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Kimmo Hilliaho

**Energy Saving Potential and Interior Temperatures of Glazed Spaces**  
Evaluation through Measurements and Simulations



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## **Energy Saving Potential and Interior Temperatures of Glazed Spaces**

Evaluation through Measurements and Simulations

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Rakennustalo Building, Auditorium RG202, at Tampere University of Technology, on the 18<sup>th</sup> of August 2017, at 12 noon.

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## Abstract

According to Finnish glazing manufacturers, balcony glazing has been installed in approximately 75 % of Finnish apartment balconies, i.e. more than 600 000 balconies over the whole country. Nearly all of the balcony glazing systems are constructed of 5 to 6 frameless single glass panes, whose 2-3 mm air gaps between panes are arranged to allow ventilation of the enclosed space. The main motivation for installing the glazing has been to increase the usability of the space by protecting it from the natural elements, and also from pollution and noise. As a rule, the glazing has not been constructed or installed to optimize the space's indoor temperature conditions, nor to maximize the heating energy-saving effects.

The purpose of this study was to evaluate the heating-energy saving potential of the glazing, and its effects on the indoor spaces, with field measurements and computer simulations. The research consisted of detailed surface and air temperature monitoring in two balconies and their adjoining flats, and monitoring of the air temperature on 22 balconies (17 glazed) and their adjacent flats in Tampere from 16<sup>th</sup> July 2009 to 24<sup>th</sup> May 2010. The research also included a detailed case-study of a glazed-in brick building in Malmö, which involved monitoring the temperature, relative humidity and air flow in the building from the 28<sup>th</sup> of October, 2013 to the 10<sup>th</sup> of February, 2015. Along with those studies, the suitability of the IDA Indoor Climate and Energy (IDA-ICE) software for glazed space energy simulations was analyzed through a literature review and the constructed model's 'goodness of fit', which was verified by model calibration. After that, the effects of the various characteristics of different flats, balconies and balcony glazing solutions on the heating energy consumption of both the flats and the balconies' indoor climates were studied with 156 different calculation cases. Furthermore, there were 63 model calculations on the impact of the added glazing on the brick building's heating energy use and indoor climate.

The temperature monitoring showed that the air temperature on both the glazed and unglazed balconies, and in the cavity spaces between the glazing and the brick walls of the Malmö building, remained almost without exception above the outdoor air temperature. The analyses also showed that the indoor climate of the glazed space and the achievable energy-saving potential is case-specific and is influenced by a variety of factors such as the building's location, the type and orientation of the balcony itself, the tightness of the glazing, the inlet air pre-heating (air entering the building from the glazed balcony), and the thermal resistance of the structures. The study also revealed that IDA-ICE is well suited for its intended purpose in simulations, which can usefully be conducted within the generally used 'goodness of fit' criteria set by ASHRAE. The

final outcome of the study was a simplified preliminary calculation procedure for evaluation of the heating energy-savings of the glazed spaces as well as the mean, maximum and minimum temperatures levels during the year. The results strongly indicate that this method is reliable for its intended purpose in Nordic countries.

## Acknowledgements

This thesis is based on research carried out between 2009 and 2016 at Tampere University of Technology. The research began in spring 2009, when the balcony glazing company Lumon Oy ordered a Master's thesis work entitled 'The energy-saving effects of balcony glazing' from Tampere University of Technology and recommended the author as the main researcher for the project. After completing that thesis, the dissertation work started with general post-graduate studies from 2011 to 2013, during which the author worked first as a structural engineer and then as an energy-saving specialist at Ramboll Finland Oy. During this period, the team leader, Jukka Merviö, initiated the project which forms the basis of the author's post-graduation studies during this period. The backers of these projects were Finnish building firms such as VVO Yhtymät Oyj, Lumon Oy and Rakennusliike Markku Haataja Oy. Over the last three years (2014-2016), the dissertation project has largely been funded through the doctoral program of Tampere University of Technology and all the articles, as well as this doctoral thesis, were completed during this period. The field work for article V was carried out during two research visits to Lund, funded by KIINKO Real Estate Education, Tampere University of Technology and the University of Lund. I would like to thank these institutions for their financial support during the project.

I would also like to thank my instructor, Jukka Lahdensivu, firstly for stimulating my motivation to apply for the doctoral program of Tampere University of Technology, and secondly for his invaluable guidance during the project. My supervisor, Matti Pentti, also deserves praise for energetically encouraging me to push the dissertation forward in what turned out to be a very favorable direction. I am also grateful to the pre-examiners, Per Heiselberg and Dirk Saelens, for their encouraging reviews, excellent comments and valuable advice, all of which have helped me to produce a more robust paper. Juha Vinha, second instructor, deserves special mention for his carefully designed and controlled master's thesis. The monitoring results from his study are an important part of this dissertation. Without this kick-start, this author's academic career might well have remained in the doldrums.

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I would also like to thank other persons with whom I have cooperated during the project. Special thanks go to Lauri Parkkinen at VVO Yhtymät Oyj and Eerik Mäkitalo at Ramboll Finland Oy. My co-operation with Lauri Parkkinen in 2012 and 2013 helped me understand how to carry out a comprehensive sensitivity analysis of a glazed space's indoor temperature behavior and energy-saving potential, as well as how to develop a simplified yet robust calculation method for evaluating these effects in practice. After this initial input, Eerik Mäkitalo tirelessly helped me put those ideas into practice by making numerous IDA Indoor Climate and energy (IDA-ICE) simulations during the article (II) work which we did together. Special thanks also go to Mika Vuolle and Bengt Hellström at Equa Simulation Finland Oy for their IDA-ICE guidance during the simulation phases outlined in Articles I, II and V. Thanks also to doctoral students Satu Huuhka, Arto Köliö and Toni Pakkala, as well as Ville Kovalainen for co-authorship of my articles. The co-operation I have received from all of my colleagues throughout this project has been most gratifying.

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Finally, I would like to remind all readers that this project only represents a few steps in the author's career – nothing more and nothing less. Although this project is over, life goes on.

Tampere 22.05.2017



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Kimmo Hilliaho

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# Terminology

Balcony	A platform projecting from the wall of a building, supported by columns, side walls or console brackets, and enclosed with a balustrade or railing along its outer edge. Usually, a balcony is situated above the ground floor and accessed from inside the building.
Balcony glazing	Prefabricated glazing system, which consists of openable single glass panes. A critical feature of this glazing system is that it is structurally so leaky that installation of the glazing does not change the balcony nature as an outdoor space and, therefore, is not counted as part of the gross floor area of the building.
Double skin façade (DSF)	A multi-layered external wall construction with an external skin (glazing), an internal skin (typically glazing) and an intermediate space used for controlled ventilation and solar protection.
Dynamic energy simulation	A single or multi-zone simulation for the study of indoor climate and energy use of a specific room or an entire building. The computer model represents the building itself, whereas the dynamic simulation represents the operation of the system over time.
Energy saving effect	Percentual or kilowatt-hourly changes in building heating energy demand, achieved by using some energy conservation measure.
Glazed balcony	A balcony in which glazing has been installed between the balustrade and the ceiling to form an enclosed space.
Glazed space	A general definition for any large or small outdoor space, such as balcony, veranda, court-

yard or street, which is connected to a building and sheltered from adverse weather by glazing.

Goodness of fit

Statistical measures, which summarize the discrepancy between observed values and the values expected under the model in question. The results describe how well the model fits a set of observations.

Manual calculation method

A simplified calculation procedure, which makes it possible to evaluate the different design options at an early design stage with paper, pen and a pocket calculator. The method does not give exact answers, but it does give an idea of magnitude with adequate accuracy.

Model calibration

Model calibration is the process of adjusting the model parameters and squeezing into the margins of the uncertainties to obtain a simulated representation of the studied processes that satisfies the pre-agreed 'goodness of fit' criteria.

Model validation

The set of processes intended to verify that the model is sufficiently accurate for its intended purpose. These processes include identifying the potential limitations of the model and assessing their possible impacts. The key concept is to make the model sufficiently accurate.

Sunspace

A general definition for a small outdoor space, such as a balcony or a veranda, which is either attached or integrated into a building and sheltered from adverse weather by glazing.

Surface temperature

The temperature of an opaque or glazed surface measured by unshielded thermocouples, which are attached to the surface.

The dry-bulb temperature (DBT)

Temperature of the air measured by a thermometer freely exposed to the air but shielded from radiation and moisture. DBT is usually referred to as air temperature and measured in degrees (°C) in this thesis.

## List of Symbols

$H_g$	= the sum of the specific losses from the glazed space to the outside ( $W/^\circ C$ ) and specific gain from the building to the glazed space ( $W/^\circ C$ )
$G$	= relationship between the specific losses from the glazed space to the outside and specific gain from the building to the glazed space (-)
$T_g$	= temperature in the glazed space ( $^\circ C$ )
$T_o$	= outside air temperature ( $^\circ C$ )
$T_i$	= temperature in the flat adjacent to the glazed space ( $^\circ C$ )
$\Phi_p$	= solar radiation absorbed to the glazed space, mean over time (W)
$\rho \cdot c_p$	= density times heat capacity of air ( $Wh/m^3^\circ C$ )
$U$	= thermal transmittances of constituent structure ( $W/m^2^\circ C$ )
$A$	= areas of the constituent structure ( $m^2$ )
$\sum_{\text{from}} UA$	= the sum of the areas of all surfaces in contact with the outside, multiplied by their U values ( $W/^\circ C$ )
$\sum_{\text{to}} UA$	= the sum of the areas of all surfaces between the glazed space and adjacent flat, multiplied by their U values ( $W/^\circ C$ )
$V_i$	= volume of flat adjacent to glazed space ( $m^3$ )
$V_g$	= volume of glazed space ( $m^3$ )
$n_i$	= number of air changes per hour (1/h) through the flat surface in contact with glazed space
$n_g$	= number of air changes per hour (1/h) through the glazed space surface in contact with outside
$S$	= solar collection property for the glazed space in question (-)
$g$	= the proportion of solar energy that finally ends up in the interior through the glazing in question (-)

$Q_{sol,gl}$	= solar radiation to the glazing in question, mean over time (W/m <sup>2</sup> )
$E_{dif}$	= the diffuse solar radiation (W/m <sup>2</sup> )
$E_{glo}$	= the global solar radiation (W/m <sup>2</sup> )
$E_{dir,norm.}$	= the direct normal solar radiation (W/m <sup>2</sup> )
$\alpha_{sol}$	= the solar elevation (degrees)
$E_{\%,base}$	= percentual heating energy savings in base case (%)
$E_{kWh,base}$	= kilowatt-hourly heating energy savings in base case (kWh)
$T_{max,base}$	= balcony maximum temperatures in base case (°C)
$T_{min, base}$	= balcony minimum temperatures in base case (°C)
$T_{avg, base}$	= balcony average temperatures in base case (°C)
X	= estimated variable in actual design situation ( $E_{\%}$ , $E_{kWh}$ , $T_{max}$ , $T_{min}$ or $T_{avg}$ )
$\Pi$	= a symbol depicting product sequence
$\alpha$	= calculation coefficient for balcony deviation (-)
$\beta$	= calculation coefficient for flat deviation (-)
i	= the index for balcony deviation calculation coefficients (a,b,c,...,m)
j	= the index for flat deviation calculation coefficients (1,2,3,4,5)
$X_{base}$	= the value of variable X for base case ( $E_{\%,base}$ , $E_{kWh,base}$ , $T_{max,base}$ , $T_{min,base}$ , $T_{avg,base}$ )
$\Delta T_{avg}$	= temperature difference between the glazed space and outdoor air (°C)
$T_{average\ outdoor\ temperature}$	= yearly average outdoor temperature of the city (°C)
$R^2$	= coefficient of determination
R	= correlation coefficient
MBE	= mean bias error (%)

RMSE	= root mean square error (%)
CV(RMSE)	= coefficient of variation of the root mean squared error (%)
MPE	= mean percentage error (%)
MAPE	= mean absolute percentage error (%)
MAX	= maximum value or maximum error (positive difference)
MIN	= minimum value or minimum errors (negative difference)
SI	= sensitivity index
$E_{\max}$	= the maximum effect (in %) of the considered parameter on output
$E_{\min}$	= the minimum effect (in %) of the considered parameter on output
$X_{meas,i}$	= the actual measured value at time interval i
$X_{model,i}$	= the modelled value at time interval i
$n$	= the number of time intervals considered
$\overline{X}_{meas}$	= the mean of the measured values



## Abbreviations

ASHRAE	= American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	= Open-source concrete panel construction system of Finnish apartment block of flats
DSF	= Double skin façade
EN	= European Standard
FEMP	= Federal Energy Management Program
FMI	= Finnish Meteorological Institute
HDD17	= Estimated heating need of building (Heating degree days), calculated by adding up the difference between the presumed indoor temperature +17 °C and the daily average outside temperature.
HVAC	= Stands for heating, ventilation and air conditioning
IDA-ICE	= Dynamic building simulation tool
IEA	= International Energy Agency
IPMVP	= International Performance Measurements and Verification protocol
ISO	= International Organization for Standardization
IWEC	= International Weather for Energy Calculations, version 1.0
IWEC2	= International Weather for Energy Calculations, version 2.0
Meteonorm	= Computer software, which offer the access to accurate climate data for any place on earth
M & V guidelines	= Measurement and verification guidelines for federal energy managers, procurement officials, and energy service providers.
NMF	= Neutral model format, a computer code
SFS	= Finnish Standards Association

- SHC = The Solar Heating and Cooling Programme, established by the International Energy Agency (IEA) in 1977.
- SMHI = Swedish Meteorological and Hydrological Institute
- WIS = A multi-purpose software tool for the thermal and solar characteristic assessment of window component and systems.

## List of Original Publications

- I. K. Hilliaho, J. Lahdensivu, J. Vinha, Glazed space thermal simulation with IDA-ICE 4.61 software-Suitability analysis with case study, *Energy Build.* 89 (2015) 132-141.
- II. K. Hilliaho, E. Mäkitalo, J. Lahdensivu, Energy saving potential of glazed space: Sensitivity analysis, *Energy Build.* 60 (2015) 87–97.
- III. K. Hilliaho, A. Köliö, T. Pakkala, J. Lahdensivu, J. Vinha, Effects of added glazing on balcony indoor temperatures: Field measurements, *Energy Build.* 128 (2016) 458-472
- IV. K. Hilliaho, V. Kovalainen, S. Huuhka, J. Lahdensivu, Glazed spaces: A simplified calculation method for the evaluation of energy savings and interior temperatures, *Energy Build.* 125 (2016) 27-44.
- V. K. Hilliaho, B. Nordquist, P. Wallentèn, A.A. Hamid, J. Lahdensivu, Energy saving and indoor climate effect of an added glazed facade to a brick wall building: case study, *J. Build. Eng.* 7 (2016) 246-262

## Author`s contribution

The author is the principal author of all five articles (I-V) referred to here and the main researcher in the studies relating to articles I-IV. The principal researchers of the project relating to article V were Birgitta Nordquist and Petter Wallentèn at Lund University. Detailed descriptions of the author`s contributions are described below.

- I. In (I), the suitability of the IDA ICE 4.6.1 software for the glazed space simulation was analyzed. The author`s contribution was notable in relation to the field site acquisition, the measurement arrangements and the installation of the sensors, and was essential in relation to collecting, processing and analysing the results. The IDA-ICE model creation and simulations studies were done entirely by the author. Juha Vinha led the research project on which the article was based, and Jukka Lahdensivu supervised the article-writing process.
- II. In (II), the heating energy-saving of balcony glazing in different design situations was analyzed. The author carried out a literature review, created a simulation model and selected the calculation variables for the sensitivity analysis. The simulations were conducted with Eerik Mäkitalo and the article was written in cooperation with Jukka Lahdensivu.
- III. In (III), the effects of added glazing on balcony indoor temperatures were analyzed. The author`s contribution to the field-site acquisition, monitoring equipment installation and measurement follow-up was considerable and the measurement results collection, processing and analysis were conducted entirely by the author. Toni Pakkala contributed to the climate and weather section of the article, Arto Kölliö to the studied building and balconies section of the article and Jukka Lahdensivu to the structuring and writing process of the article. Juha Vinha directed the research project relating to the field measurements.
- IV. In (IV), the simplified method for glazed space interior temperature and heating energy-saving evaluation was implemented. The author carried out the method development and reliability analysis. Satu Huuhka contributed to the article`s background section as well as helping in structuring and writing the article. Ville Kovalainen assisted in structuring the equations and the error analysis of the simplified method. Jukka Lahdensivu led the article writing process.

V. In (V), the heating energy saving and indoor climate effects of an added glazed facade to a brick wall building were analyzed with the help of field measurements and computer simulations. The author made the IDA-ICE model, carried out the computer simulations and analyzed the results. Site inspection and monitoring system calibration as well as data collection and analysis were carried out by co-authors Birgitta Nordquist and Petter Wallentèn, together with their research groups. Akram Abdul Hamid generated the climate data to be used in the simulations. Jukka Lahdensivu contributed to the organization of the research visits, participated in the brainstorming and led the article writing process.

# 1 Introduction

## 1.1 General

The building of concrete blocks of flats increased dramatically in Finland in the 1960s due to social and economic changes resulting in the large-scale migration of Finland's rural population to urban growth areas. This move drove the construction industry to develop more efficient construction techniques, which led to the development of an open precast concrete element system in the late 1960s known as BES [1]. The advantage of this open system was the standardization of structures and their assemblies, which opened up the market for manufacturers, designers and contractors working in the precast concrete industry.

Indeed, the structures, panels and plans of most of the blocks of flats built in Finland from the 1960s onward are highly standardized [2, 3, 4, 5]. The floor plan is usually composed of single-staircase lamellas that hold 3-4 apartments/floor. These lamellas can be assembled sequentially to form longer buildings. Most typically, the residential buildings have 2-3 staircases (lamellas) and are 3-5 storeys high. Since 1969, Finland has produced 38,500 BES-system-based blocks of flats, and a further 37,500 office buildings in which prefabricated concrete units have been used, either in the whole building or significant parts of it [6]. These buildings account for 37 % of the Finnish building stock (excluding small detached and terraced houses constructed mainly of timber) [6].

The concrete panels used in the exterior walls of BES buildings have chiefly been sandwich-type panels with thermal insulation placed between two concrete layers. The thermal insulation capacity of the wall structures has been controlled by building codes which stipulate a thermal transmittance coefficient (U-value) requirement for the buildings. Since 1962, these requirements have gradually been tightened up. From 1962 to

1974 the requirement was  $0.70 \text{ W/m}^2\text{°C}$ . Stricter requirements were then set in 1974, 1976 and 1978 ( $0.35$ ,  $0.40$  and  $0.29 \text{ W/m}^2\text{°C}$  respectively). In 1985, the requirement was set to  $0.28 \text{ W/m}^2\text{°C}$ . Following this, still tighter regulations were implemented in the 2000s, namely in 2003, 2007 and 2010 ( $0.25$ ,  $0.24$  and  $0.17 \text{ W/m}^2\text{°C}$  respectively) [7]. How closely the buildings have followed the requirements was shown in a survey conducted on 2,161 existing prefabricated wall structures [8]. U-values have also been laid down for windows and doors. The requirement for windows was set at  $2.10 \text{ W/m}^2\text{°C}$  in 1976. This was changed to  $1.40 \text{ W/m}^2\text{°C}$  in 2003, and most recently to  $1.00 \text{ W/m}^2\text{°C}$  in 2010, which is where it stands today. The U-value for doors was set at  $0.70 \text{ W/m}^2\text{°C}$  in 1976,  $1.40 \text{ W/m}^2\text{°C}$  in 2003, and has been  $1.00 \text{ W/m}^2\text{°C}$  since 2010 [7].

