V_a^b$ and $\pm 0.25 V_a^c$ 2% drop in displayed reading <sup>d</sup>
Air humidity	MM0037	$T_a - T_d < 25\text{ °C}^e$	$T_a - T_d < 10\text{K}$ : $\pm 0.5\text{ K}$ or $\pm 0.05\text{ kPa}$ $10\text{ K} < T_a - T_d < 25\text{K}$ : $\pm 1.0\text{ K}$ or $\pm 0.1\text{ kPa}$
Dry heat loss <sup>f</sup>	MM0057	-20 °C to +50 °C	$\pm 0.5\text{ °C}$ for 5 °C to 40 °C $\pm 1.0\text{ °C}$ for -20 °C to 50 °C

<sup>a</sup> For any flow direction greater than 15° from rear of transducer axis <sup>b</sup> For flow directions perpendicular to transducer axis <sup>c</sup> For flow directions more than 15° from rear of transducer axis <sup>d</sup> Displayed reading will drop 2% when a standard 6 m extension cable is used

<sup>e</sup> Dew-point range:  $T_a$  is the air temperature and  $T_d$  is the dew-point temperature <sup>f</sup> 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.

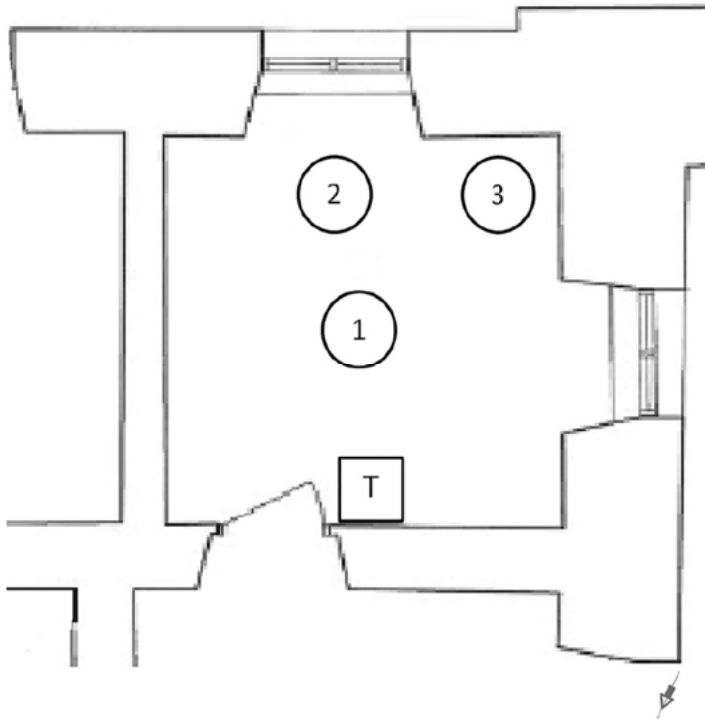


Figure 12. Measurement locations in the representative room. The arrow points to the north. NOTE: T represents the BMS room thermostat.

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	
	<i>PPD</i> (%)	<i>PMV</i>	Draught Rate ( <i>DR</i> ) (%)	Vertical air temperature difference <sup>a</sup> (°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

<sup>a</sup> 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  $\pm 0.3$  °C at the range 0 - 35 °C [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.

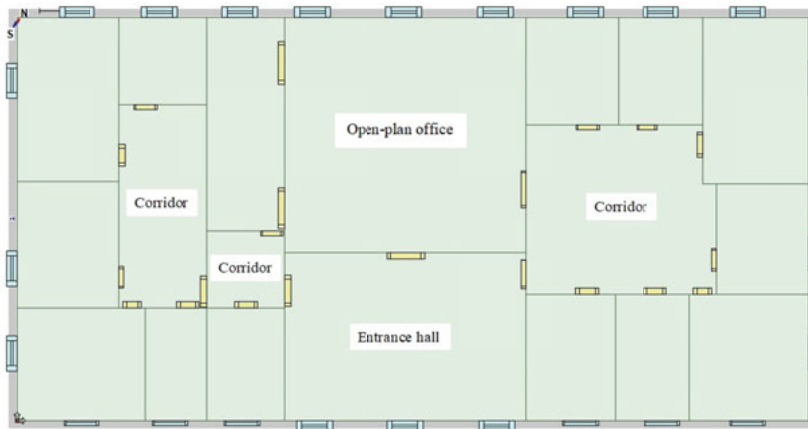


Figure 14. The model of the representative floor level on IDA-ICE 4.8. (unlabeled zones are offices)