## 1.2 Finnish balconies

Balconies in Finnish residential buildings are generally projecting structures supported by the building's frame and external balcony towers with their own foundations are the most common type. There are also modular structures supported by tailored suspension solutions and balconies of various mixed types characterized by varying methods of support and varying degrees of prefabrication. [9]

In the 1960s, the facades of Finnish blocks of flats were typically built of band wall panels that enable continuous window lines. Balconies were typically fully or partly integrated into the building (recessed from the facade surface). Most of these balconies were BES element structures. However, in older buildings, there are also fully or partly integrated balconies which were cast in-situ. Such balconies were supported by the load-bearing partitioning walls, which have short steel girders passing through the wall insulation space into the main frame of the building [10].

Towards the end of the 1960s, builders realized that the integrated balconies were laborious to build, and that they were incompatible with element-based construction work. As a result of this, extended balcony towers supported on their own foundations became commonplace. These prefabricated load-bearing structures are often supported via load-bearing frame walls, columns, or a load-bearing external wall envelope on its own, dedicated foundations. [10]. The prefabricated balcony units are joined to the main frame of the building with reinforced concrete connections, and supported with steel joints which counteract the horizontal forces. These external balcony towers have been the most common type of balcony in Finland since the late 1960s. [9]

Since the 1980s, the architecture of balconies has become more diverse and new support solutions have become more commonplace [9]. The possible solutions include suspended balconies, which are typically either modular balconies or balconies supported by the frame walls of the building. In the case of prefabricated modular balconies, the slab, parapet, and frame walls form a single element suspended by steel lugs from the top or bottom corners of the external frame walls, the partition walls, or the intermediate floor edges. Balconies supported on frame walls are assembled from a special parapet, a slab, and frame elements. However, the entire balcony structure can be suspended from the building's frame using frame element starter bars which can withstand both the vertical and horizontal forces on the structure. Since 1960, by far the most common balcony type has been the protruding, self-supporting balcony with load-bearing sidewalls [5, 9]. According to a 2014 market survey of glazed balcony solutions, construction companies favor interconnected balconies with two open sides, on to which the balcony glazing can be installed (Figure 1) [11].



Figure 1. Two examples of the most typical balcony, balustrade and balcony glazing solutions currently in use in Finland in new constructions (pictures courtesy of Lumon Oy). The commonly used balcony glazing blinds [12] are shown in the left picture.

However, there have been some drawbacks with this method. For example, previous studies on protective pore ratios have shown that the frost resistance of these balconies is poor, especially in the balcony frame walls, where over two thirds of the surveyed balconies showed insufficient frost-resistance properties. Many of the reinforcement cover depths have also been found not to meet the minimum requirements for corrosion protection. Thus, a large proportion of balconies exhibit local, or in some cases, widespread corrosion damage. Nevertheless, despite the structures' poor frost resistance, visible frost damage is still relatively rare. [8]. Since both types of degradation are highly dependent on moisture, the control of moisture is crucial in mitigating and preventing further corrosion or degradation-related damage. Therefore, balcony



glazing is one potential way to control the exposure of balconies to moisture, both in new construction and in renovation work [13].

### **1.3 Balcony glazing**

Glazed balconies really began to gain in popularity in the mid-1980s. Their popularity increased in the 1990s (Figure 2) and they had become established as a feature of Finnish blocks of flats by the early 2000s. At first, the installation of balcony glazing was either due to the owner-occupant's own alteration work to his/her balcony or by centralized investment by the housing cooperative for all the balconies in a building. As architects, engineers and builders gained experience in how to build and utilize glazed balconies, they also became common practice in new constructions, and nowadays most new blocks of flats in Finland boast glazed balconies, which were planned for during the initial design phase. However, the balconies in older blocks of flats were usually designed as unglazed spaces, so most of them have glazing which has been added later on in the building's life. One can get an idea of just how popular glazed balconies are in Finland by comparing the number of glazed balconies (more than 600 000) to the housing database for 2016. This reveals that approximately 75 % Finnish apartmental balconies have already been glazed. In fact, in 2012, glazing was added to 9000 more balconies than were built [11, 14], and at this installation rate, all of Finland's glazing-eligible balconies will have been glazed in the next ten years. Of course, an installation rate of 100 % is not really achievable in practice. There are, for example, many buildings in which balcony glazing can not be installed, either for structural reasons, or simply because it is not considered desirable by the apartment owner. These facts may, to some extent, explain why the number of glazed balconies has been tailing off somewhat since its peak in the mid 2000s (Figure 2).

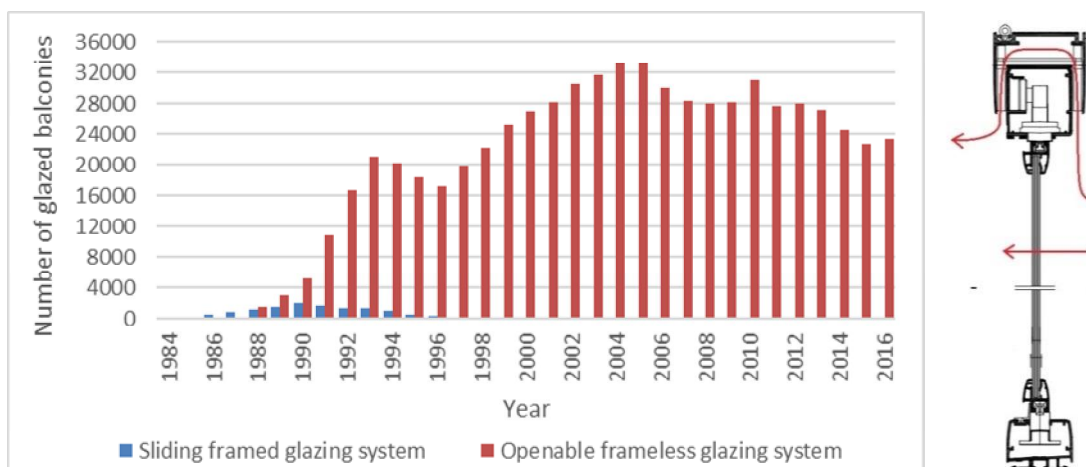


Figure 2. Balcony glazing installation in Finland during the period 1984 – 2016 and most commonly used glazing system [11, 15]. Ventilation routes are shown by the red arrows on the left.

The installation of glazing in single-family detached or terraced houses is less common than it is in urban blocks of flats. According to information received from Finnish glazing manufacturers, about 60 000 of these buildings' terraces had been glazed in by the end of 2016, which means that less than 10 % of single-family houses have glassed-in terraces. Nevertheless, the focus of the glazing market is changing slowly from blocks of flat to detached or terraced houses, largely because most of the newer blocks of flats already have purpose-built glazed balconies and most of the older blocks have already had glazing fitted.

Sun protection devices are now a common feature of balcony glazing solutions. For example, factory-made shades for balcony glazing had been installed in about 80 000 glazed balconies by the end of 2016, and as Figure 3 shows, these are increasing in popularity all the time.

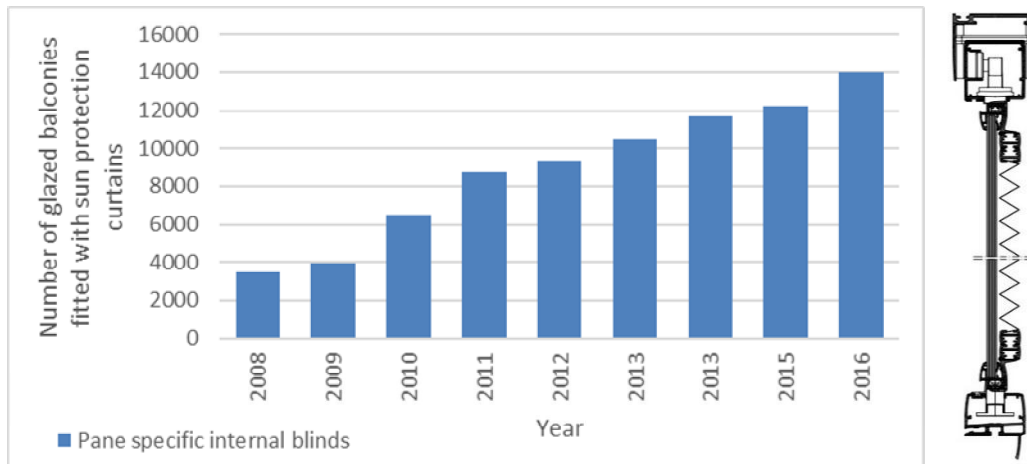


Figure 3. Number of glazed balconies fitted with sun protection curtains in Finland during the period 2008 – 2016 and the most commonly used internal blind solution [15].

Nearly all of the balcony glazing systems have similar components consisting of aluminium profiles, aluminium strips and glass panes. The installed components form a transparent glass 'wall' between the balcony balustrade and the ceiling. These glazing systems typically consist of 5 to 6 hardened glass panes ( $U=5.8 \text{ W/m}^2\text{°C}$ ,  $g=0.82$ ). The first pane of the system is always held in place by hinges. It can be opened with a handle and locked in a ventilating position (from closed to fully open) using a cord lock. The rest of the panes can be slid away from the first pane, and can be folded in parallel with each other. Adjustments to the balcony structure can be made using edge seals, fastenings, and adjustment profiles. Sub-sills made of plastic-coated sheet steel or aluminium are typically used for water control. The system can also be fitted with additional structures, such as sun blinds and partitions. [15]

The glazed spaces have to be ventilated in order to prevent moisture condensation. This ventilation occurs passively through air gaps of 2-3 mm [15] between the glass panes. In some glazed balcony solutions, there is also an air gap of 7 mm between the two mounting profiles at the top of the system (Figure 2) or a gap between the upper mounting profile and the ceiling (Figure 4). Because the balconies are uninsulated and the glazing solutions are not airtight, continuous heating of the balcony is very rare and is generally considered to be uneconomical in these latitudes [16]. If the glazing structurally resembles an airtight external wall, then according to Finnish building regulations that space would have to be calculated into the gross floor area of the building [17] and regarded as an indoor space in relation to the ventilation arrangements, etc. This would sharply increase the cost of the glazing solution.



Figure 4. Example of typical balcony renovation work. The balcony slab and side wall are fixed, the balustrade varies from a concrete parapet to a glass-aluminum balustrade with balcony glazing installed (pictures courtesy of Lumon Oy).

As can be deduced from the above, in current balcony design the glazing has not been constructed and installed to optimize the space's indoor temperature conditions or to maximize the heating energy-saving effects. The main reasons for this are: a) the general belief that glass-enclosed spaces do not have any clear energy-economy benefits in terms of energy consumption in the Nordic climate; b) the lack of easily accessible information about key factors affecting the heating energy-savings and the indoor climate of glazed spaces; c) the complexity and labor intensity of the current calculation procedures, and d) there are no special requirements for the indoor air condition of glazed balconies in Finnish building regulations. It is indicative of the general public's poor awareness of the heating-energy saving benefits of glazing that some residents leave their balcony glazing partly open in the winter season, or fully closed in the summer.

Depending on the season, this either lowers the heating-energy saving potential of the glazing or increases the risk of overheating. [18, 19]. Thus, there is a pressing need to make practical information about the impact that balcony glazing can have on energy consumption and the indoor climate available to the general public, as well as more simplified design methods for new glazed balconies which would maximize the heat-energy savings for the building. Indeed, the need for such information to be more widely disseminated has been pointed out in many previous studies [20].

## 1.4 Double skin facades in Nordic countries

The thermal behavior of a glazed balcony is similar to that of a double skin façade (DSF), especially when the DSF's internal layer is opaque with a high thermal mass (Figure 5). This is significant because some DSF applications, such as box window facades, are structurally very similar to glazed balconies. As a result, many of the research findings from DSF studies can be exploited in the study of the thermal behaviour of Finnish glazed balconies. The most significant differences are the cavity depths in DSFs, which are usually much less than the depth of a balcony, and the structure of the external layer, which in a DSF is usually tightly sealed and impossible to open completely.



Figure 5. Example of a double skin façade with an opaque internal layer.

In general, a DSF consists of an external and an internal layer with a 0.2 to 2+ m deep [21] cavity space, which acts as a buffer and can be used for controlled ventilation and for solar protection [22]. The inner and outer layers are typically made of glass [23] which is single glazing for the external skin [24] and there are shading systems located inside the cavity [25] (much like the sun protection solutions used for Finnish balconies).

From the researcher's point of view, there have been remarkably few field-measurements or simulations of the thermal characteristics of structures where the internal skin of the façade consists of material with a high thermal mass [21]. Similarly, measures for adding glazing to protect old facades while they are being renovated [26] have also received little attention. Most of the time, such glazing solutions involve using either solar-protection glazing (low solar factor) in cooler climates [27] or solar-permeable glazing (high solar factor) in warmer climates. High solar factor glazing (as

in Finnish balconies) is more beneficial than low solar factor glazing when the cavity is used to pre-heat the ventilation air for the main building's interior [28], because it increases the solar heat gain of the space.

The ventilation of the cavity can be passive, forced, or a combination of the two. It has been suggested that the cavity ventilation be integrated with the building ventilation system [29] and adjusted according to the prevailing climate conditions [30]. On the other hand, there is also the notion that high-efficiency heat recovery will lower the overall benefits of the DSF, and in such cases it is suggested that the intake air for the ventilation should bypass the cavity [28]. Ground-coupled heat exchangers have also been evaluated [31], but rarely in connection with double facades.

According to the design strategies introduced in [32, 33], previous DSF solutions in Finland and Sweden do not seem to have been particularly well optimized. Typical DSFs cover a whole façade from top to bottom [34] and are equipped with venetian blinds placed inside the cavity. Any gaps in the façade are closed during the winter and opened during the summer [34]. Although there have been some studies of the energy-saving effects of DSF solutions [35] very few full-scale measurement studies have been made in real buildings [36, 37, 38] and even fewer such studies have been made in Nordic climatic conditions.

Article V makes up for this by presenting full-scale measurements and simulation studies on the heat-energy saving potential of a DFS building from the unique perspective of the Nordic climate. Some specific characteristics of the studied brick building are listed below:

1. A DSF was chosen as a renovation solution for this old and architecturally significant building, because the building's facade cannot be touched, as it needs to be visible and preserved for its architectural value. The literature reveals one similar study [26], but the solution is almost unique.
2. The DSF's internal skin is not glass, but is an opaque material with a high thermal mass. There are some studies of DSFs with a concrete internal skin in the literature [2], but none on buildings with a brick wall façade. Typically, a DSF consists of two glazed skins which are between 0.2 m and 2 m apart. The outer skin is typically hardened single glazing while the inner skin is double glazing.
3. The DSF is connected to a supply and exhaust ventilation unit with a highly efficient heat exchanger. One study of a similar system was made in Norway, but in connection with a new office building [28]

4. There are two options for controlling the air intake, which can either come directly from outside, or from the air in the DSF's cavity. Control between those two options can be changed by changing the set-limits of the cavity temperature (if the temperature is higher than the set limit, then the air comes directly from outside to the ventilation unit).
5. The cavity has an air circulation unit which circulates the heat between the different-facing facades of the building. No such system has been found in the literature.
6. The cavity can be cooled using a ground duct system connected to the double skin façade in the building. Ground duct systems are, on the whole, pretty rare, especially in apartment buildings. However, one study of a ground duct system connected to a three-storey office building was found in the literature [31].
7. The cavity can be cooled in three different ways: 1) inlet air from the ground duct system, 2) mechanical air exhaust to the outside air and 3) passive air exhaust passively through two windows. The temperature set-point can be adjusted for all three of these methods

More information about the advantages and challenges of double-skin facades (DSFs) are discussed in reference [39].

## 1.5 Why balcony glazing?

For centuries, large glazed spaces have been architecturally and structurally interesting features in buildings. Their attraction lies in the large enclosed spaces, novel architectural solutions and interesting details [40, 41, 42]. Nowadays, these spaces are not usually built solely for architectural reasons, but for functional ones, as they often serve as hospital waiting areas, for example, or reception areas in office buildings. Nowadays, the design of such spaces is controlled by the required indoor air conditions, such as minimum acceptable indoor air temperature, desired average temperature, and maximum acceptable temperature. These factors determine the design solution, which takes into account issues such as heat losses in the building and the glazed space, the storage of solar radiation (or protection from it), and the minimisation of cooling and heating needs if the required indoor conditions cannot be realized without an external energy source. [20]

At first glance, the glazed spaces in most Finnish building stock do not appear to have been designed for the grandeur of the enclosed space or their novel architectural solutions and detailing. Most of the glazed spaces in Finnish residential buildings are quite simple, and relatively small. They are attached to residential apartments or houses and

their main function is to serve as an outdoor space for urban Finnish flat-dwellers [18], and are commonly referred to as the ubiquitous 'glassed-in balconies'. Since the 1970s, most blocks of flats in Finland have been built with their own balconies. Research has revealed that these outdoor spaces, hereafter referred to as balconies, are regarded as an extra room in a dwelling [18, 11], which, if well designed, can increase the value of an apartment [11] and improve the resident's quality of life [43]. For most Finns, the important features of the balcony are its functionality, size, brightness, durability and aesthetics [11]. In residential buildings, balconies are commonly used for recreational activities, and are most frequently used in the summer, usually in the afternoon and evening [18, 43]. Apart from the size of the balcony, the main factors that hinder its use for the average Finnish flat-dweller are rain and snow, or leaves, dirt and dust blown in from outside. Wind and noise pollution may also prevent the use of balconies [18, 43]. Most of these problems with balconies can be mitigated with openable glazing, [18, 43, 44] which is why the 'glassed-in balcony' has become such a desirable upgrading option. It is especially favoured in sheltered homes for instance, [43] and is the recommended design guide for government-subsidized construction [45].

At the onset of the popularization of the 'glassed-in balcony' (hereafter referred to as the glazed balcony), the reason for installing glazing was to increase the usability of the space for the residents [13]. Nevertheless, from an architectural and engineering perspective, a glazed balcony forms a structural layer which shelters the balcony's inner structures from rainwater, snow and (in the cities, certainly) air pollution. Another benefit is the increased indoor temperature [13, 46], which extends the annual and daily use of the balcony [18]. Together, the reduced exposure to rainwater and the increased interior temperatures lower the moisture stress in the balcony, and in the exterior walls of the adjoining flat. A good structural protection is particularly helpful in extending the service-life of non-freeze-thaw-resistant concrete structures common in 1970s blocks of flats [13]. As sunspaces, they also provide a buffer space against wind pressure [47], improve noise protection [48] and make it possible to take a pre-heated supply air from the glazed space, thus reducing the building's overall heating-energy consumption [48, 49]. On the other hand, research has also shown that balcony glazing can lead to uncomfortably high indoor temperatures during the summer months [44], so the designers of the balconies also have to pay attention to sun protection.

Studies show that the existing glazed balconies are not optimised from the energy efficiency, indoor climate and sound insulation point of view, because they have been designed more for protection from the weather. One reason for this might be that there is very little publicly available information about the impact of balcony glazing on energy costs, sound insulation and the indoor climate. Another reason is that building industry guidelines and regulations limit the design of the glazing solutions. For example, the



Environmental guide 72 [17] states that a glazed balcony need not count as part of a building's floor area as long as it can be defined as an outdoor space after the glazing installation. This means that it can be protected with movable glazing structures, such as sliding windows, as long as 30 % of the glazing can be opened and if the glazing structure is loose enough to allow for passive ventilation through the air gaps between the panes of glass [17, 50]. Fire safety [51], sound insulation and rainwater removal regulations do have to be taken into account. The glass panes must be toughened or laminated glass, and they must be installed in such a way that they can be washed easily and safely both inside and out [50]. This thesis discusses glazing products which have been manufactured according to these criteria. The energy saving potential and options for improving the indoor climate of the glazed balcony itself, and preventing the balcony from exerting any negative effects on the adjoining flat are also discussed.

## 1.6 What is special about glazed balconies physics?

It has often been argued that conventional building-energy simulation software is not up to the task of calculating the building-energy needs of buildings with highly glazed spaces and double skin façades, as these are special design tasks for which such software has not directly been designed. The main reason for this is that it is difficult to estimate how much of the solar heat gains will penetrate through the DSF cavity or glazed space into the building, and how much of it will be captured by the air in the cavity or balcony space, especially with naturally ventilated cavities and glazed spaces, which are the usual solution for Finnish balconies. The references [20, 52] deeply discuss the problems with numerical modeling of glazed spaces [20] and DSF buildings [52]. The main considerations of the above references are listed below.