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 °C;
- (3) The ambient temperature is over 10 °C;
- (4) The ambient temperature is at least 2 °C 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 °C (i.e., setpoint temperature  $\pm 0.5$  °C). 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.

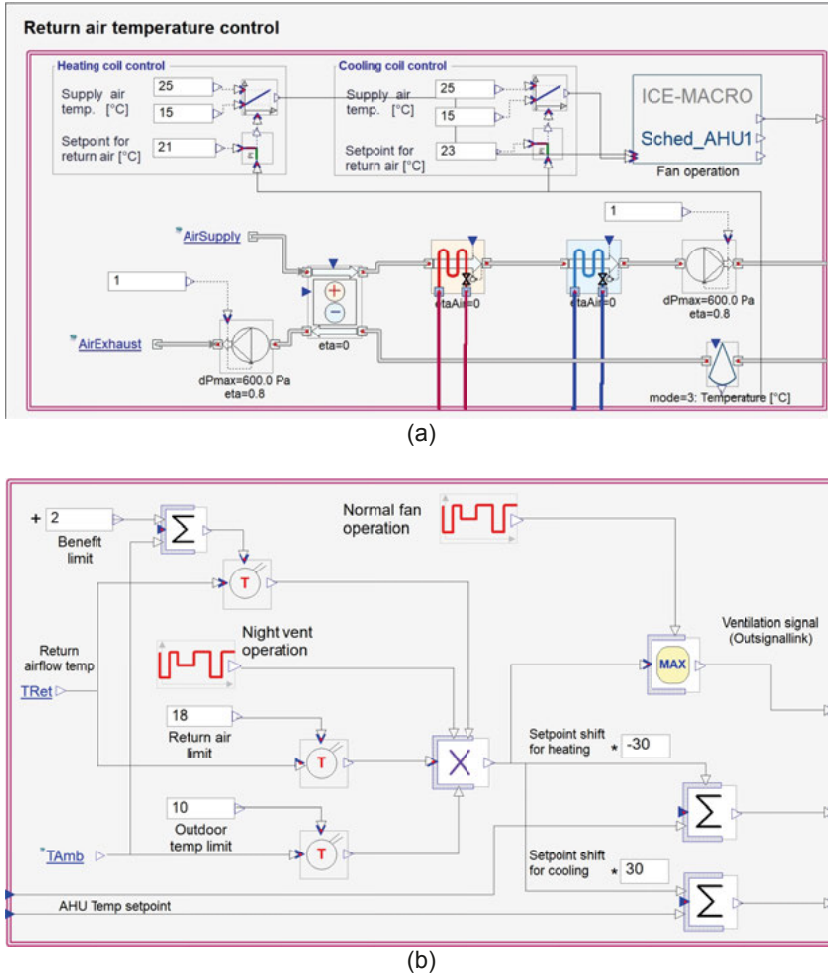


Figure 15. The schematic of (a) the predefined ventilation unit (b) the predefined detailed model of NV strategy (the detailed configuration of the ICE-MACRO on the ventilation unit).

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.,  $0.35 \text{ l/s}\cdot\text{m}^2 + 7 \text{ l/s person}$ ) [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 <sup>1</sup>	Northern offices' doors <sup>2</sup>
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

<sup>1</sup> representing offices with southeast orientation with higher internal solar gains compared to other offices <sup>2</sup> 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  $10^\circ\text{C}$  to  $5^\circ\text{C}$
- (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

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<sup>3</sup>/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<sup>3</sup>/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 <sup>1</sup>	11.7 <sup>1</sup>
SFP model 3	0.1	0.1	0.2	0.7	1.5

<sup>1</sup> 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.

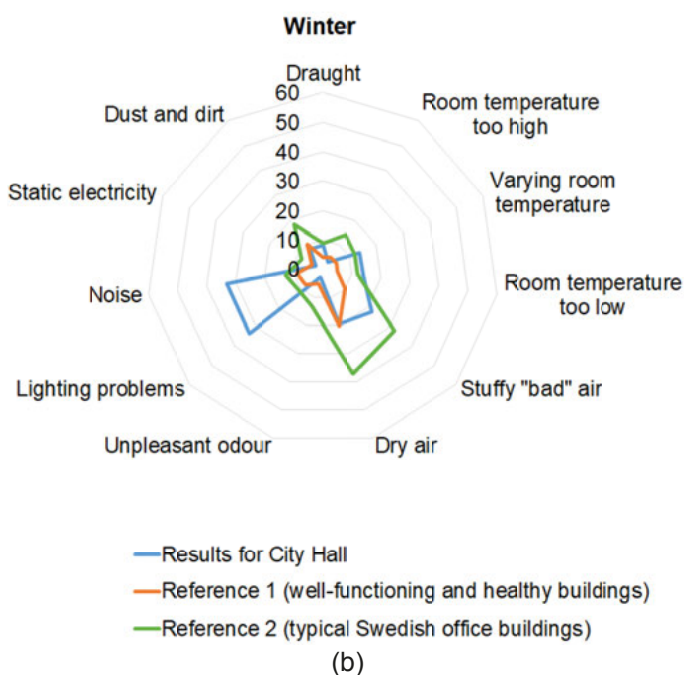
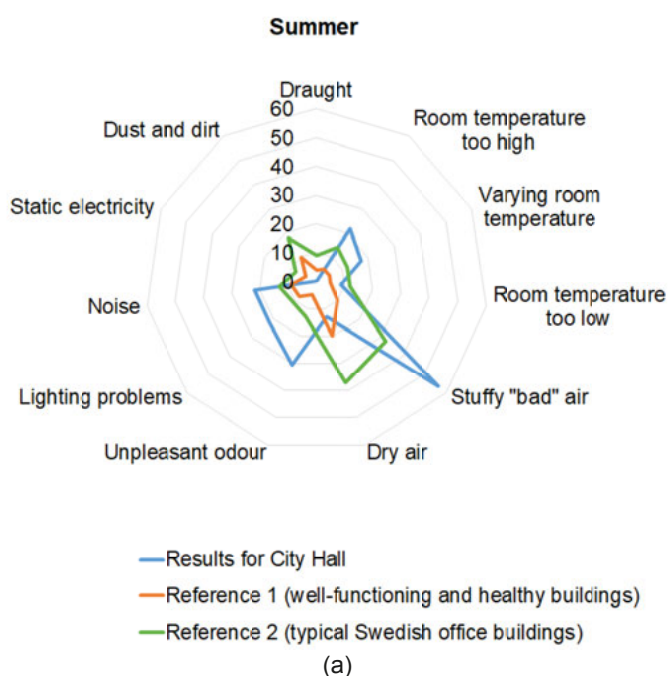


Figure 16. Environmental disturbing factors based on the responses to the MM- questionnaires during (a) summer (b) winter.



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 <sup>a</sup>		1.1 m <sup>b</sup>	
	<i>PMV</i>	<i>PPD</i> (%)	<i>PMV</i>	<i>PPD</i> (%)
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

<sup>a</sup> the values represent *PMV/PPD* for the body as a whole for a seated person

<sup>b</sup> 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 <sup>a</sup>		1.1 m <sup>b</sup>	
	<i>PMV</i>	<i>PPD</i> (%)	<i>PMV</i>	<i>PPD</i> (%)
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

<sup>a</sup> the values represent *PMV/PPD* for the body as a whole for a seated person

<sup>b</sup> 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 °C 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.