**Solar radiation:** The intensity of the solar radiation and the position of the sun in relation to the glazing is constantly changing. Therefore, the amount of solar radiation which is transmitted, absorbed and/or reflected through the glazing also changes continuously. This creates a requirement for a detailed 3D calculation of the solar radiation in simulation software [52]. Reference [20] highlights the fact that a geometrical description of the building provides an appropriate basis for a more detailed calculation of the distribution of solar radiation in and between rooms.

**Window model:** The G-value (solar heat gain coefficient) of the DSF cavity or the balcony space is highly dependent on the rate of the airflow, the air temperature and the flow regime in the cavity or space. These values depend on the height of the cavity or space, and the type and usage of any sun protection system. As a consequence of this,

one cannot calculate g-value by simply combining the transmitted solar radiation with that part of the solar radiation which is absorbed by the glazing panes and then transferred to an adjacent zone. This is because such a calculation method assumes that the major part of the absorbed solar radiation is transferred to the adjacent zone and not to the cavity of the glazed space, which is what actually happens [52]. This leads to a misinterpretation of the effects that a DSF or a glazed space has on the building's heating and cooling needs, and on its indoor climate.

**Long wave radiation exchange:** Assessing the longwave radiation exchange with detailed view factor calculations is important in any building-energy simulation, and especially so in simulations of DSFs and highly glazed spaces. This is because any error calculations will be higher in those buildings than they would be in the calculations for a traditional building because of the higher temperature difference between the construction layers (between the panes in the DSF and between the different surfaces in a glazed balcony). For example, the higher surface temperature of a shading device or inner window pane in a DSF building will, in reality, result in additional heat gains in the occupied zone, unlike with the traditional external façade [52]. This effect should be taken into account in all such calculations .

In practice, long-wave radiation exchange also takes place between the sky and the external surfaces of the building. As a result, the surface temperature of the outer surface of the glazing may be cooler than the temperature of the outside air, especially on cold, clear winter nights. This sets a special demand for any detailed longwave sky radiation calculations, especially in the case of a glazed roof. For example, it is difficult to estimate the temperature in the upper part of a space under a glazed roof unless the sky radiation is taken accurately into account. This may be difficult, as the sky radiation is affected by the cloud cover and temperature of the sky [20], but it must be accounted for as accurately as possible.

**Convective heat transfer:** The procession of convective heat transfer in the simulation is particularly difficult, and even more difficult when calculating it for DSF cavities or glazed spaces. Choosing the right expression for the convective heat transfer coefficient is always a lively topic of discussion in building physics calculations. It is defined by the thermal conditions, the flow rate and the flow regime, all of which can change rapidly, especially in naturally ventilated cavities. This sometimes leads to a flow condition in which more than one expression may be required. The simulation tool must be able to handle the changes in flow regime and thus in the convective heat transfer. [52]. More information about the challenges of convective heat transfer and air flow rate calculations through building components are discussed, for example, in Petter Wal-lentèn`s dissertation "Heat Flow in Building Component, Experiment and Analysis".

**Air flow in the cavity:** The air is heated up or cooled down after entering the DSF cavity or glazed space because of the convective heat transfer from the surfaces and from any shading devices. The air mass thus rises and falls due to the forces of buoyancy. The strength of these forces is, in turn, strongly dependent on the air temperature and the convective heat transfer at the surfaces [52]. The higher the temperature, the greater the strength of the buoyancy force. In other words, the increased buoyancy force speeds up the air change rate in the cavity, which lowers the surface and cavity air temperature. This leads to a drop in the air change rate, which then starts another increase in the temperature of the cavity air and surfaces [52]. Consequently, the mass flow rates and temperatures change regularly, much like a self-regulating vent [53].

An increase in the cavity temperature indicates the amount of additional heat the building could gain if the cavity air were used instead of outdoor air for the building's ventilation. It also shows the amount of surplus solar gain, which should be removed from the system in the summertime (for example with solar shading and airing). In both cases, the higher the temperature of the air when it is leaving the cavity, the more efficient the system is. For this reason, it is important to trap as much solar radiation as possible in any DSF cavity or glazed space. [52]

**Wind forces:** One random and highly fluctuating driving force is the wind. It is difficult to estimate and simulate, but it is particularly important in connection with naturally ventilated double skin facades or glazed spaces. In those situations, the wind and buoyancy forces may either counteract or complement each other, which will determine the mass flow in the cavity. The close interrelation between convective heat transfer and the rate of random air changes in the cavity makes an evaluation of the air temperature in the DSF cavity even more complicated. This is because the proportion of the solar heat-gain which is transported away from the cavity (usually to the adjoining flat) changes all the time and according to the prevailing wind. [52]

The above special requirements for simulations of highly glazed spaces and DSF buildings have to be taken into consideration when designing and using DSF simulation software. With regard to the IDA-ICE program, these properties are discussed in more detail in Section 2.3.4.

## 1.7 Objectives of the study

The purpose of this study was to investigate the effect that an unheated, glassed-in outdoor space can have on the building's total energy consumption, and to investigate the balcony's indoor climate here, cold northern climatic conditions. Most of the measurements were taken from seasonally-used glazed-in balconies equipped with structurally leaky glazing and relying on the passive ventilation provided by the gaps between the glazing. The main focus of the measurement and simulation studies was to evaluate the main factors which affect the temperature difference between the balcony space and the outside air during the cooler months in the autumn, winter and spring. This temperature difference is a key indicator of how much energy a building can save with a glazed in balcony, as the higher the temperature difference, the greater the quantity of energy which could potentially be saved. As the vast majority of residential blocks of flats in Finland and Sweden are not air-conditioned, the effects the glazing has on the building's consumption of cooling energy has been excluded from the study. However, it is important to pay attention to the properties of solar shading and adequate ventilation in order to create comfortable indoor climate conditions in the balcony spaces and adjacent flats during the summer. Therefore, these issues are discussed in the thesis.

The whole study is divided into five smaller projects with specific objectives, with one article having been written for each theme:

1. Monitor the air and surface temperatures of two balconies (one glazed and one unglazed) and the adjoining flats to evaluate the impact of balcony glazing on the balcony temperatures. Furthermore, to monitor the heat losses from the building's envelope structures between the balconies and the adjoining flats, i.e. the back wall, window and door of the flat. This work was carried out in Tampere and involved intensive site inspections and field monitoring. These were later used to evaluate the suitability of the IDA Indoor Climate and Energy (IDA-ICE) software for glazed space energy simulations.
2. Through sensitivity analyses conducted with IDA-ICE, to determine the effects the following factors have on the energy consumption of the flat: the building's location, the balcony type and its orientation, the tightness of the glazing, the pre-heating of the inlet air (air entering the building from the glazed-in balcony), and the thermal resistance of the structures.
3. Through extensive field research, to measure and compare the temperatures in different types of glazed and unglazed balconies under varying conditions. This data was used to build up a more comprehensive picture of the temperature

variations in the balconies and to verify that the IDA-ICE simulation results in the sensitivity analysis (Article II) are observable in practice.

4. To develop a simplified assessment method for the evaluation of heating-energy savings and effects on the indoor climate of glazed balconies in the preliminary design stage. The method was developed by using the information about the percentual and kilowatt-hourly energy savings as well as the mean, maximum and minimum temperatures of the sensitivity analysis (Article II). The reliability of the method for its intended purpose was also evaluated.
5. To deepen the theoretical and practical knowledge of the research topic, a completely different set of measurements were gathered from a DSF building in Malmö and used as inputs for the IDA-ICE simulations. The aim of this study was to use the IDA-ICE to evaluate the effects of the added glazing on this old building's energy use.

The research has produced a lot of practical information on the impact glazed balconies can have on the balcony indoor climate and heating-energy consumption of a building, and also on the benefits that can be gained by adding glazing to a brick-walled building. The tools developed for this study will also be useful in building design and renovation work, as they can be used to evaluate the energy and indoor climate performance of glazed balconies. The literature review had revealed a distinct lack of practical information on this topic, and a scarcity of user-friendly tools for studying it, so this thesis aims to expand our knowledge in this research area [20].

## **2 Background**

### **2.1 Field monitoring**

#### **2.1.1 Previous monitoring studies**

Glazed space air temperatures have been measured to evaluate indoor climate and thermal comfort almost all over the world. However, many of these studies have focused on very different climates than in Finland [54, 55, 56], often outside Europe [57, 58, 59], or in central and southern Europe rather than the Nordic countries [60, 61]. Nevertheless, there have been a few studies in Finland and its neighboring countries [20, 13, 46, 19, 62].

Some studies have focused on atriums [54, 57], sunspaces [56, 59, 63] or some other type of highly glazed space attached to a main building, which utilize passive solar energy (winter gardens, solariums, greenhouses, etc.). Although some studies have been made of balcony glazing [60, 61, 62], in most of them, either the number of measured balconies has been small [20, 13, 62] and/or their research perspective has been on something other than improving the thermal behavior of a glazed balcony [13, 62]. There are some studies which have focused on the potential of balcony glazing for heating-energy savings [20, 46, 19, 62], a topic also discussed in [18, 7], though without temperature measurements. Generally the older measurements have focused on indoor climate behavior [56, 60] and the later ones, either partially [59] or wholly [56, 63], on the validation of simulation programs. The only extensive field study monitoring glazed balconies is over ten years old. This was conducted under the auspices of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) program, Task 20, 'Solar energy in building renovation'. The results of this study are discussed in, e.g. [48, 49, 64]. Extensive field measurements were not carried out, so the factors affecting the

temperatures in glazed spaces have mainly been analyzed with computer simulations [65, 66].

According to the literature, the glazing studied has generally been single [13, 61] and/or double glazing [16, 66, 67] with sliding [62, 68] and/or non-sliding panes [56], and, as a rule, with vertical frames [16, 62, 66, 67]. However, previous studies have rarely focused on the most commonly used type of balcony glazing in Finland, which consists of frameless single glazing with a sliding, pane-by-pane opening system, such as that in [13]. A special feature of this type of glazing is its 2-3-mm air gaps between the panes, which makes the Finnish balcony-glazing system significantly leakier than the glazed spaces studied in most previous research.

### 2.1.2 Measurement techniques

The air temperature in a sunspace is a complex mixture of solar heat gain, envelope heat loss, infiltration, the energy storage and release effect of internal masses, energy exchange with an adjacent air-conditioned space, and occupant activity [59]. For this reason, the measurements of air temperature are generally accepted as a useful method for evaluating the functionality of the solar design of a sunspace because they reveal the dominant pathways for heat gain and loss and they give an indication of thermal buffer effects and thermal comfort [69, 70].

According to the literature, sunspace air temperatures have frequently been measured to evaluate thermal comfort and operative temperatures, to validate and calibrate simulation software, and to study the efficiency of the implemented passive solar design concepts, etc. all over the world [54, 55, 56, 57, 59, 60, 61, 63]. In these studies, the temperatures of the sunspace, the adjacent living space, and the outside air have usually been monitored using factory-calibrated data loggers [55, 57, 59, 60, 61], temperature sensors [59], and/or thermocouples [54, 56, 57, 63]. By measuring those temperatures, it is possible to obtain information about the temperature of the sunspaces and the overall level of reduction in heat loss in that section of the building which is adjacent to the sunspace (usually a flat) (Equation 1)

$$\text{Heat loss reduction} = 1 - \frac{T_{\text{FLAT}} - T_{\text{SUNSPACE}}}{T_{\text{FLAT}} - T_{\text{OUTDOOR}}} \quad (1)$$

The temperatures have been recorded at 10-min [59], 15-min [55, 58, 60, 61], 20-min [54] or 1-hour intervals, and the measurements lasted from a few days to several years

[13]. The most common temperature recording interval has been 10 or 15 minutes, but one monitoring study has established that a logging interval of one hour would be sufficient [60]. It is particularly important to use the same measurement intervals with individual loggers [60] and to start temperature recording simultaneously as this helps with any later comparison of the results.

In many cases, it has been found helpful to measure the internal and external surface temperatures of the sunspace's opaque and glazed surfaces [59, 63] using thermocouples. The advantage of the surface temperature measurements is that they reveal something about a material's ability to store and release heat energy, although it must be admitted that discrete surface-temperature measurements cannot completely represent the thermal behavior of a large solid mass such as a concrete wall due to its slow stabilization [71]. As a consequence, the measured surface temperature under a thermocouple may be much warmer or cooler than it is on another, immediately adjacent point. Nonetheless, surface temperature analysis is useful and indicates mass temperature patterns [59].

In addition to those measurements, it is also good practice to record actual weather conditions with a dedicated weather station built on the monitoring site. Weather stations have typically been utilized for the comparison of various sunspaces in different locations [59, 60, 61] or for the production of detailed input data for software validation [57, 72]. Typically, these weather stations measure several [60, 61] or all [59] of the following quantities: ambient temperature, relative humidity, wind speed, wind direction, air pressure, global horizontal radiation, direct normal radiation and diffuse radiation. Depending on the intended use of the measurements, it is also worthwhile measuring the surface heat fluxes [59], the radiation levels in the sunspaces [59, 63], the brightness of daylight in the flats (with and without glazing) [60, 61, 67], the space heating and ventilation levels [60], the use of water and electricity [60], the airtightness [58], the heat allocation from the radiators [61] and the air flow from the sunspace to the flat [73]. In addition, the buildings' residents have filled in questionnaires which assess different quality factors affecting the tenants' satisfaction with the glazing solutions [60].



### 2.1.3 Observation errors

An observation error (or measurement error) is the difference between a measured quantity and its true value. It could be a random error, which is unpredictable and unrepeatable, or it could be a systematic error, which is consistent and repeatable. Random error is typically unavoidable, but its likelihood can be reduced by using average measurements from a larger set of measurements, or by increasing the sample size [74]. Systematic errors can be due to the following causes [52]:

- The inaccuracy of the measuring instruments
- The inaccuracy of the experimental methods
- Errors in the data processing
- Errors in the experimental set-up and measurement conditions and procedures
- Uncertainty about the reporting characteristics and the properties of the test facility

Systematic error is usually more important and more difficult to deal with than random error [74]. However, the risk of systematic errors can be considerably reduced by, for example: a) checking all measurements for accuracy, b) making sure that observers and field operatives are well trained, c) taking the measurements with high-precision instruments, d) taking the measurements under carefully controlled conditions, e) pilot-testing the measuring instruments, and f) using different types of measurements for the same construct.

Observation accuracy is highly important in situations where the monitoring results are to be used as an input parameter for simulation software (indirect error) or for a comparison with the results of simulations (direct error) [75]. Observational accuracy is also important in situations where, for example, the observed air temperature is used to adjust a building's heating or ventilation system. This is particularly true of the DSF studied in this thesis because it is an integral part of the building's ventilation system, the operation and control of which is adjusted according to temperature measurements taken in the DSF cavity. In the Malmo case study described in Article V, the whole building's energy performance is highly dependent on the accuracy of the air temperature measurements. Unfortunately, the on-site measurement equipment was faulty, as the sensors were exposed to direct solar radiation, which increased the temperatures they recorded and lead to high-magnitude errors. Other DSF studies have encountered similar problems with the use of thermocouples, covered or not [74]. In order to get really accurate measurements of the air temperature in a glazed space, the thermocouples need to be shielded from the sun and mechanically ventilated [74].

## 2.2 Calculation techniques

### 2.2.1 The manual calculation method

The ISO standard 13789 [76] introduces a general method for calculating a building's thermal performance. ISO 13789 also has an equation for unconditioned space temperature calculation (equation A.1) which is given here in a simplified form as Equation 2:

$$T_g = T_o + \frac{1}{1+G} (T_i - T_o) + \frac{\Phi_g}{H_g} \quad (2)$$

where G is the relationship between the specific losses and the specific gain (Equation 3). This relationship mainly determines the temperature level of the space during the winter months at high latitude [20].

$$G = \frac{\text{specific losses (W/°C)}}{\text{specific gain (W/°C)}} = \frac{\sum_{\text{from}} UA + V_g n_g \rho c_p}{\sum_{\text{to}} UA + V_i n_i \rho c_p} \quad (3)$$

$H_g$  is the sum of the specific losses from the glazed space to the outside (W/°C) and the specific gain from the building to the glazed space (W/°C) and calculated with Equation 4.

$$H_g = \sum_{\text{from}} UA + V_g n_g \rho c_p + \sum_{\text{to}} UA + V_i n_i \rho c_p \quad (4)$$

Other symbols in the equations are:

$T_g$	= temperature in the glazed space (°C)
$T_o$	= outside air temperature (°C)
$T_i$	= temperature in the flat adjacent to the glazed space (°C)
$\Phi_p$	= solar radiation absorbed by the glazed space, mean over time (W).
$\rho * c_p$	= density times heat capacity of air (Wh/m <sup>3</sup> °C)
U	= thermal transmittances of constituent structure (W/m <sup>2</sup> °C)
A	= areas of the constituent structure (m <sup>2</sup> )
$\sum_{\text{from}} UA$	= the sum of the areas of all surfaces in contact with the outside, multiplied by their U values

$\sum_{to} UA$	= the sum of the areas of all surfaces between the glazed space and the adjacent flat, multiplied by their U values.
$V_i$	= Volume of the flat adjacent to the glazed space (m <sup>3</sup> )
$V_g$	= Volume of the glazed space (m <sup>3</sup> )
$n_i$	= number of air changes per hour (1/h) through the flat surfaces in contact with the glazed space
$n_g$	= number of air changes per hour (1/h) through the glazed space surfaces in contact with the outside

The influence of solar radiation on highly-glazed spaces is quite evident, but its effect is difficult to calculate manually. One option, however, is to determine the effect of solar radiation with Equation 5. In this method, the solar collector property for the glazed space in question (S) has been pre-calculated with dynamic simulation software. Maria Wall [20] has calculated these factors for some types of glazed spaces with different glazing combinations.

$$\Phi_g = S \sum g Q_{sol,gl} A \quad (5)$$

where

S	= solar collection property for the glazed space in question (-)
g	= the proportion of solar energy that finally ends up in the interior through the glazing in question (-)
$Q_{sol,gl}$	= solar radiation to the glazing in question, mean over time (W/m <sup>2</sup> )

An equation for calculating monthly solar radiation levels ( $Q_{sol,gl}$ ) by measuring the global and diffuse radiation to a horizontal surface is presented in [77]. Further information about the manual calculation can also be found in references [20, 76, 78].

## 2.2.2 Steady-state calculations and dynamic models

Another option for the analysis of the interior temperature of a glazed space is to use readily available steady-state or dynamic calculation tools, some of whose suitability for glazed-space simulations already have been analyzed in [20]. Also, Poirazis' publications [24, 34] include useful information about the calculation problems of glazed spaces, although these publications focus on calculations for DSFs. The accuracy of the calculation software introduced in the literature varies considerably in terms of its level of detail and the purpose of the software. The rougher methods are based on manual calculations while the more precise ones are based on simulations. In addition, the purposes of the programs range from component level tools (e.g. the Window Information System (WIS) software tool for complex windows and the active façade calcula-

tion [79]) to whole- building energy simulation software. The most flexible software can handle most of these calculations with a relatively high degree of accuracy. [24, 34]

The manual calculation method, such as the one described in Chapter 2.2.1, has been found to underestimate the indoor temperatures of the spaces [78]. On the other hand, some dynamic calculation tools have been found to overestimate the interior temperatures of glazed spaces due to the simplified processing of the solar radiation [20]. For this reason, the calculation software should be carefully investigated and validated before making a final decision on which program to use in glazed-space simulations.

One important consideration for glazed-space calculations is that any dynamic simulation software should take daily and yearly climatic variations into account. It should model the spaces geometrically, divides the solar radiation into direct and diffuse radiation and correctly distribute the solar radiation which comes through the glazing structure into the sunspace. It should also capture the way this radiation is spread around the space, and onward into the adjoining building, or back outside if it has not been totally absorbed into the space. Furthermore, the surface resistances must also be calculated as temperature-dependent variables, and it should also take into account long-wave sky radiation calculations, which is often ignored in energy calculations [20].