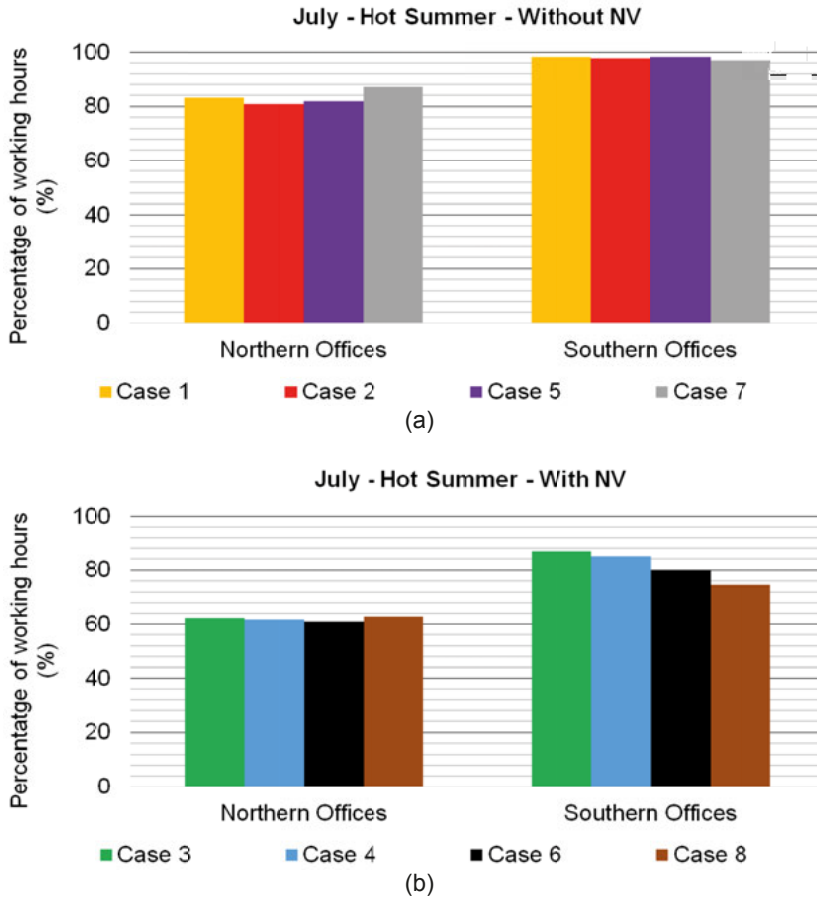


Figure 17. The percentage of exceedance hours in offices during July 2018 (a) without NV (b) with NV. Cases 1 & 3: All doors always closed, Cases 2 & 4: Northern offices' doors always closed / Southern offices' doors open during working hours, Cases 5 & 6: Northern offices' doors always closed / Southern 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 <sup>c</sup>			Northern offices <sup>d</sup>		
	June	July	August	June	July	August
case 1 <sup>a</sup> to case 7 <sup>b</sup>	-10.5	-1.4	-3.0	+5.7	+4.1	+1.3
case 3 <sup>a</sup> to case 8 <sup>b</sup>	-5.7	-12.3	-5.2	+1.0	+0.5	+2.2

<sup>a</sup> cases 1 & 3: all doors always closed <sup>b</sup> cases 7 & 8: all doors always open <sup>c</sup> southern offices represent offices with southeast orientation with higher internal solar gains compared to other offices <sup>d</sup> 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 °C 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.

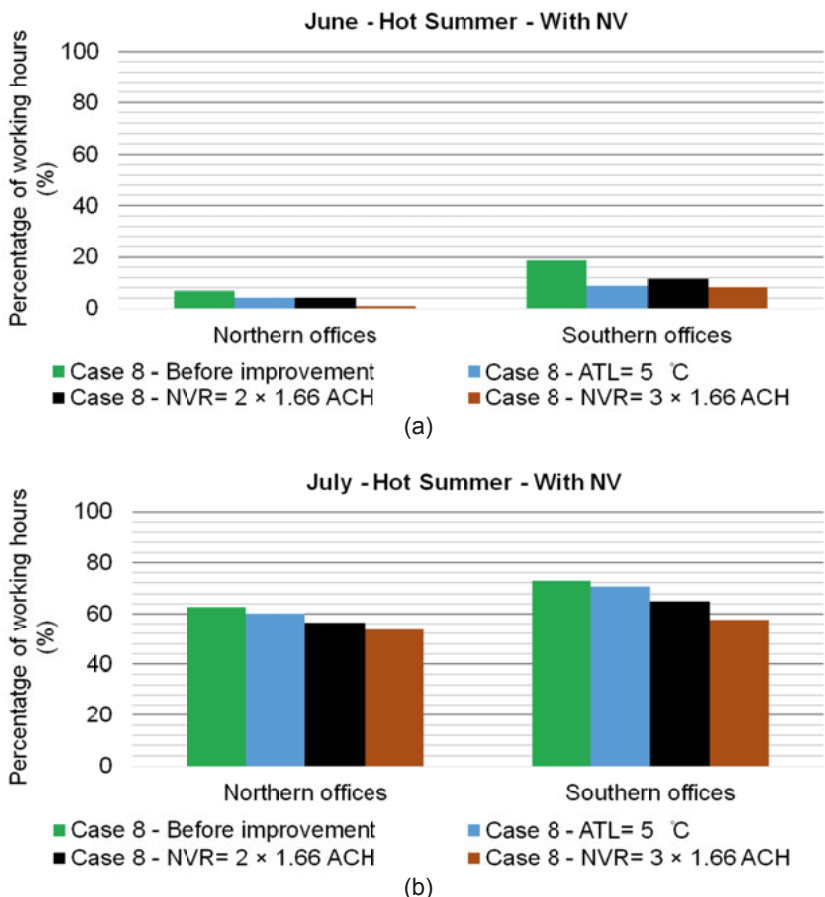


Figure 18. Percentage of exceedance hours in offices for thermal comfort improving measures for (a) case 7 and (b) case 8 during the hot summer of 2018.

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 °C 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.

#### ***4.3.2. 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<sup>2</sup> (40%) and 0.4 kWh/m<sup>2</sup> (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 ( $0.5 \times 1.66$  ACH), cooling machine's COP = 3, for the optimum case with all office doors always open (case 8), and at temperature setpoint of 26 °C. For the same situation, decreasing the temperature setpoint from 26 °C to 24 °C leads to increase in the electricity use for cooling by 2.1 kWh/m<sup>2</sup> during the hot summer of 2018.