To achieve realistic energy-saving results with glazed balconies, detailed calculations for the glazed spaces need to be performed at the earliest possible stage in a building's design. However, those calculations are complicated, and have to take many factors into account, so architects and engineers need practical, user-friendly software for this stage of a building's design. Such software should not increase the designer's workload too much, and nor should it demand too much expertise from its users. The ideal solution would be a calculation method which is as detailed as the most detailed of the currently-used simulation softwares, yet as simple as the simplest manual calculation tool. Unfortunately, we do not live in an ideal world, so in practice, the software for such calculations will always be a compromise between the level of detail it can capture and its ease of use.

## 2.3 Calibrating building-energy simulation models

### 2.3.1 About simulation models

An understanding of scientific models in general is a good basis for a more detailed understanding of building-energy simulations [80]. Scientific models can be classified as diagnostic or prognostic models, and law-driven or data-driven models. Diagnostic models are used to identify the nature of a phenomenon, while prognostic models predict the behavior of a system. From the law- and data-driven models (Table 1), the law-driven models use a system's properties and conditions to predict the system's behavior while the data-driven models use the system's behavior to define its properties. [81]

Table 1. A simple comparison between the law-driven and data-driven models.

<b>Law-Driven model</b>	Detailed physical Model -> Simulated Data
<b>Data-Driven model</b>	Measured Data -> Statistical Model(s) -> Detailed Physical Model

The prognostic law-driven modeling approach includes building energy simulation models such as DOE-2 [82], EnergyPlus [83], TRNSYS [84], ESP-r [85] and IDA-ICE [86]. The objective of these models is to predict the behavior of a complex system based on the use a given set of well-defined laws (e.g. energy balance, mass balance, conductivity, heat transfer, etc.) [80]. Such models have become prevalent in energy assessment calculations over the last two decades [87]. However, making accurate simulations for existing buildings is challenging, as there are many complicated input parameters which need expensive and time-consuming on-site inspections to verify [88].

Models which are calibrated with measured data are classified as the data-driven approaches [80]. These can be further classified as 1) black-box approach, 2) grey-box approach and 3) detailed model calibration [89]. This last is the most detailed approach and during its establishment an explicit link between the computer model and the physical building (and its systems) is created by comparing the measured and simulated performances with each other. This method is, for example, used in connection with retrofit analysis [80].

This study has chosen the third option, a detailed model calibration. However, the purpose of our calibration was not to make an exact parameter fitting of the model to replicate the field results. It was designed to assess the behavior of the IDA-ICE model in a qualitatively realistic way ('good enough') against the field-test measurements taken from the actual buildings.

### 2.3.2 Calibration methodologies

Several studies emphasize the great difference between simulated and measured energy performances [90, 91, 92]. There are also studies which point out the pressing need for accurate calibration of the simulation model [93]. The process of fine-tuning the simulation inputs in order to achieve a better fit between simulation outputs and measured energy consumption is also illustrated [94]. This is particularly important for on-going and post-construction building projects. For example, in existing buildings it is needed for 1) optimization of control strategies and 2) for identification of further energy saving possibilities [95, 96, 97]. Despite the clear need for such a well-calibrated model, there is not as yet any such formal and universally recognized process for the calibration of simulation models [98]. Often, such models rely on calibration by 'trial and error' which means that the users of the system often waste a lot of time and effort when trying to find the best fit for the monitoring and simulation data as there is no systematic approach. In addition, any outcomes from the process are highly dependent on the individual user's own skills and judgement [93], parameters which are difficult to control.

In practice, the purpose, method and level of the calibration are all dependent on the model's intended purpose, the user's experience and, of course, the resources available, including the budget. The reasons for the calibration could be, for example [98]:

- To assess a building's performance by simulation [99].
- To provide information about a building's thermal and/or electrical usage profile through a scaled simulation [100].
- To predict the impact of different load-control measures on the electrical load by using commercial on-site survey data [101].
- To support investment-grade recommendations
- According to the M&V, for one or more of the following circumstances [98]: (1) to identify a proper, contractually-binding baseline for energy use, against which energy savings can be measured, (2) to enable the correction of baseline energy use under unanticipated changes, (3) to allow retrofit verification, (4) to enable the sensitivity analysis of retrofits without having to monitor each subsystem individually, (5) to allow pre- or post-retrofit analysis without monitored data and (6) to reduce the time taken on post-retrofit analyses .
- To provide a capability for implementing (1) continuous commissioning or fault detection and (2) optimal supervisory control, equipment scheduling, and operation of a building and its systems, either under normal operation or under active load control.

Calibration methods can be classified into the following four main categories [102], which can be used separately or combined with each other during the same calibration process.

- manual, iterative and pragmatic approaches;
- graphical-based methods;
- special tests and analysis procedures; and
- automated analytical and mathematical approaches.

The first category is still the most commonly used in simulation applications [87, 103, 104] and includes all calibration simulation applications without a systematic or an automated procedure. The second category includes graphic representations of various plots and time series. These are used both with manual methods and with statistical indices (MBE and CV(RMSE)) for analyzing the 'goodness of fit' of the building model [93]. The third category includes special test and analysis procedures, but is distinguished from the fourth category, because it does not employ mathematical or statistical procedures for the calibration process. The last category encompasses all approaches that cannot be considered as user-driven, and are based on some sort of automated procedure [97]. One example of this calibration category is Bayesian calibration, which has recently been used in building calibration simulations [105, 106, 107]. More detailed information about the various approaches to model development and calibration is presented in the literature review of Coakley et al [80] and Fabrizio et al [93].

It is essential to define the required level of calibration level right at the beginning of the calibration simulation study (Table 2). It is also essential to ensure that the available information about the building is adequate for the desired purpose. Table 2 defines Level 1 as the minimum level of information needed to calibrate a simulation. This includes construction documents and utility bills. Level 5, the most detailed level of calibration, includes detailed audited information combined with long-term monitoring data. These calibration levels are described in more detail in [93] as well as in Table 2.

Table 2. Calibration levels classification according to the available building information [98, 108].

Calibration level	Building information available for simulation input					
	Utility bills	As-built data	Site visit or inspection	Detailed audit	Short-term monitoring	Long-term monitoring
Level 1	•	•				
Level 2	•	•	•			
Level 3	•	•	•	•		
Level 4	•	•	•	•	•	
Level 5	•	•	•	•	•	•

Once the level for the calibration has been decided on, the next step is to define possible error sources, and to make an uncertainty analysis. According to Heo [109], the four main categories for uncertainties are scenario uncertainty, building physical/operational uncertainty, model inadequacy and observation error (Table 3). The first category relates to outdoor weather conditions and the building's use, while the second category is concerned with modeling the building. The third category relates to the model or software itself, including the basic assumption behind it, and the sophistication of the model's algorithms. The last category refers to observation errors in the measured data. [93]

Table 3. Possible error sources in the evaluation of the accuracy of building-energy simulations [93].

Category	Factors
<b>Scenario uncertainty</b>	- Outdoor weather conditions - Building usage / occupancy schedule
<b>Building physical / operational uncertainty</b>	- Building envelope properties - Internal gains - HVAC systems - Operation and control settings
<b>Model inadequacy</b>	- Modeling assumptions - Simplification in the model algorithm - Ignored phenomena in the algorithm
<b>Observation error</b>	- Metered data accuracy

### 2.3.3 Assessing a model's performance with statistical indicators and regression

In the early years of building energy performance simulation (BEPS), the percentual difference calculation of measured and simulated data was the primary method for assessment of calibration performance [110, 111, 112]. This often meant that overestimations were cancelled out by underestimations because of the compensation effect [110]. Statistical indices are more suitable for calibration because they represent the real performance of a model in more detail [113, 114, 115]. Statistical indices have been the most commonly used criteria for evaluating the accuracy of calibration [93] since the



three main international bodies recommended the method for international reference in the ASHRAE Guidelines 14 [116], International Performance Measurements and Verification protocol (IPMVP) [117] and M & V guidelines for FEMP [118].

### Statistical indices

According to references [116, 117, 118], building energy simulation models are generally considered calibrated if they meet the set criteria for Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)) and Mean bias error (MBE). These criteria vary according to whether the model uses monthly or hourly measurement data, as seen in Table 4.

Table 4. Standard criteria for calibrating a building- energy simulation model

Statistical Indices	Monthly Calibration			Hourly Calibration		
	St. 14	IPMVP	FEMP	St. 14	IPMVP	FEMP
MBE [%]	±5	±20	±5	±10	±5	±10
Cv(RMSE) [%]	15	-	15	30	20	30

The MBE (%) is the sum of the error between measured and simulated data and is used as an indicator of the overall bias in the model.

$$MBE(\%) = \frac{\sum_{i=1}^n (X_{meas,i} - X_{model,i})}{\sum_{i=1}^n (X_{meas,i})} \quad (6)$$

where

$X_{meas,i}$  = the actual measured value at time interval  $i$

$X_{model,i}$  = the modelled value at time interval  $i$

$n$  = the number of time intervals considered

Mean bias error captures the mean difference between measured and simulated data points. A positive result shows an underestimation while a negative result indicates an overestimation of the simulated results compared to the field measurements. The MBE calculation allows for the cancellation effect (the positive biases compensate the negative ones), which is why the MBE method should be used with another measure of model error.

The Root Means Square Error (RMSE) is one index which is not affected by the cancellation effect. It is a measure of the variability of the data. It is calculated by first summing up the squared difference between measured and simulated data points

$(\sum_{i=1}^n (X_{meas,i} - X_{model,i})^2)$ , then dividing that sum by the number of time intervals ( $n$ ) and then finding the square root of the result. After that, the CV(MRSE) is obtained by dividing the Root Means Square Error (RMSE) by the average value of the measured data points.

$$CV(RMSE)(\%) = \frac{MRSE}{\overline{X_{meas}}} = \frac{\sqrt{\frac{\sum_{i=1}^n (X_{meas,i} - X_{model,i})^2}{n}}}{\overline{X_{meas}}} \quad (7)$$

where

$$\overline{X_{meas}} = \text{the mean of measured values}$$

The MBE measures how closely the simulated data correspond to the monitored data. The CV(RMSE) specifies the overall uncertainty in the simulated energy consumption model more exactly, because it also reflects the size of the error and the amount of scatter. The MBE can be either positive or negative, but the CV(RMSE) is only positive. The lower the value of the CV(RMSE), and the closer the MBE is to zero, the better the model is calibrated. "In this connection, it should be noted that current calibration criteria relate solely to predicted energy consumption, and do not account for uncertainty or inaccuracies of the input parameters, or the accuracy of the simulated environment (e.g., temperature profiles)" [80].

### Regression analysis

The coefficient of determination ( $R^2$ ) is used in trend analysis and is calculated by squaring the Pearson [119] correlation coefficient  $R$ .

$$R = \frac{n \sum_{i=1}^n X_{model,i} X_{meas,i} - \left( \sum_{i=1}^n X_{model,i} \right) \left( \sum_{i=1}^n X_{meas,i} \right)}{\sqrt{n \left( \sum_{i=1}^n X_{model,i} \right)^2 - \left( \sum_{i=1}^n X_{model,i} \right)^2} \sqrt{n \left( \sum_{i=1}^n X_{meas,i} \right)^2 - \left( \sum_{i=1}^n X_{meas,i} \right)^2}} \quad (8)$$

The coefficient of determination is an important tool in determining the degree of linear-correlation of variables ('goodness of fit') in regression analysis. It indicates how accurately the simulation results match the measurements, by comparing the values at each time step to the measured value and determining the level of accuracy as an evaluation of the overall difference between them. It is not only a measure of how well the pattern of the model follows the pattern of the measurements, but also a measure of accuracy,

determining the error at each time step [120]. The accuracy of the simulation can be judged by the closeness of  $R^2$  to 1.0 and a target value of  $R^2 > 0.8$ .

The accuracy of the simulation was also evaluated by calculating the mean percentage error (MPE) and Mean absolute percentage error (MAPE) as well as maximum (MAX) and minimum (MIN) errors. Mean percentage error is calculated by the equation:

$$MPE(\%) = \frac{1}{n} \sum_{i=1}^n \frac{X_{meas,i} - X_{model,i}}{X_{meas,i}} \quad (9)$$

The benefit of the MPE is that it gives a view of the level of the simulation results (is the simulation over- or underestimating the results). On the other hand, the problem with MPE is that the negative and positive values cancel each other out when averaged. Therefore, the Mean Absolute Percentage Error (MAPE) is also calculated. It is a measure of the total size of the error in percentage terms.

$$MAPE(\%) = \frac{1}{n} \sum_{i=1}^n \left| \frac{X_{meas,i} - X_{model,i}}{X_{meas,i}} \right| \quad (10)$$

### Sensitivity index, SI

The sensitivity of the different parameters to the model's performance was analyzed with a sensitivity index (SI), which is calculated by the following formula [81]. It is a one-at-a-time (OAT) approach to sensitivity analysis, which means it is calculated by varying one input parameter at a time while keeping all the others constant. Any uncertainties in one parameter can thus be calculated in order to ascertain how the variations affect the model's output. The higher the SI, the more sensitive or influential the considered parameter is to the output of a model. For example, 50 % means high sensitivity and 1 % very low sensitivity.

$$SI(\%) = \frac{E_{\max} - E_{\min}}{E_{\max}} \quad (11)$$

where

$E_{\max}$  = the maximum effect (in %) of considered parameter to output

$E_{\min}$  = the minimum effect (in %) of considered parameter to output

This method is one of the simplest methods for screening the most important parameters over the investigated output in a model [93]. The drawback with the method is that it does not take into account the interaction between the model inputs. This interaction is discussed in connection with the development of the simplified method for glazed space interior temperature and heating energy-saving evaluation, i.e. in connection with Article IV.

### 2.3.4 IDA Indoor Climate and Energy (IDA-ICE) overview

The IDA Indoor Climate and Energy (IDA-ICE) is an extension of the general IDA simulation platform, the IDA simulation environment, and has been under development since the 80s [121]. It was initially developed at the Royal Institute of Technology (KTH), and the Swedish Institute of Applied Mathematics, ITM [122]. The basic design principle behind the IDA ICE library was to provide the best possible resolution of key phenomena while enabling whole-building, full-year simulations within commercially acceptable execution times [123]. It features equation-based modeling (NMF-language [124] or Modelica language [125]) and is equipped with a variable time step differential-algebraic equation (DAE) solver [121]. IDA-ICE uses the multizone technique (also called the nodal method) for problem solving (Figure 6). It considers each building zone as a homogeneous volume (or a node) that is described by a unique temperature, pressure, concentration, etc. A node can represent a room, or a wall, but it can also represent something more specific, like a load. The temperatures of all the walls in a zone that is connected to another zone, to the outside or to the ground are calculated separately. The physical equations are solved for each node of the system. The huge advantage of this technique lies in its ability to describe the long term behaviour of a multiple zone building in a small computation time. [126]

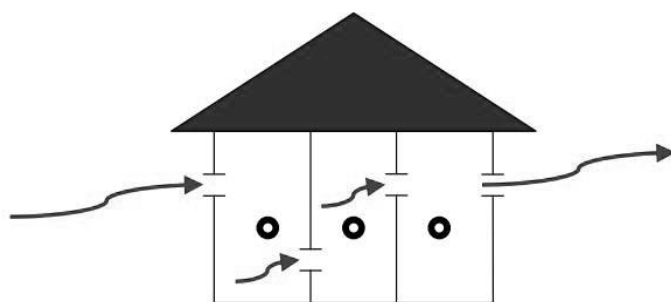


Figure 6. Schematic representation of IDA-ICE problem solving [127].

As with many other whole-building simulation tools, the software is based on the building's geometrical description, which provides the basis for a more detailed calculation of the distribution of solar radiation in and between rooms. The software calculates the

energy balances dynamically taking into account climatic variations and a dynamically varying time-step. The software solves heat-balance equations according to the user-defined geometry, construction, HVAC conditions and internal heat loads of the building. The software allows the use of measured climate and weather files containing information about the air temperature, relative humidity, wind direction and speed, direct normal radiation and diffuse (sky) radiation on a horizontal surface and calculates, for example, the solar radiation based on the building's location and the position of the sun in the sky.

IDA ICE offers separate user interfaces for different user categories [128, 121]:

- Wizard interfaces lead the user through the steps of building a model for a specific type of study. This interface is intended for less experienced users with a particular focus on a certain type of study.
- The standard interface is for users to formulate a simulation model using domain-specific concepts and objects, such as zones, radiators and windows. It corresponds roughly to the graphical user interface (GUI) of a typical 3D graphical multi-zone building performance simulation tool, requiring the building designer to formulate a meaningful simulation model in terms of thermal zoning, etc.
- The advanced level interface allows the user to browse and edit the mathematical model of the system. One clear benefit of the advanced level is that it enables the implementation of adaptive features and custom control macros directly into the mathematical model, for example, in the context of an adaptive facade [129].
- NMF and/or Modelica programming—for developers.

The basic features of IDA-ICE were contrasted with the other main building simulation tools by Crawley et al [128] in 2008 (Table 5) and its ability to simulate adaptive facades was reviewed by Loonen et al [129] in 2016. These studies give an insight into the current model's features of selected building energy simulation programs, and they confirm the fact that the basic principles of IDA-ICE calculations are in line with the characteristics of comparable building-energy simulation programs. There has been further development of model simulation environments. For example, the IEA Annex 60 [130] and the general prospects and requirement of the new generation simulation tools presented in reference [131]. The goal of the Annex 60 project is to develop and demonstrate a new generation computational tool for building and community energy systems, based on the Modelica and Functional Mockup Interface standards [132].

Table 5. Comparison of the DOE-2, ESP-r, EnergyPlus, IDA-ICE and TRNSYS zone load, building envelope, daylighting, solar, infiltration, airflow, ventilation and HVAC systems calculation principles [128]

	DOE-2	EnergyPlus	ESP-r	IDA-ICE	TRNSYS
<b>Interior surface convection</b>					
• Dependent on temperature		•	•	•	•
• Dependent on air flow		P	•		E
• Dependent on surface heat coefficient from CFD		E	E		
• User-defined coefficients (constants, equations or correlations)	•	•	E	R	•
<b>Internal thermal mass</b>	•	•	•	•	•
<b>Automatic design day calculation for sizing</b>					
• Dry bulb temperature	•	•		•	
• Dew point temperature or relative humidity	•	•		•	
• User-specified minimum and maximum	•	•		•	
• User-specified steady-state, steady-periodic or fully dynamic design condition				•	•
<b>Outside surface convection algorithm</b>					
• BLAST/TARP		•			
• DOE-2	•	•			
• MoWITT		•	•		
• ASHRAE simple		•			
• Ito, Kimara, and Oka correlation			•	•	
• User-selectable		•	•	•	•
<b>Inside radiation view factors</b>		•	•	•	
<b>Radiation-to-air component separate from detailed convection (exterior)</b>		•	•	•	•
<b>Solar gain and daylighting calculations account for inter-reflections from external building components and other buildings</b>		•	•		•
<b>Single zone infiltration</b>	•	•	•	•	•
<b>Automatic calculation of wind pressure coefficients</b>		P			
<b>Natural ventilation (pressure, bouyancy driven)</b>		•	•	•	O
<b>Multizone airflow (via pressure network model)</b>		•	•	•	O
<b>Hybrid natural and mechanical ventilation</b>			I	•	O
<b>Control window opening based on zone or external condition</b>		•	•		O
<b>Displacement ventilation</b>		•	•	•	O
<b>Mix of flow networks and CFD domains</b>			E		
<b>Idealized HVAC systems</b>		•	•	•	•
<b>User-configurable HVAC systems</b>		•	•	•	•
<b>Pre-configured systems (among 34 identified)</b>	16	28	23	32	20
<b>Discrete HVAC components (among 98 identified)</b>	39	66	40	52	82
• = has capability; P = partially implemented; O = optional feature; R = optional feature for research use; I = feature with difficult to obtain input data; E = feature for expert use					

In order to construct a glazed-space simulation model with the correct physical processes, the outdoor climate, the glazed space and the building and its control strategies all have to be modelled correctly. Furthermore, the 'goodness of fit' requirements have to be quantified and the accuracy of the model has to be justified. There are many factors to consider in order to make an accurate glazed-space simulation. For example,

the procession of the solar radiation, the heat exchange in connection with a shaded window system, the air flow in the cavity due to buoyancy and wind, the longwave radiation exchange and the convective heat transfer are all essential parameters that need to be modelled as accurately as possible. These features of the IDA-ICE are described in more detail below.

### **Solar radiation procession**

The average hourly solar radiation values (direct normal and diffuse horizontal) given in the climate files for each location are used for the simulations. The direct radiation values are then recalculated for each façade taking into account the building's location, the orientation of the facades and the angles of the surfaces in relation to the exact position of the sun. The diffuse radiation is also recalculated for each façade using three optional methods as demonstrated in ASHRAE [133], Kondratjev [134], and Perez [135]. The Perez model is used as a default, as according to IEA Task 34 [136], the Perez model's results corresponded best with measured global vertical irradiance on the southwest façade. Noorian et al [137] also compared the efficiency of 12 diffuse irradiation models on inclined surfaces and concluded that the Perez [135] model showed the best agreement with the measured tilted data.

### **Window models**

The windows can be modelled in IDA-ICE by using either a simple or detailed models. In the simple model, the optical and thermal properties for the whole glazing (at normal incidence) are given as input data and only the temperatures of the innermost and outermost panes are modelled. Those panes, or the external and internal surfaces of the window, have their own links for shortwave radiation and heat exchange. An exterior window surface is exposed to longwave radiation and convection. An interior window surface has an exchange of longwave radiation with zone surfaces in the same zone and convective heat exchange with the zone air. The conduction through the glass combination is calculated by adding up the surface resistances to the window 'pane resistance'. In this model it is assumed that solar absorption takes place only in the innermost and outermost panes. From these surfaces, the heat is transmitted inwards and outwards. The split between the sides is calculated based on the assumed surface resistances. Any integrated window shading (internal or external shades in the plane of the window) is calculated by multiplying the shading effect with the window's basic g-value. [138, 86] This is simplest way to calculate the g-value for the whole system [139]

An ISO-15099-based detailed window and window shading model [140] was employed to compute overall heat transfer through the glazing. It is a detailed, pane-by-pane cal-

ulation and uses the optical and thermal properties of all the window panes and the gasses in the gaps between the panes. The thermal bridges of the frame mountings were added to the thermal transmittance of the window frame [136]. There is also a separate model for external window shading which calculates the combined shading effect on a window created by a set of obstructing objects. These objects could be the surrounding buildings, the calculated building itself, or local exterior shading devices, such as fins or a window recess. The model calculates the sun's position to evaluate the instantaneous shading effect on direct solar radiation, but does not reduce the diffuse radiation. [138]

The angle-dependent optical properties of the glazing are calculated with consideration of multiple reflections and the solar absorption in each pane. From this, both the solar light and the heat transmission are calculated and even the heat capacity of the panes is taken into account. Because the ISO-15099 standard does not cover the calculation of single-pane angular properties, the angular properties of uncoated panes are calculated with the so-called Fresnel equation. From those models, the detailed window model provides better simulation performance in cases where there is detailed knowledge of the window parameters requiring access to an extensive window database [136].

### **Long wave radiation exchange**

Once it has reached inside the zone, the diffuse solar radiation is spread diffusely while the beams of direct radiation hit their exact target locations. The direct radiation is diffused as soon as it hits an opaque surface, and the area of diffuse reflection is assumed to occur over the whole surface (not just on the sunlit portion of the surface). The reflected radiation from the sky and the ground is diffusely spread after it comes through the window in the zone. When calculating the diffuse shortwave radiation between surfaces in a zone, the openings are counted as surfaces. The radiation is calculated using view factors (in the detailed zone model) or surface areas (in the simplified model). The reflection from openings is zero. All radiation 'absorbed' by an opening passes to the adjacent zone and is regarded there as diffuse radiation coming from the opening (the anisotropy is ignored). The 'temperature' of the opening is calculated from the balance of radiation in the opening.

For the long-wave radiation exchange between the ground and the building façade as well as the sky and the building façade, the ground temperature is assumed to be the same as the air temperature and the sky temperature is five degrees below that [138]. This assumption for the sky temperature has proved to be a surprisingly good average value in the long term [141]. However, a more sophisticated sky temperature model,



based on cloudiness, is introduced in IDA-ICE 4.7. In this sky model, it is assumed that the degree of cloudiness is recorded in the weather file, but if it is not, the old sky temperature model is used.

### **Energy and climate models**

At the core of the NMF library [124] are both a detailed and a simplified zone model. The detailed zone model, available only for rectangular zone geometries, has been developed for the detailed calculations needed for indoor climate studies, for example, calculations of displacement ventilation, mean radiant and operative temperature, comfort indices and daylight levels. The simplified zone model is intended for multizone energy simulations in which accuracy can be sacrificed for the sake of speed [124]. The main difference between the climate- and energy-zone models is that in the former, the diffuse solar and thermal radiation distribution between the surfaces is calculated by view factors, while in the energy-zone model these are just distributed according to the sizes of the surfaces.

In the energy model, the internal walls without a thermal connection to the surrounding zones are assumed to be adiabatic, whereas the external walls and partitions connected to other simulated zones are handled separately. This is because the conditions on the opposite side are different from those in the zone. The geometry of the zone is not known in detail, although the surface areas are known and are used for distribution of radiation. The slopes of the surfaces are also known and are used to calculate on-linear convective transfer. The model handles the diffuse radiation that comes into the zone from the windows and from the reflection of direct light (which is not reflected back out) by dividing it between the surfaces according to the surface's area multiplied by its absorption value. The longwave radiation for every surface is calculated using the mean radiant temperature in the zone.

In the (detailed) climate zone model, the incoming short-wave radiation is distributed diffusely according to the Li Yuguo subroutines [142]. The view factors between the surfaces are calculated and the emitted and reflected irradiation is distributed accordingly by solving a series of radiation-balance equations for all the surfaces. The distribution and absorption of diffuse light at the different surfaces is treated in a similar way. As a result, properties such as the displacement ventilation and room temperatures vertical stratification in the zone, as well as operative temperatures, comfort indices and daylight levels at arbitrary room locations can be calculated with this model. The subroutines have several limitations: 1) all the surfaces have to be rectangular, 2) all the surfaces have to be in sight of each other and 3) it does not deal with obstacles [138, 86, 123].

## The convective heat transfer

The wind-dependent external surface convection is calculated according to the method introduced in reference [143]. It is calculated from wind data in the climate file (normally measured at 10 m height in an open area), the height of the building and the choice of the wind profile parameters. The latter are used for recalculating the wind speed at roof height [144]. The model for calculating the heat-transfer coefficient from the wind speed and direction is taken from reference [143].

The internal surface convection model is a reproduction of the BRIS model [145]. The BRIS is an extensively validated heat-balance program for non-linear radiation and convection calculation [146]. The optional models for calculation in IDA-ICE are listed below, from which IDA uses max(BRIS model, Ceiling Diffuser Model) as a default.

- BRIS Model [147]
- Detailed Natural Convection Model [148]
- Simple Natural Convection Model [148]
- Ceiling Diffuser Model [149]
- Max(BRIS model, Ceiling Diffuser Model) (default)
- Max(Detailed Natural Convection Model, Ceiling Diffuser Model).

**BRIS Model [147]:** The BRIS model calculates the internal surface convection coefficient as a function of the temperature difference between the air and the surface, and the slope of the surface [150]. The data is given in terms of a table where intermediate values are evaluated using linear interpolation.

**Detailed Natural Convection Model [148]:** The detailed natural convection model is based on plate experiments and correlates the convective heat transfer coefficient to the surface orientation and the difference between the surface and zone air temperatures.

**Simple Natural Convection Model [148]:** The simple natural convection model uses constant coefficients for each of the heat transfer configurations. The criteria to calculate reduced and enhanced convection conditions are similar to those used in the detailed model.

**Ceiling Diffuser Model [149]:** The ceiling diffuser model is based on a room outlet temperature reference. The heat transfer coefficient is expressed as a function of Air Change per Hour (ACH).

The interior convective heat transfer coefficients are, in reality, extremely dependent on the exact position of the inlet ducts, the airflow path, the position of heaters etc. All simulation programs use some kind of 'standard' model for this. Even though the significance of modeling internal surface convection in dynamic whole-building simulation programs was highlighted by [151] in 1999, the internal convective heat transfer still seems to present significant challenges. This is particularly evident in glazed balconies, in which the external single glazing's heat resistance is low, and the airflow change in the balcony space is high. Good modelling accuracy for convective heat transfer is difficult to achieve without accurate measurement of the airflow in a space.

### **Air flow in the cavity**

IDA-ICE includes a multi-zone airflow model that can handle four different types of airflows: the supply and exhaust air terminals, air leakage paths through the envelope and additional flow paths for other openings [138, 86].

The air flow model of IDA-ICE is based on pressure differences between the indoor and the outdoor climate, and the defined air leakage through the building at a pressure difference of 50 Pa. The pressure differences depend on temperature differences and the effect of the wind on the building envelope. The airflow between the zones and outdoors caused by the pressure differences is simulated by means of a nodal network, where the flow paths, cracks or openings between the zones or outdoors are described as flow resistances. This approach is commonly used in multizone energy simulations, and also widely accepted in measurements and air infiltration standards [152, 153]. The theoretical basis of this empirical power law equation has been developed by Sherman [154].

IDA-ICE uses a linearized power law equation around a zero pressure difference, and a normal power law equation when the pressure difference equals or exceeds a limit value of linearization [155]. The effect of the wind is calculated by using the normal assumption in building engineering that the wind flow is horizontal and an atmospheric boundary layer is neutral without vertical air flow [156]. The air movement in one zone is non-existent, because IDA models each zone as one node of mass. The flow between zones is modelled in the same way as above, but without the wind pressure.

### **Other zone features relating to the glazed space simulation**

There are two options for the modelling the heat transfer between a surface and the ground. The first is the ICE3 model and the second is the ISO-13370:2007 [157] model. In both models, the ground heat transfer is modeled as two 1D heat transfer paths, one to the surface and one to a ground temperature. In the ICE3 model [86], the outermost

surface layer is connected to a constant ground temperature, which is computed as the mean air temperature of the selected climate file. In ISO, the outermost layer is connected to a virtual ground temperature, which is calculated on a monthly basis from the selected climate file. Even though the ISO model is the more complicated (and realistic) of the two, both the ISO and IDA ground models are simplifications and intended mainly for energy simulation.

The current software package does not include the possibility to connect an adjacent zone to the ventilation unit (air supply from the cavity), nor is there any model to handle the ground duct system. This means that the air supply through the cavity has to be simulated by placing an extra exhaust ventilation unit inside the cavity space and connecting it to the attic ventilation unit. The ground duct system, in turn, should be modeled as small underground zones connected to each other. By doing this, a rough estimate of the impact of the ground duct system can be obtained. An even better method is to add, for example, a simplified NMF-based Ground to Air Heat Exchanger model in IDA-ICE [158].

### **Validation of the building simulation softwares**

There are standardized procedures for the validation of building energy simulation tools, for example, EN ISO 13791:2012 [159], EN 15265 [160] and ANSI/ASHRAE standard 140 [161]. The EN ISO 13791:2012 [159] standard defines test cases for heat conduction through opaque walls, internal long-wave radiation exchange, shading of windows by external structures, and a test case for the whole calculation method. It is mainly intended for the calculation of typical buildings, and it does not contain sufficient information to calculate the effects of sunspaces, for example. The EN 15265 [160] standard specifies a set of assumptions, requirements and validation tests for the procedures used for the calculation of the annual energy needs for space heating and cooling. This validation procedure is significantly simplified, however, and does not cover non-linear film coefficients, dynamic solar patch tracing or the full Stephan-Boltzmann radiation between surfaces in the reference model. A test procedure called BESTEST [161] has been implemented within the International Energy Agency (IEA) Solar Heating & Cooling programme (SCH) and published in the ANSI/ASHRAE Standard 140 [161]. This methodology defines a comparative set of tests run on single-zone and double-zone shoebox configurations with variations in mass, windows, overhangs, and fins. The main reason for performing the tests is to ascertain that the computational models give reasonable values compared to other software programs. The IEA has also employed empirical validation studies and has implemented empirical validation procedures, for example, within the IEA SCH Task 34 and ECBCS Annex 43 [136, 162]. The purpose of those studies was to create data sets for use when evaluating the ac-

curacy of models for glazing units and windows, both with and without shading devices. The program outputs were compared with experiments performed at an outdoor test cell in Switzerland and a facility in the United States. Other validation procedures are, for example, the ETNA and GENEC tests for empirical validation [163] and the CIBSE accreditation test for the building-energy simulation tools [164]. Nowadays, there are a number of high-quality outdoor test facilities, which have been documented within IEA Annex 58 [165]. IDA-ICE have undertaken most of the previously mentioned validation studies. The key findings from those validations are shown in Table 6.

Table 6. Key findings of the IDA-ICE validation studies.

IDA-ICE version	Validation study (year)	Key findings	Ref.
<b>IDA-ICE 2.1</b>	IEA Task 22 (2001)	The agreement between simulated and measured data was good and disagreements generally fall within the range of experimental uncertainty of the measured data.	[166]
-	EN 13791 (2001)	After adapting the model to the simplification of the EN13791 reference standard, IDA-ICE gave the results as demanded by the standard.	[167]
<b>IDA-ICE 3.0</b>	RADTEST (2003)	IDA-ICE provided a good agreement with the reference programs	[168]
<b>IDA-ICE 3.0</b>	IEA SHC Task 34/ ECBCS Annex 43 Project C (2007)	Errors and deficiencies with respect to solar radiation, glazing, shading, and surface heat transfer was identified. The new Detwind model was proved to perform better than simplified window model and Perez 1990 tilted surface radiation model made as a default. The best performing softwares (EnergyPlus and IDA-ICE) featured dynamic convective heat transfer coefficient algorithms and more accurate longwave radiation models.	[136, 72]
<b>IDA-ICE 4.0</b>	CIBSE (2007)	After adapting the model to the simplification of the CIBSE TM33 reference model, IDA-ICE passed the test	[169]
<b>IDA-ICE 4.0</b>	ANSI/ASHRAE Standard 140 (2010)	IDA ICE 4 performs well in the test series. In all cases, the software performed on a similar level than other softwares	[170]
<b>IDA-ICE 4.0</b>	EN 15255 and EN 15265 (2010)	EN 15255-2007 and EN 15265-2007 is significantly simplified with respect to state-of-the-art thermal building models. The sufficient simplification was adapted to the model and the test passed within given error boundaries. The ambition has not been to match the reference model as closely as possible.	[171]

## 2.4 Factors affecting the thermal behavior of glazed spaces

A glazed balcony is a non-heated outdoor space receiving its heating energy from outside (Figure 7). The two primary heat sources are solar radiation energy and the adjoining building's heat losses. The intensity of both heat sources varies significantly depending on the time of day and the season. The building's heat losses are the greatest during the coldest days of winter and the solar radiation the strongest in spring, summer, and autumn. [19]

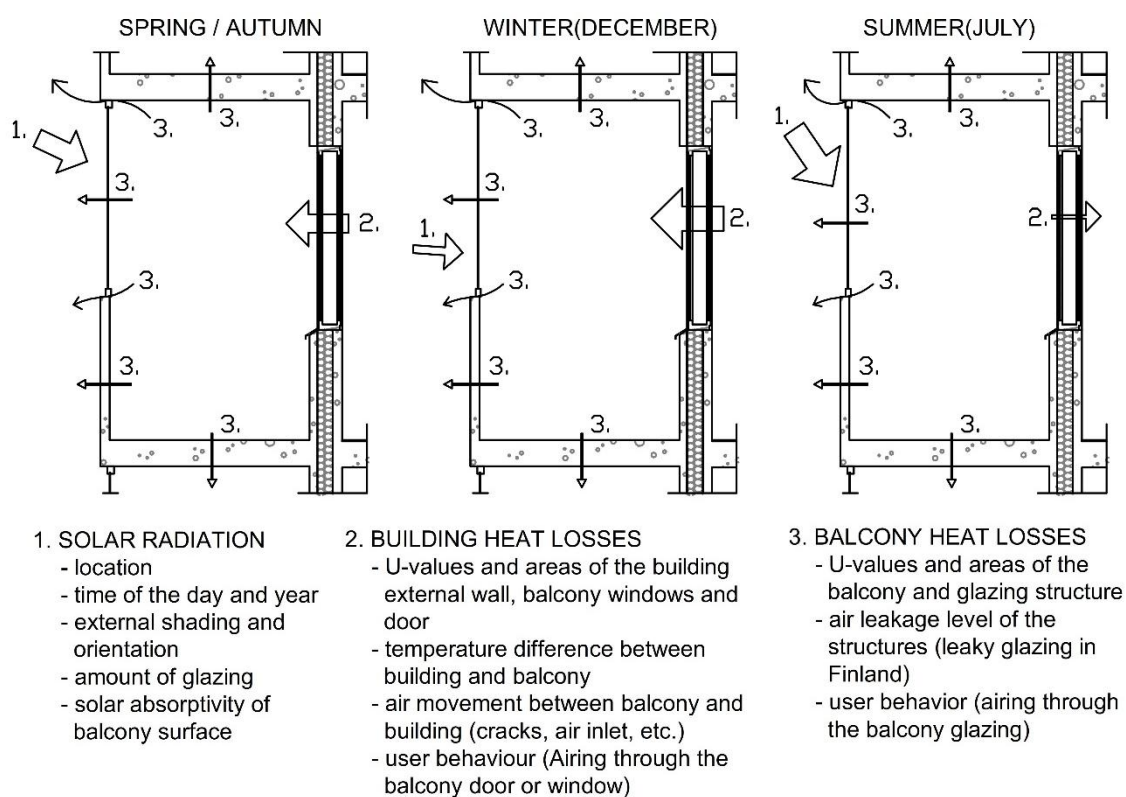


Figure 7. Glazed balcony heat balance at different times of year. [19]

Loose balcony glass and balustrade solutions contain a lot of routes through which the air can leak, so warm air can flow out of the balcony quite freely. Additionally, because of their poor insulation, the load-bearing balcony structures, the balcony glazing and the balustrades release significantly more thermal energy through conduction than the building's external walls do. Heat losses and air leaks increase in cold weather and decrease if the weather becomes milder. At the same time, the temperature difference between the glazed balcony and the outdoors also changes. [19]

In order to maximize the temperature difference between the glazed space and the outdoor air, it is really important to optimize the balcony's type and size, as well as its thermal insulation capacity and the air-tightness of the structures. Increasing the length of a balcony also increases heat losses from the building to the balcony. In general, a long and narrow balcony is recommended for maximizing heating energy savings and natural light [172]. Earlier research suggests that, compared to newer protruding balconies, the influence of balcony glazing is more significant in blocks of flats with recessed balconies constructed in the 1960s (Figure 8). This is due to the following factors, inter alia [46]:

- As compared to protruding balconies, recessed balconies profit more from the building heat losses and solar energy absorbed by the walls that connect the balcony space to the interior space.
- As compared to newer buildings, the heat loss level is higher in the 1960s buildings because of the significantly lower thermal insulation capacity of the external wall, windows and doors of the adjoining flat.
- Protruding balconies need the installation of balcony glazing on several sides, which means that the area of relatively loose glazing increases and there are more air leaks.