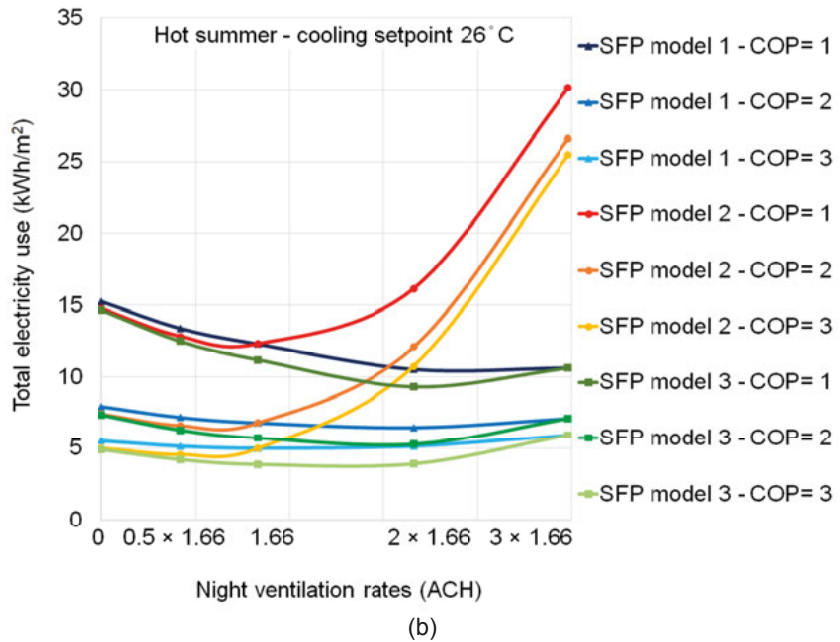
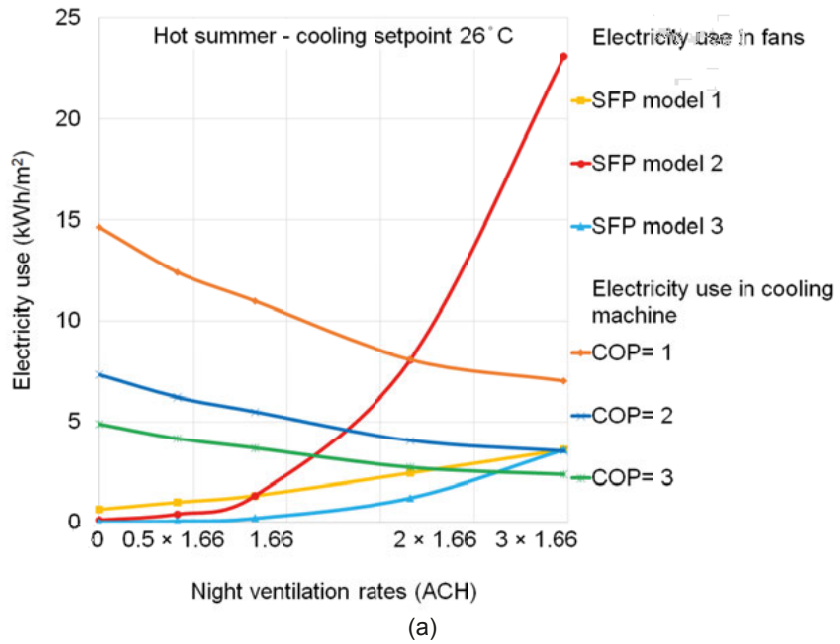
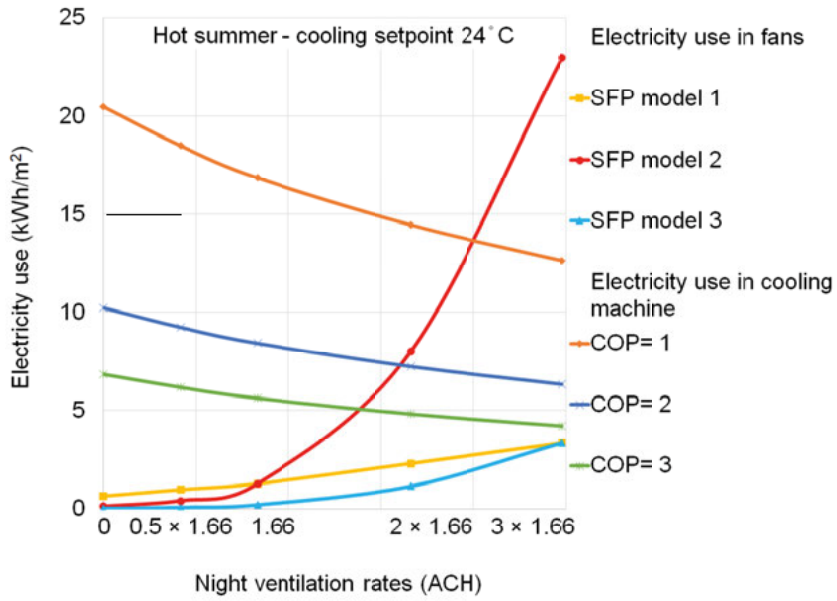
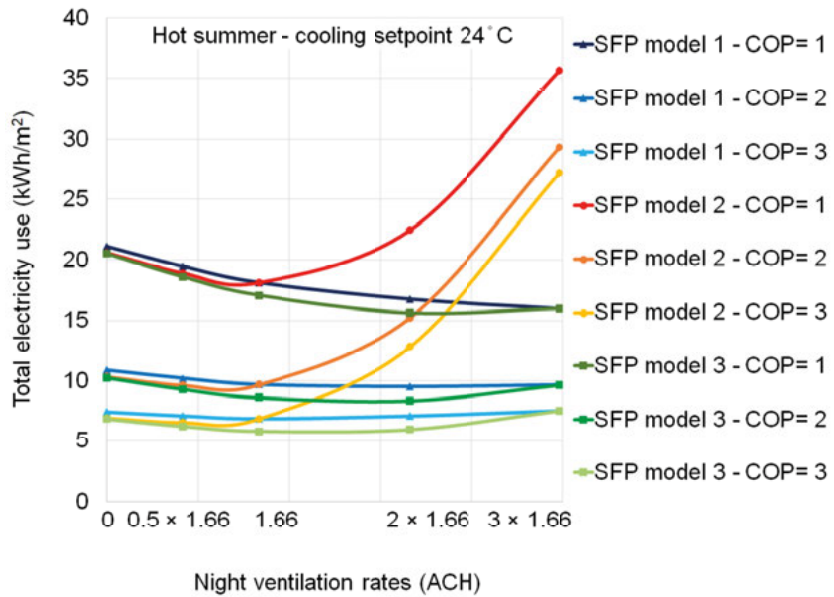