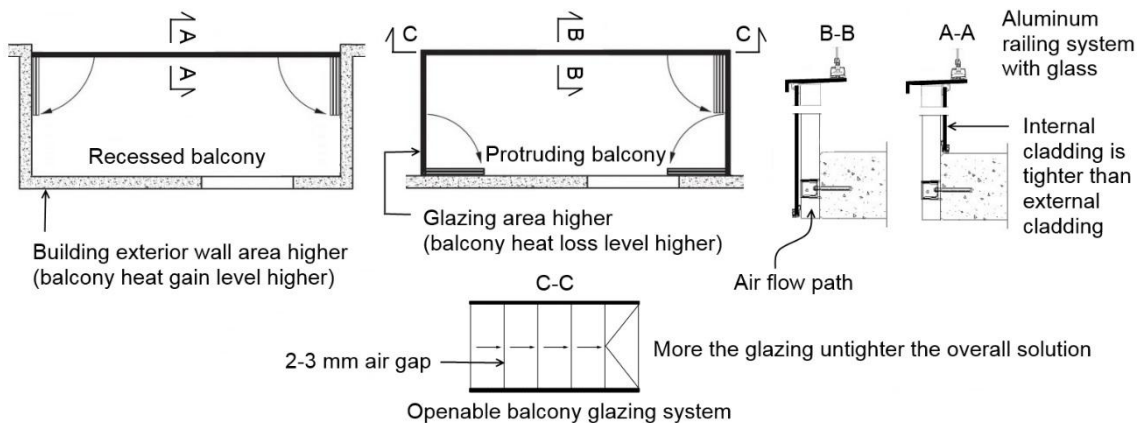


Figure 8. A recessed glazed balcony is superior to a protruding glazed balcony, and internal cladding on the balustrade is better than external cladding for the building's heating energy-savings and for the indoor balcony climate (warmer in the winter time).

The temperature of a glazed balcony can be raised in winter by optimizing the equation 3 relationship between the specific losses and the specific gain at the balcony (the lower the better). Some examples of the current G-value levels can be seen in Figure 8, in which a recessed glazed balcony in a 1960s apartment building with internal cladding of the balustrade (left) results in a G-value of 3 and a protruding glazed balcony in a 2000s apartment building with external cladding of the balustrade (right) results in a G-

value of 18 (a 6-fold difference). In the Finnish climate, a good rule of thumb for the design of a new balcony is that the G-value should be as close as possible to 1, if the aim is to get the space temperatures to stay above zero during the winter without a separate heating device.

Obviously, a building's geographical location also affects the indoor climate and heating energy-savings achieved by a glazed space [64]. A different location means different outdoor air and wind conditions, which will result in reduced or increased heat losses through transmission and infiltration. The basic principle regarding location is that the more southern and milder the climate is, the greater the heating-energy savings percentage-wise. This is due to the increased amount of energy absorbed by the space due to the increased intensity of solar radiation in the south [173]. However, the heating energy savings in kilowatt hours may decrease the further south you go [174]. It is typical of cloudy and rainy climatic conditions that there is a high proportion of diffuse short-wave solar radiation [59]. In windy areas, the glazing plays an important role as a thermal buffer zone, reducing the heat losses from transmission and infiltration [64]. Rain falling on the glazing is also significant because it cools down the exterior surface of the glazed structure and increases the heat losses to outdoor air. Spray irrigation is actually used as a cooling method in warm climates [54].

The orientation, external obstructions, and shade from the sun also have an effect on the amount of stored solar radiation, because these factors all limit the amount of radiation entering the space. Although it is important that the space is oriented towards the equator ( $\pm 30^\circ$ ), a building's orientation is not a major contributor to the energy savings of a glazed balcony [68]. Nevertheless, it has been proved that external obstructions and solar shading significantly affect the solar radiation stored in a glazed space. The presence of shading during the winter months increases the thermal resistance of the sunspace's external walls and blocks radiation exchange between the walls and the deep sky [173, 66].

The air-tightness of the balcony has a marked impact on the temperatures of the glazed space. Ventilation with outdoor air removes some of the absorbed energy and consequently lowers the temperature of the sunspace [173]. The air exchange rate of loosely-sealed glazed spaces varies daily and is highly dependent on the temperature difference between the glazed space and outdoor air, as well as wind conditions [20]. The building's ventilation solution also affects the end result. In terms of the heating energy-savings of the building, it is advisable to integrate the glazed space with the mechanical exhaust ventilation from the building, and thus use the glazed balcony as a pre-heater for the air intake (Figure 9) [48, 64]. However, if the supply and exhaust ventilation unit has heat recovery, the situation is the other way round, and it is advisable



to take the supply air from outside the glazed balcony [28]. In addition, the volume of supply air through the balcony should be carefully adjusted in the winter by taking into account the temperature drop effect of the balcony air (the temperature drop is roughly 1-3 ° C, depending on the volume of air flowing through the balcony). This means that the air volume is low enough to allow the balcony air to be warmed by the effect of building heat losses and solar radiation. A good starting point for a new balcony design [48] could be that between one-half or one-third of the incoming air is passed through the balcony. If the air supply inlets between the glazed balcony and the flat cannot easily be closed off [62], it may lead to overheating in the adjoining flat on hot summer days. To avoid this adverse effect, it is important that the vents are easily adjustable, and that they can be closed during unfavourable climate situations.

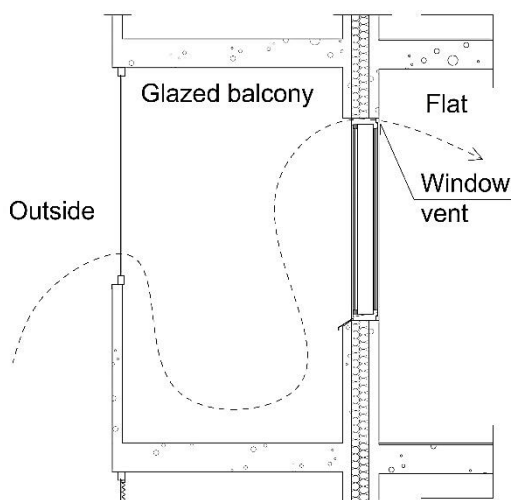


Figure 9. In terms of the heating energy-savings of the building, it is advisable to integrate the glazed space with mechanical exhaust ventilation, and thus use the glazed balcony as a pre-heater for the air supply [48, 64]. This is a typical solution in Finnish blocks of flats from 1970s.

The material and surface properties of the glazed space and the building's external wall affect the indoor temperature and thus the heating energy-savings of the glazed space. According to [63], the thermal conductivity of the wall strongly affects the heat flux through the wall, although its density and heat capacitance have only a small effect [63], albeit heat capacitance affects temperature variations and the thermal comfort of the space. However, the absorption coefficients of the surfaces have a strong impact on the interior temperatures of the glazed space and the achieved heating-energy savings. [20]

In summer, the absence of shading can lead to overheating in the glazed balcony or in the adjacent rooms [16] even in northern climates [65]. This has also been confirmed

by field monitoring and resident interviews in Finland. For example, in the temperature measurements taken in Tampere during this study, some glazed balconies reached almost 40 °C as early as in May [19], and even higher temperatures have been reported to the authors during this work (some residents have reported their own measurements to the author). Also, the interviews with the balcony users confirm the occurrence of this problem. For example, survey interviews conducted by the VTT Technical Research Centre of Finland in the 1980s revealed that 75 % of the interviewees who had glazed balconies said that their balconies warmed up more after the installation of glazing than they had done before, if the glazing was completely closed [44]. On the other hand, the awareness of overheating problems in the summer is generally good, and balcony users have found ways to react to the recurring problem. For example, in another resident survey carried out in connection with Jari Heikkilä's doctoral dissertation [18], about 80 % of glazed balcony owners kept at least one pane ajar (airing position) during the summer. The airing position is not, however, an efficient enough solution for glazed balcony temperature control during a really hot summer's day, because a) it does not sufficiently cool down the balcony temperatures and b) it does not eliminate the harm of direct solar radiation (e.g. glare).

Studies also show that a balcony's capacity to capture solar radiation also has a significant impact on its temperature during the summer months. In addition to the absorption coefficients of the balcony's surfaces, the critical factors affecting the balcony's storage capacity are any outside obstructions to the balcony, the amount of glazed surfaces on the balcony and the balcony's orientation. Field measurements and simulations all indicate that increasing the amount of glass on the balcony directly increases the absorption of the sun's energy. The same effect is also achieved with darker surfaces. For example, the most effective solution to optimize the received solar radiation is a terrace with a glazed roof and a black interior (Article II). In such cases, it is difficult to remove the effect of solar radiation, even if very effective external solar shading ( $g=0.06$ ) and effective airing are used (examined separately within this study). In the same context, it was noticed that a recessed balcony or protruding balcony with opaque side walls (only one glazed side) is the best solution for preventing overheating. Similar results were also obtained in reference [175].

Excessive indoor temperatures can be prevented by using an appropriate solar shading solution with the glazing [65] and by increasing the air flow by opening the balcony glazing [73]. Spanish studies show that the optimum openness of the glazing is 25 %. This degree of openness combined with external solar shading offers pleasant indoor climate conditions even in very hot conditions, as occurs in Spain [175]. This study has also produced similar results. However, the most commonly used sun protection solu-

tion for Finnish balconies and terraces has usually been internal sun protection curtains with  $g$  values of between 0.5 - 0.7 [12]. Also, the number of installations of these devices is relatively low (Section 1.3.), even though they are freely available on the Finnish market [12]. Very little external sun protection was encountered during this study in Finland.

## 2.5 Conclusions of the literature review

The literature review showed that in recent years there have been markedly few studies or analyses of the temperature behavior of glazed spaces and their energy-saving potential in Nordic climate conditions. In addition, the studies that have been carried out have usually been quite narrow in focus, and have rarely dealt with the type of frameless single glazing most commonly used on balconies in Finland. The literature review also reveals that the DSF solutions used so far in Finland and Sweden have not really been optimized, either. Because of the above, and the generally poor awareness of the benefits of glazing, the construction techniques and the seasonal use of glazed spaces have not been optimized in terms of their energy-saving potential, balcony indoor climate or the avoidance of overheating in the summer. Thus, simple tools for assessing the effect of balcony glazing on a building's energy consumption and the balcony's indoor climate will be of great benefit for the optimal utilization of Finnish housing stock.

The spaces monitored in this study are non-heated outdoor spaces which receive their 'heating' energy from outside. The two primary heat sources are solar radiation energy and the building's heat losses. The intensity of both heat sources varies significantly depending on the time of day and the season. The building's heat losses are the greatest during the coldest days of winter and the solar radiation the strongest in spring, summer, and autumn [19]. According to the literature review, the relationship between the heat losses from the glazed space to the outside and the heat gain from the building to the glazed space (equation 3) are the main factors that determine the temperature level of the space during the winter months at high latitudes [20]. This relationship includes the air leakage through the glazing, which has a marked impact on the temperature of the glazed space. Ventilation with outdoor air removes a significant proportion of the energy absorbed, and consequently lowers the temperature of the sunspace [173]. It is also important that the space is oriented towards the equator ( $\pm 30^\circ$ ) and that dark surface colors with high solar absorption [20] are used. It is also advisable to supply the inlet air through the glazed balcony in winter, and thus use the glazed balcony as a supply air pre-heater, if the building is equipped with a mechanical exhaust venti-

lation unit or if the building is naturally ventilated [48, 64]. However, if the air supply and the exhaust ventilation unit are linked with an efficient heat recovery system, then it is more efficient to use that [28]. The absence of shading can lead to overheating problems in the balcony or the adjacent rooms, and such overheating problems can be intensified if the supply air comes through the glazed space in the summer. However, excessive indoor temperatures can be prevented by using an appropriate solar shading solution [65] and by increasing the airflow by opening the balcony glazing [73]. If there is a supply air inlet between the glazed balcony and the flat, it is advisable to shut it off in the summer [62].

Air temperature measurements are accepted as a useful method for evaluating the functionality of the passive solar design of a sunspace. They reveal the dominant pathways of heat gain and loss and give an indication of thermal buffer effects and thermal comfort [69, 70]. By combining those measurements with the internal and external surface temperature measurements, it is also possible to reveal a structure's ability to store and release heat energy, and to get some kind of indication of the real energy-saving potential of the glazed space. However, several studies have highlighted the importance of accurate field monitoring, especially in a situation where the monitoring results are used as an input parameter for simulation software (indirect error) and where the simulation results are compared with monitoring data (direct error) [75]. However, there is no formal and recognized process for calibrating a simulation [98]. The 'trial and error' method is still commonly used, as it is in this study. The results from these methods are highly dependent on the individual user's skills and judgement [93].

In practice, the purpose, method and level of the calibration depend on the aim of the project, the intended use of the model, the user's experience and the available monitoring and calibration budget. The calibration methods can be classified into the following four main categories [102]: 1) manual, iterative and pragmatic approaches; 2) graphical-based methods; 3) special tests and analysis procedures; and 4) automated analytical and mathematical approaches. It is also essential to define the required calibration level right at the beginning of the calibration simulation study (Table 2) and, more importantly, to verify that the available building information is adequate for the intended purpose. Once the calibration level has been defined, the next step is to define possible error sources and perform an uncertainty analysis. According to Heo [109], four main categories for uncertainties are scenario uncertainty, uncertainties regarding the building's physical/operational characteristics, model inadequacies and observation errors (Table 3). These are the error sources that have been evaluated in this study. The calibration criteria were taken from the ASHRAE Guidelines 14 [116] for building-energy simulation model calibration (Table 4).

There are many whole-building simulation tools available on the market, and the IDA-ICE software is one of them. This software has undergone many commonly-used validation procedures with acceptable results (Table 6). For this study, its suitability is analyzed in relation to the key physical phenomena of a glazed space in section 2.3.4. Due to the proven accuracy of the software, its user-friendly interface and the fact that it has been under continuous development with Finnish technical support (developed and maintained by EQUA Simulation AB [176]), the IDA-ICE was the natural choice as an analytical tool for this thesis. The IDA-ICE's chief advantage is its symbolic equation structure; (most other building performance simulation tools use variable assignment). The IDA-ICE software allows the existing model's functionality to be extended fairly easily [129] and the software can be used, for example, in complex ventilation control models, as is done in article V. Therefore, the selection of IDA-ICE as the simulation tool for this study is well grounded.

## **3 Research material and methods**

### **3.1 Outdoor climates**

The monitored balconies were located in Tampere, Finland (between 60<sup>th</sup> and 70<sup>th</sup> northern latitude) and the building with added weather protection glazing that was used for the case-study is located in Malmö, Sweden (between 55<sup>th</sup> and 70<sup>th</sup> northern latitude). The climate of both countries is much milder than the latitudes might suggest, mostly due to the relatively warm and steady air flow from the Gulf Stream in the Atlantic Ocean. In addition, the geographical features of the Scandinavian Peninsula prevent Finland and, to some extent, Sweden from experiencing the more extreme weather conditions suffered in, for example, the coastal areas of Norway. In the Köppen Climate Classification system, the southern part of Sweden and Finland's southern coastline lie in a humid continental zone (Dfb), while the northern part of Sweden and most of mainland Finland is in a continental subarctic zone (Dfc) [177].

#### **3.1.1 Tampere's climate**

The city of Tampere (61°29'53" N, 23°45'39" E) is located approximately 200 km north of Finland's southern coast. The city's winter is cold and the summer is mild. In normal years, the average temperature from November to March is below 0 °C and below 17 °C over the whole year. Tampere's annual average temperature is 4.4 °C and it has 4,424 heating degree-days (HDD17) in a normal year [178]. The climate information used in the analysis of the field-monitored balconies and flats during 2009-2010 was acquired from the Finnish meteorological institute (FMI). The temperature, relative humidity and wind information were gathered from Tampere-Pirkkala weather station and the solar radiation information from the nearest radiation observatory, which is about 100km south of Tampere, in Jokioinen. Figure 10 shows a summary of the temperature

and radiation data over the measurement period (2009 – 2010), which is compared with data showing Tampere and Jokioinen's 'normal' temperature and radiation data from the preceding 30 years [178]. As can be seen, our measurement data reflects the long-term averages quite well (Article III).

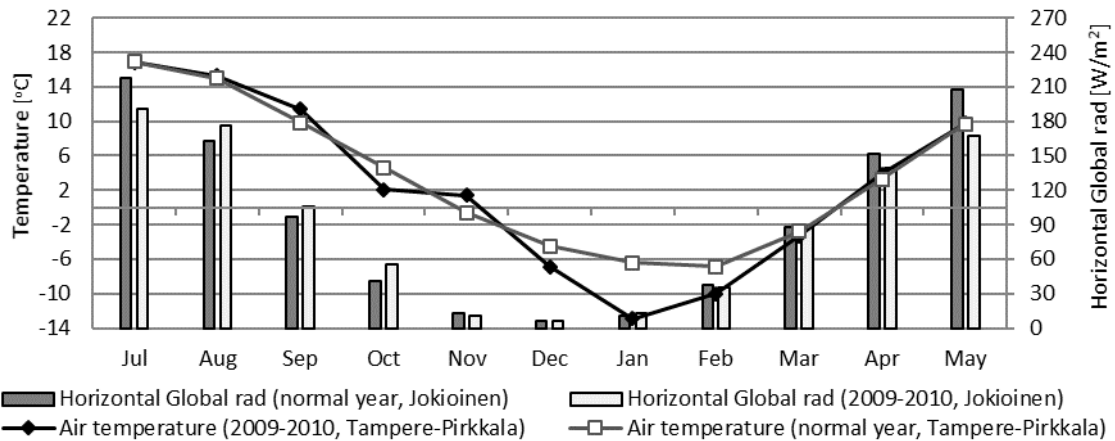


Figure 10. Monthly average temperatures of Tampere and horizontal global radiation of Jokioinen during the field measurement period and a normal year.

### 3.1.2 Malmö climate

The city of Malmö (55°36'21" N, 13°02'09" E) is located near the southwestern tip of Sweden. The annual average temperature of the city is 9.1 °C [179] and there are 3,250 heating degree-days (HDD17) in a normal year [180]. The outdoor climate values for the analyzed monitoring period (2014) used in the Malmö-case building simulations were provided by the Swedish Meteorological and Hydrological Institute (SMHI). The MetObs service [181] provided data on air temperature, relative humidity, wind direction and wind speed for Malmö Airport (Sturup) and global radiation for Malmö. The direct solar radiation has been calculated through SMHI's service Strång [182, 183, 184]. The diffuse solar radiation has been calculated using Equation 6:

$$E_{\text{dif}} = E_{\text{glo}} - E_{\text{dir.norm.}} \cdot \sin(\alpha_{\text{sol}}) \quad (6)$$

Where

- $E_{\text{dif}}$  = the diffuse solar radiation (W/m<sup>2</sup>)
- $E_{\text{glo}}$  = the global solar radiation (W/m<sup>2</sup>),
- $E_{\text{dir.norm.}}$  = the direct normal solar radiation (W/m<sup>2</sup>)
- $\alpha_{\text{sol}}$  = the solar elevation (degrees)

The solar elevation was calculated with [185], based on the latitude, longitude and the elevation of the simulated locations. Missing data have been interpolated. Figure 11 shows a comparison between the results of the 2014 weather file and the 'normal' yearly figures, which are the mean of the relevant weather data provided by Meteoronorm [179] for 1999 to 2010. Once again, the data match each other pretty closely, although the radiation level for the monitored year, (2014) was clearly higher than the long-term average.

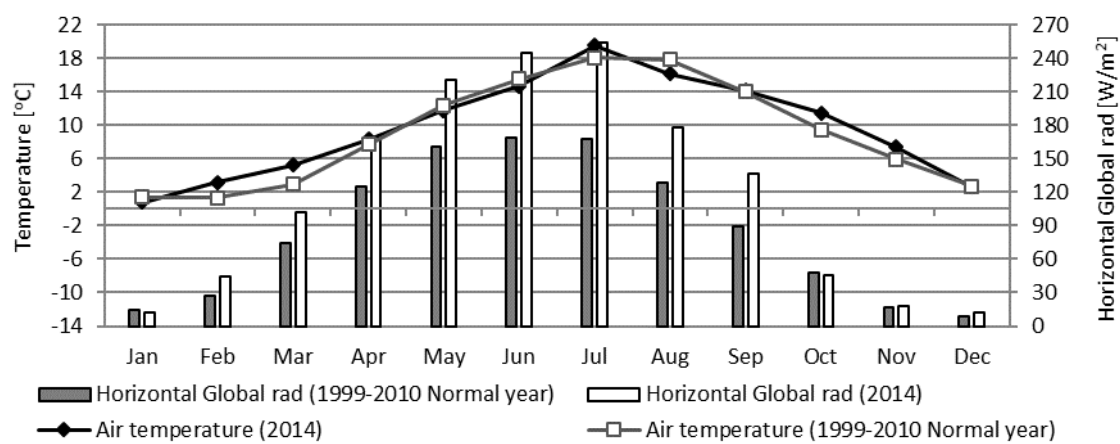


Figure 11. Monthly average temperatures and horizontal global radiation in Malmö during the field measurement period and a normal year.