Figure 19. (a) individual electricity use; electricity use in fans and electricity use in cooling machine (b) total electricity use for cooling (electricity use in fans + electricity use in cooling machine); during the hot summer of 2018 for operative temperature cooling setpoint of 26 °C.



(a)



(b)

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 °C.



## 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<sub>2</sub> 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!)

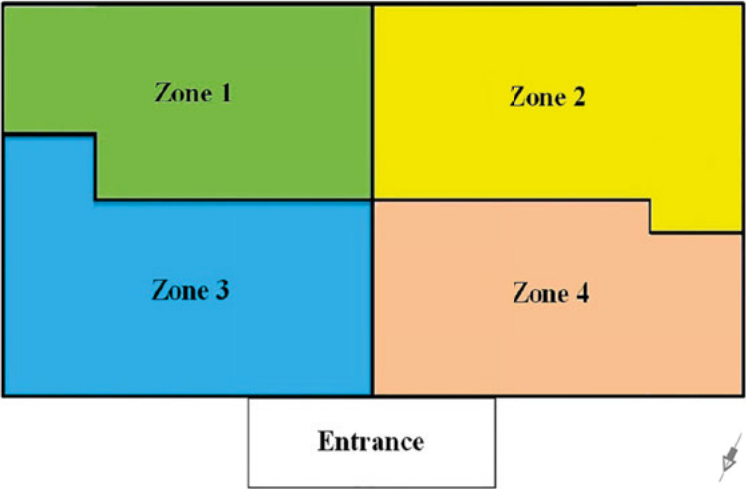
	Yes, often (every week) (1)	Yes, sometimes (2)	No, never (3)
Draught	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Room temperature too high	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Varying room temperature	<input type="checkbox"/>	<input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

### 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	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Feeling heavy-headed	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Headache	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Nausea/dizziness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Difficulties concentrating	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Itching, burning or irritation of the eyes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Irritated, stuffy or runny nose	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Nose-bleeding	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Hoarse, dry throat	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cough	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Dry or flushed facial skin	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Scaling/itching scalp or ears	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Hand dry, itching, redskin	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Suffering from stress	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Easily irritated about small matters	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Difficulties to sleep	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other .....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

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)



## **Papers**

Associated papers have been removed in the electronic version of this thesis.

For more details about the papers see:

<http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-33941>