### 3.1.3 Other weather files in use

The international weather files for energy calculation, v. 1.0 [186] and 2.0 [187] (IWECC and IWECC2) were used in the yearly simulations and, if those were not available for some locations, the Finnish test reference year (version 2012) [188] or the climate measurements from the Finnish meteorological institute (year 2010) were used. The IWECC files are derived from up to 18 years of hourly weather data and the IWECC2 files' measurements have been taken at least four times a day for up to 25 years [186, 187]. The Finnish test reference year, 2012, was based on the weather logs at Vantaa, Jyväskylä and Sodankylä weather stations from 1980 to 2009. They consist of weather data for twelve months, which have weather conditions close to the long-term climatological average [188].



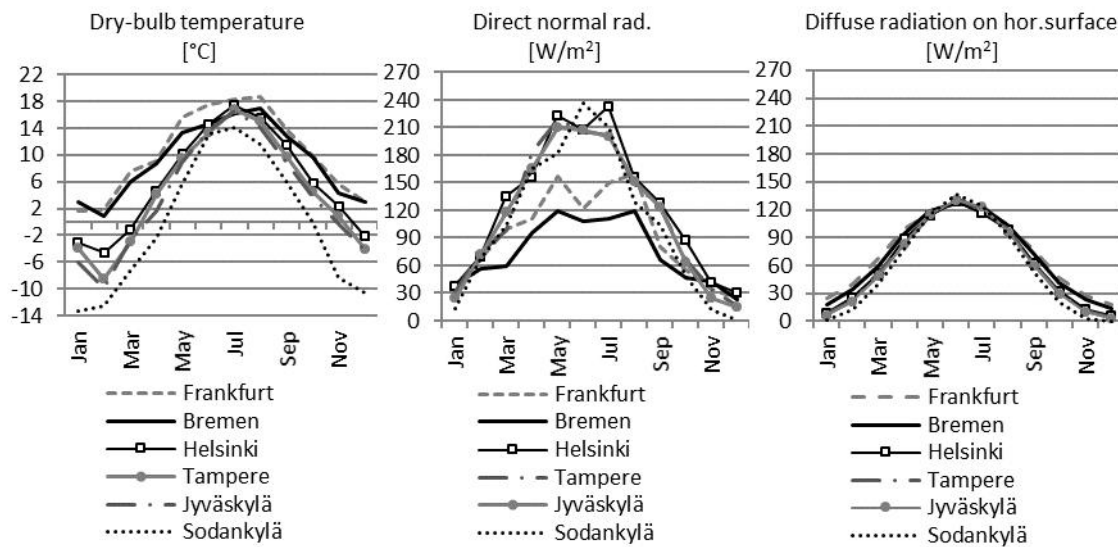


Figure 12. Results charts of the IWE2 weather files used in the simplified calculations (Article IV).

The geographical location for the simplified calculation (Figure 12) covers the area from the northern part of Finland to Central Europe. These locations are selected from one weather data source (ASHRAE IWE2) in order to ensure that the files are created in a consistent way, and are thus comparable. As seen in the figure, the climate conditions of the areas differ slightly from one another. Unsurprisingly, Sodankylä's weather is, in general, clearly colder than the other cities and Germany's climate is obviously milder in winter than it is Finland. The largest deviations in the radiation levels can be found between Germany and Finland's direct normal radiation levels, which differed noticeably from each other, especially in the summer. However, the diffuse radiation levels were quite similar, regardless of location.

## 3.2 Field monitoring

### 3.2.1 The balcony glazing studies in Tampere

Eleven blocks of flats in four different urban areas of the city were chosen for the study and placed in chronological order from the oldest to the newest with individual letter codes (Figure 13). The oldest building is from 1966 (Building A) and the most recent from 2006 (Building K). Most of the buildings are prefabricated, element-based constructions, typical of the 1970s. Four pre-1978 buildings did not originally include balconies for all the flats, but balconies have later been added to two of them (buildings C and D in Figure 13). In their external wall, window, door, and balcony structures, the

buildings B - F from the 1970s were all pretty similar at the time of their completion, but have since been renovated. The only exception was building E, which was still in its original state during the measurement period. The majority of the balcony facades of the buildings are oriented between the sector from the north west to the south east. (Article III)



Figure 13. Balconies in the studied blocks of flats, reflecting the different styles of construction over the decades. The buildings are identified by a letter code, A - K. (Article III)

### 3.2.1.1 Detailed monitoring on two balconies and flats

For the detailed measurements, monitoring was carried out with computerised equipment on two balconies, one glazed and the other unglazed. The balconies were located in the central part of the building's southern facade, one above the other (Figure 14). Field measurement equipment was used to measure the outdoor temperatures and the balcony air temperatures, plus the surface temperatures on both sides of the balcony

glazing and the balcony wall, door, and window (inner and outer) surfaces. In addition to this, the temperature of the flat was also measured. (Article I)



Figure 14. South-western façade of the building F (left) and the measuring equipment (right).

A special measuring system was assembled for the study and installed in a movable measurement cabinet (Figure 14). The measurement cabinet was transported to the test site and placed in the living-room of the flat, close to the balcony back wall. The main components of the monitoring system were a portable computer, a data logger, measurement sensors, sensor transmitters and power sources. The measurement was controlled by the Agilent Benchlink Data Logger software and an Agilent 34970A Data Logger.



Figure 15. Photos of the assembly of the surface temperature sensor [19]

Semiconductor sensors were used for the surface temperature sensors; the output voltage generated by the sensors changed as the temperature changed. The semiconductor sensors used were of the type LM 355 (manufacturer: National Semiconductor Corporation). The sensor contact surface was approx. 17 mm. For assembly of the surface temperature sensors, a semiconductor sensor was first attached by 'super

glue' to a round aluminium disc. After the glue dried, long-term adherence was ensured with the help of putty. Finally, the sensor's external surfaces and approx. 20 cm of the sensor wire were painted white (Figure 15). After that, the sensors were calibrated using Vaisala calibration equipment. The surface temperature sensors were installed on two vertically adjacent balconies (Figure 14) and flats in building F (Figure 13) and placed as shown in the connection diagram (Figure 16). The sensors are coded in a combined letter and number code. Letter C represents a temperature sensor and the letters RH represent a related humidity sensor. In addition to the letters, the sensors are identified by a three-digit number code. Vaisala A-E have Vaisala Humicap HTM100 type RH/T sensors.

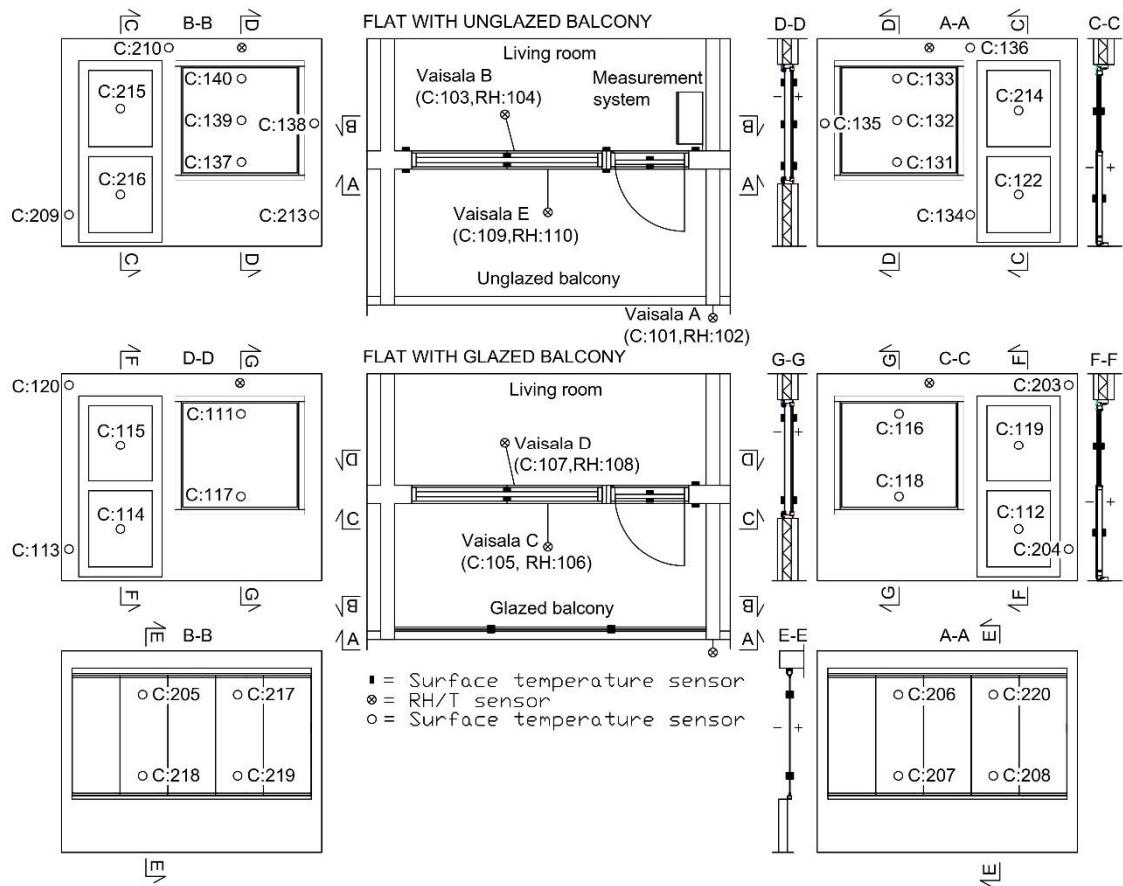


Figure 16. Connection diagram of the detailed monitoring of two flats and their balconies.

The balcony door sensors were placed in the middle of the door's glass pane and on the inner and outer sides of the solid part. The sensors were attached to the surfaces with polymer paste and the wires were duct-taped at approx. every 15 cm in order to ensure a secure attachment. In all, four sensors were installed on the top and bottom

part of the bottom flat window. In the case of the top flat's window, the sensors were also placed in the middle of the pane, outside and inside. The back wall sensors were placed case-specifically. Their placement was made difficult by hot-water radiators located under the window, which interfered with the wall surface temperatures. Two pictured from the placed sensors are shown below (Figure 17)



Figure 17. Sensors were placed on the balconies and flats according to the connection diagram (Figure 16).

The balcony, flat, and outdoor air temperatures, and the relative humidity, were measured at the surface temperature measurement locations by HMT 100 type sensors (RH/T sensors) manufactured by Vaisala Oy. The temperature and humidity transmitters consisted of a sensor component connected by a wire to an electronics unit. The indoor air RH/T sensor was located in the living-room near the balcony back wall, and the balcony's RH/T sensor was located close to the ceiling. The sensor measuring outdoor air temperature and relative humidity was placed on the balcony frame wall and protected against solar radiation and precipitation by a special factory-made outdoors sensor guard (Figure 18).



Figure 18. Outdoor weather sensor inside the factory-made outdoors sensor guard.

The system was used to measure the outdoor temperature, the flat and balcony air temperature, as well as the surface temperatures on both sides of the balcony glazing, the balcony wall and the door and window (inner and outer) surfaces. Temperatures were recorded at 1-hour intervals for approx. 10 months (from 16<sup>th</sup> July 2009 to 24<sup>th</sup> May 2010). More detailed information about month-specific actions performed at the detailed monitoring site are described in Table 7. (Article I)

Table 7. Month-specific actions performed at the detailed monitoring site.

Month	Actions
June	<ul style="list-style-type: none"> <li>- acquisition of field measurement equipment and surface temperature sensors</li> <li>- information about the external window and door properties acquired from producers</li> <li>- preparation and calibration of the sensors</li> <li>- acquisition of energy audit, structural drawings and other site-related information available</li> </ul>
July	<ul style="list-style-type: none"> <li>- installation of measurement sensor</li> <li>- specification of balcony structures and dimensions.</li> <li>- photographing</li> <li>- briefing of the inhabitants about the survey</li> </ul>
September	<ul style="list-style-type: none"> <li>- the measurement results were taken for the first time</li> <li>- it was agreed with the inhabitants that meter readings will be taken approx. once a month</li> </ul>
November-December	<ul style="list-style-type: none"> <li>- the computer was replaced in early December</li> <li>- because of computer problems, the measurements were interrupted for about one month.</li> </ul>
January-February	<ul style="list-style-type: none"> <li>- ventilation and air leakage value determination through one-time measurement</li> <li>- determination of walls, windows, doors and radiators surface temperatures by thermal camera</li> <li>- measurement of radiator and supply air valve sizes</li> <li>- determination of the building's external wall thermal insulation level</li> <li>- mapping of the power needs of electrical equipment</li> <li>- the inhabitants were interviewed about the flat usage habits and use of electrical equipment</li> <li>- the flat monthly electricity consumption acquired</li> </ul>
May	<ul style="list-style-type: none"> <li>- retrieval of measurement equipment</li> </ul>

As described in Table 7, the air change rate, airtightness and thermal insulation level of the apartment were determined by one-off measurements for later simulations. At the same time, the inhabitants were interviewed about the flat's habitual usage and electricity consumption. The investigation focused on the flat with a glazed balcony. The air change rate was determined by measuring the air flows of the flat's exhaust air valves located in the kitchen, storeroom, and toilet. An Airflow LCA 6000 VA wing wheel anemometer was used for these measurements. The air volumes were measured at different ventilation device operation modes, including both normal and high power opera-

tion. Before commencing the measurements, all of the doors and windows were checked to be closed. A single measurement at a measuring point lasted for about 0.5 to 1 minute.

The airtightness was measured on a one-off basis using the pressure test equipment Minneapolis Blower Door supplied by The Energy Conservatory, while the software was from TECTITE. Before commencement of the actual pressure test, the windows and doors of the flat were closed and any intentionally made apertures (such as air change valves, cooker hoods and supply air valves) were closed and sealed. After that, a door blower system was installed on the flat's front door. With the help of the computer-controlled blower, a differential pressure was created in the building between the stairwell and the flat. Air flows were measured sequentially at five differential pressures (0-60 Pa). The building's air leakage value was determined based on these measurements. The measurement instruments, along with their range and accuracy, are shown in Table 8.

Table 8. Measurement instruments with range and accuracy

Company	Measurement points	Properties	
<b>Surface temperature sensors</b>			
NATIONAL SEMICONDUCTOR LM335	Surface temperatures: 37 pts	Range	-40°C to 100°C
	(internal and external surface of balcony glazing, building exterior wall, window and door)	Accuracy	±0.4°C (calibrated to the range -20°C to 30°C)
<b>Air temperature sensors</b>			
VAISALA HUMICAP HTM100	Air temperatures: 5 pts	Range	-40°C to 80°C
	(Outdoor, balcony and flat air temperature)	Accuracy	±0.2°C (at 20°C)
			±0.6°C (at -25°C to 65°C)
COMARK DILIGENCE N2003/N2013	Air temperatures: 4 pts	Range	-20°C to 60°C
	(Balcony and flat air temperature)		±0.5°C (-20°C to 50°C)
<b>Relative humidity sensors</b>			
VAISALA HUMICAP HTM100	Relative humidities: 5 pts	Range	0 % to 100 % RH
	(Outdoor, balcony and flat air temperature)	Accuracy	±1.7 % RH (0 - 90 % RH) at +15°C...+25°C
			±2.5 % RH (90 - 100 % RH) at +15°C...+25°C
COMARK DILIGENCE N2003/N2013	Relative humidities: 4 pts	Range	0 % to 97 % RH
	(Balcony and flat air temperature)	Accuracy	±3 % RH (-20°C to 60°C)
<b>Ventilation airflows measurements</b>			
AIRFLOW LCA6000VA	Flat ventilation airflows: 3 pts	Range	0.25 to 30 m/sec
	(outlet vents in wc, kitchen and walk-in-closet)	Accuracy at 20°C and 1013 mbar	Calibrated better than ±1 % of reading ±1 digit
<b>Flat airtightness measurements</b>			
MINNEAPOLIS BLOWER DOOR	One-Point 50 Pascal Pressurization Test (blowing air into the flat): 1 pts	Maximum flow	2879 l/s at free air and 2524 l/s at 50 Pa
	(test arrangement built into the flat door)	Minimum flow	5 l/s to 141 l/s according to used ring
		Accuracy	±3 % RH with DG-700, rings D&E ±4 %

The interviews of the flat's occupants which determined the habitual usage of the flat, and the electricity consumption, were conducted during the measuring visits. The occupants provided information about the number of electrical devices, their specific power and their daily operating times. Electricity consumption at the measurement site proved to be clearly below average (1,500 kWh/year). The reason for such a low electricity consumption was the absence of a dishwasher and washing-machine, and the generally low level of electrical equipment in the flat. In addition, the inhabitants used the electrical equipment rather infrequently, mainly using the microwave oven for cooking, for instance.

### 3.2.1.2 RH/T monitoring on 22 balconies and flats

In the same period (17<sup>th</sup> July 2009 to 17<sup>th</sup> May 2010), the air temperature and relative humidity on 17 glazed and 5 unglazed balconies and adjacent flats (Figure 19) were recorded. Battery-powered Comark Diligence EV (N2003 and N2013) data loggers were installed in the flats and on their balconies to measure air temperature and relative humidity. In all cases, there was one data logger in the flat and another on the balcony.

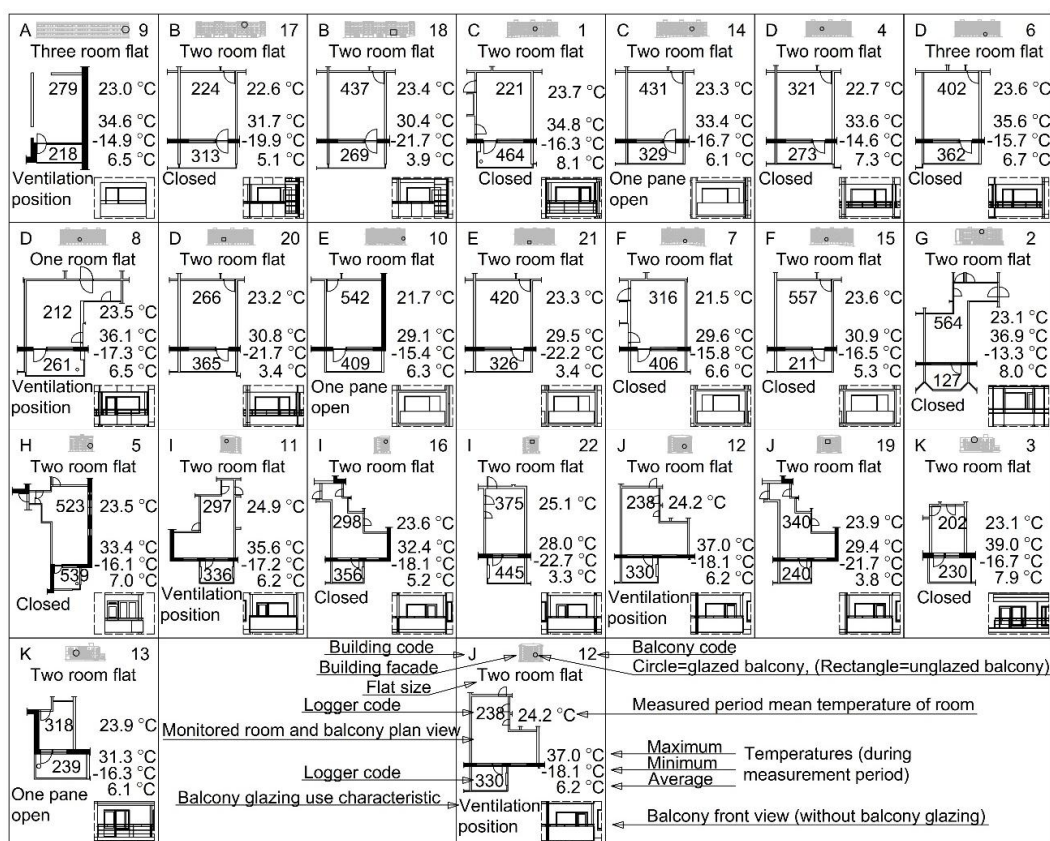


Figure 19. Data loggers in the flats and balconies of the studied blocks of flats.



The data loggers were installed at a height of about 2 meters from the floor of the flat and at least 4 meters from the external walls. External loggers were installed on the balcony ceilings, hidden from direct sunlight, and at least 0.5 meters from any external walls. The most common installation arrangement is shown in Figure 20, and schematic drawing of the measured apartments in Figure 19. In Figure 19, the buildings are identified by a letter code, A – K and the balconies by a number code 1-22. The data loggers are further identified by a three-digit number code. The graph also shows the facade of the building, the apartment size and the balcony type, as well as a balcony front view, the balcony glazing, the inhabitants routines and some temperature data.

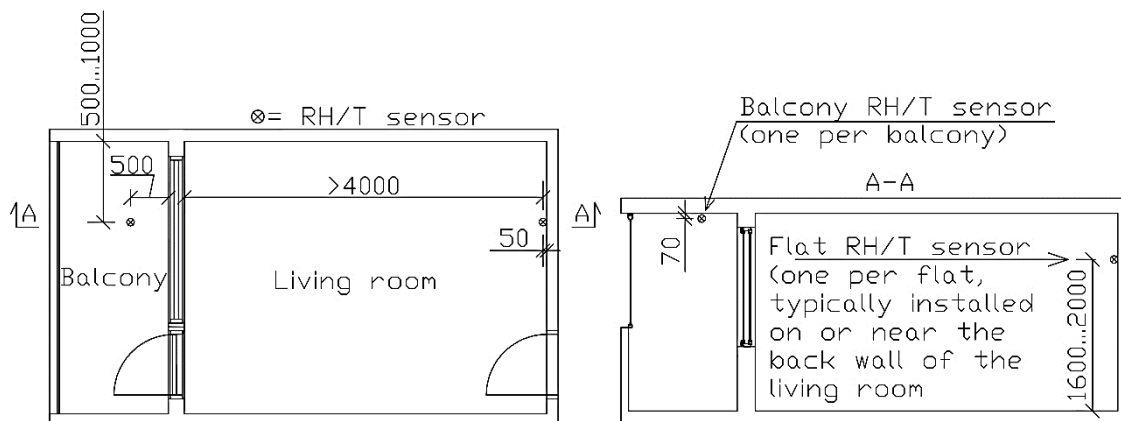


Figure 20. Installation arrangement of the data loggers in a typical balcony and flat (Article III).

The test sites for the study were found in the Tampere area using VVO's real estate database. The chosen sites were acquired by putting notices in the inhabitants' mailboxes, door-stepping and phone mapping. Once a site was selected, attention was paid to the building's age, structural solutions, and facade orientation. Obviously, a positive attitude towards the research was required from the inhabitants, so this was a crucial selection criterion for the chosen blocks of flats. Another important criterion was to use buildings in which only some of the balconies were glazed, because this allowed temperatures to be monitored on glazed and unglazed balconies in the same building. The test site acquisition and the measurement visits were divided into four periods, as seen in Table 9.

Table 9. Month-specific actions performed on the balconies RH/T monitoring.

Month	Actions
June	- test sites acquisition by notice forms, doorstepping and phone mapping - temperature/humidity sensor calibration
July	- specification of balcony and balcony structures dimensions - estimation of the thermal insulation levels - temperature/humidity sensors installation - photographing - briefing of the inhabitants about the survey.
January-February	- updating of test site inhabitant data - checking of balcony glazing usage (openess grade of glazing) - taking of temperature/humidity sensor readings.
May	- temperature/humidity sensor retrieval and condition checking. - checking of balcony glazing usage (openess grade of glazing)

The data loggers were used to show the influence of the balcony type, orientation, amount of glazing, and the balcony's wall, door, and window U-values on the glazed balcony temperature conditions. The loggers recorded a reading every hour, and they had the memory capacity allowed to store almost a year's worth of data. The loggers were accurate to  $\pm 0.5$  °C for temperature and  $\pm 3$  % RH for relative humidity (Table 10).

Table 10. Measurement instruments with range and accuracy

Company	Measurement points	Properties	
<b>Air temperature sensors</b>			
COMARK DILIGENCE N2003/N2013	Air temperatures: 4 pts (Balcony and flat air temperature)	Range	-20°C to 60°C $\pm 0.5$ °C (-20°C to 50°C)
<b>Relative humidity sensors</b>			
COMARK DILIGENCE N2003/N2013	Relative humidities: 4 pts (Balcony and flat air temperature)	Range Accuracy	0 % to 97 % RH $\pm 3$ % RH (-20°C to 60°C)

### 3.2.2 Added glazing study in Malmö

The brick building with 1 ½-brick-thick walls was erected in the 1930s. In 2010-2011 the building was renovated by adding an outer layer of glazing at roughly 0.75 m distance from the south, east and west façades of the building (Figure 21). The north façade was not glassed in because of lack of space. The vertical glazing added to the brick façade is single-pane clear glass and the horizontal glazing added to the top of the cavity is argon-filled clear double glazing. The building faces 30° east of south. It is heated by a hydronic heating system with radiators and ventilated by two independently working ventilation systems; 5701 for the building and 5702 for the cavity. (Article V)

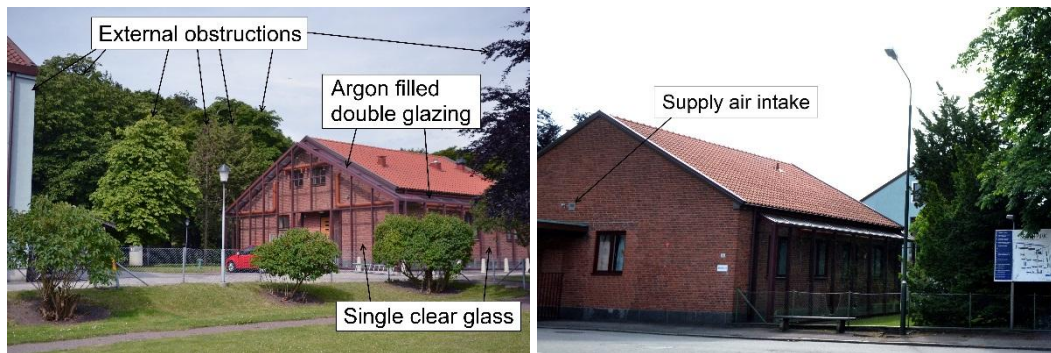


Figure 21. The main external obstructions in front of the studied building (left photo) and the supply air intake (only used in non-heating conditions), which is located on the north façade (right photo). (Article V)

There is also a ground duct system, a cavity-air exhaust fan (FF2) and two openable window in the south cavity (Figure 22). The ground duct system consists of a large inlet pipe (concrete), an underground pipe and cavity inlets. Outdoor air is supplied to the ground duct via a large concrete pipe with an outside diameter of 1.2 m (Figure 22) and a height of 1.5 m above the ground. The underground ducts are 400 mm in diameter and the distance from the concrete pipe to the bottom of the glazed space is 7 m. There are 4 air inlets of 100 mm diameter in each of the east, west and south sides of the cavity (a total of 12 inlets) at the bottom of the cavities. The two cavity windows are both about  $0.5 \times 0.7 \text{ m}^2$  in size (Figure 22). The standard air flow through the ground duct and cavity exhaust fan (FF2) is 150l/s in the cavity cooling mode.

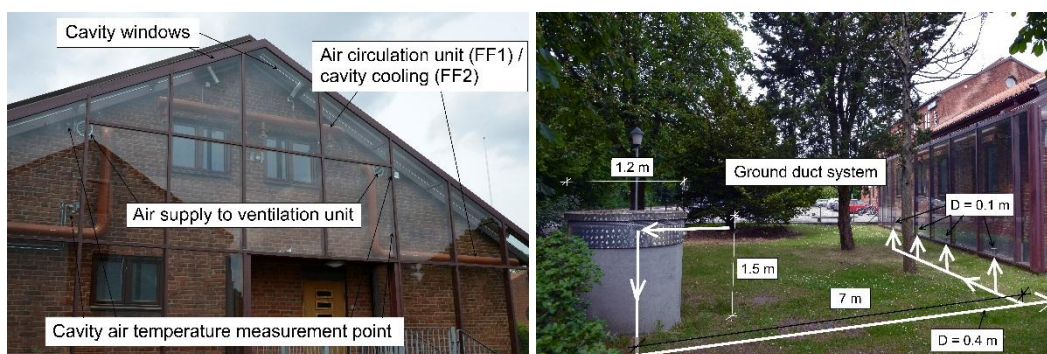


Figure 22. South façade (left photo) and ground duct system (right photo) with description of the visible system components. (Article V)

### 3.2.2.1 Description of the ventilation systems

A mechanical supply and exhaust ventilation system was installed in the building during the renovation. The ventilation unit; a Systemair VR 700 DC located in the attic, in-

cludes filters, a rotary heat exchanger and a heating coil (Figure 23). The air is supplied to each room through insulated ducts.

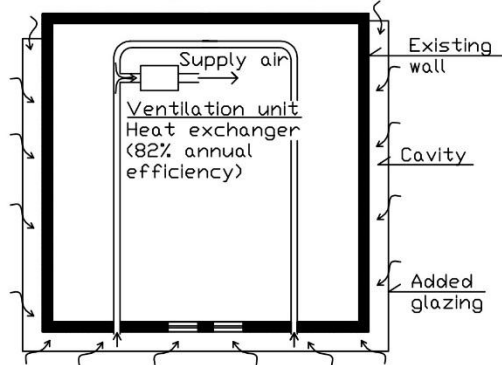


Figure 23. Picture of the ventilation unit; a Systemair VR 700 DC, and a monitoring screen located in the attic.

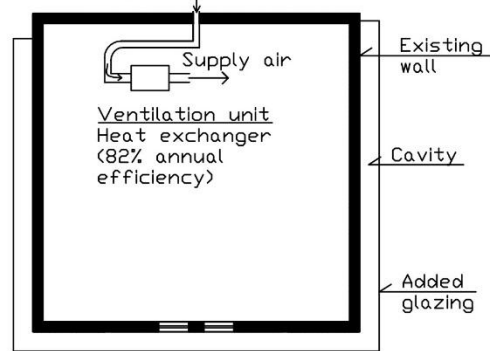
### **The building ventilation system – 5701**

The building ventilation system (5701) has two operating modes (Figure 24); one for a heating period and one for a non-heating period. The first mode is used, when heating is needed. In this mode, the outdoor air is passed through the cavity before it enters the ventilation unit. The second mode is used for warmer periods, like the summertime. In this mode, the outdoor air is not passed through the cavity. To avoid the air being overheated it is supplied directly to the ventilation unit from an air intake located on the north façade (Figure 21).

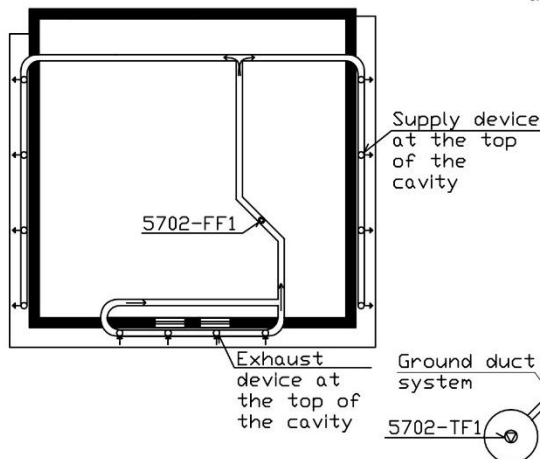
Heating period (winter case) - system 5701  
If the temperature of two south cavity sensors (GT31, GT32) is below 20 °C, supply air comes through the cavity.



Non-heating period (summer case) - system 5701  
If the temperature of two south cavity sensors (GT31, GT32) is above 20 °C, supply air comes directly from outside.



Heating period (winter case) - system 5702  
If the mean temperature of two south cavity sensors (GT21:1, GT21:2) are above east (GT32:1, GT32:2) or west (GT32:1, GT32:2) cavity sensors mean value, the air circulation starts (fan 5702-FF1).



Non-heating period (summer case) - system 5702  
If the mean temperature of two south (GT21:1, GT21:2), east (GT33:1, GT33:2) or west (GT34:1, GT34:2) cavity sensors are above 20 °C, the supply (5702-TF1) and exhaust (5702-FF2) fan starts. If the sensor GT41 temperature is above 23 °C, cavity windows also open.

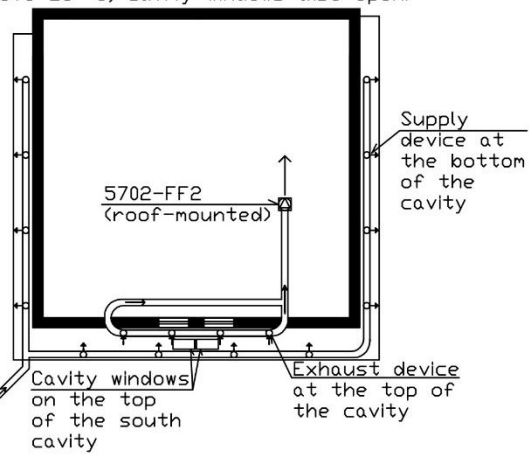


Figure 24. The four principle operating modes for the two ventilation systems 5701 (supplying the building) and 5702 (supplying the cavity).

### The cavity ventilation system - 5702

Another ventilation system, 5702, is used for control of the cavity air temperature. This system works independently of the main ventilation system. It also has two operation modes (Figure 24). The first mode circulates the air between the facades, when the south façade temperature is above the temperature of the east or west façades. The second mode, which uses the ground duct system (Figure 22), the cavity air exhaust fan (FF2) and two openable windows, is intended for cavity cooling, and only operates when there is a danger of the building overheating. Further information about the control options and operation modes are described in Section 3.2.2.2.

### 3.2.2.2 Monitoring system and ventilation control

The building has been equipped with a monitoring system (Figure 25). Measurement sensors for temperature, relative humidity, air flow and other parameters have been installed at various points in the building; inside the cavity, inside the ventilation unit and in the ventilation ducts. The temperature inside the cavity is measured at 4 different points on the south façade, 4 points on the east façade and 5 points on the west façade. These sensors have been attached to the brick wall and shielded with aluminum foil (Figure 26). Ten temperature measurement instruments are installed for the main ventilation system, and fifteen for the cavity system (Figure 25). Most of the sensors are used to evaluate the performance of the system, but some are also used to control its operation.

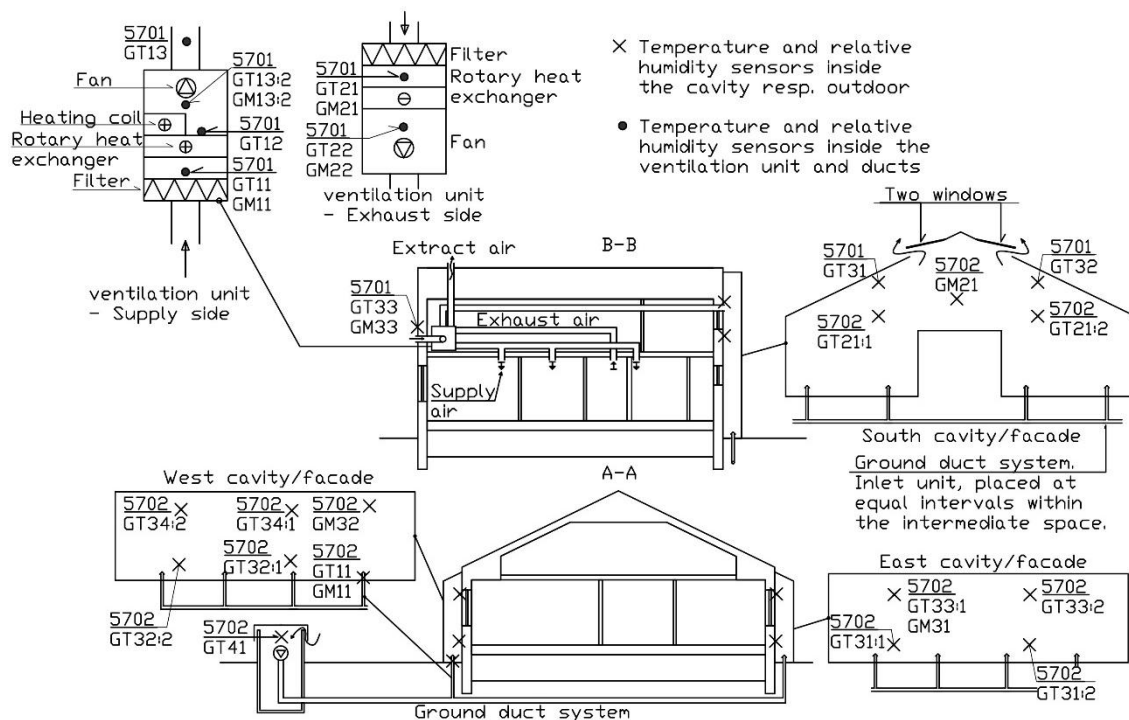


Figure 25. Schematic drawing of the measurement arrangements. (Article V)

All the sensors are connected to a Programmable Logic Controller (PLC) located in the HVAC room in the attic. This is also connected to the city of Malmö's overall monitoring system for all public buildings. The temperatures are sampled and saved every minute. The measurement values have been retrieved from the files kept by the city of Malmö. The analysed monitoring period was from the 28<sup>th</sup> of October, 2013 to the 10<sup>th</sup> of February, 2015 and the main focus was between the 7<sup>th</sup> of April, 2014 and the 10<sup>th</sup> of February, 2015. The building was unoccupied during the whole measurement period except for one week in August, 2014 (from 15<sup>th</sup> to 23<sup>th</sup> of August). Human behavior has

therefore not influenced the building's indoor climate or its energy balance. It is noteworthy that the ventilation units have always been shut down at night.



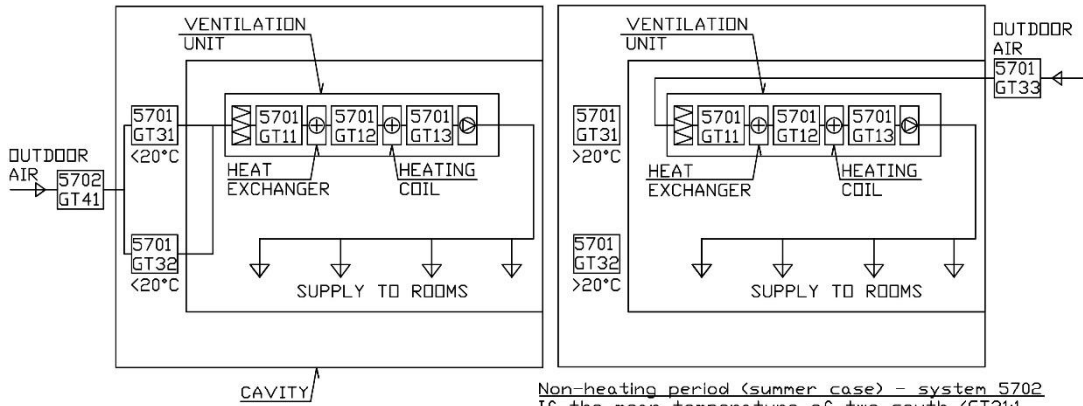
Figure 26. Temperature sensor shielded with aluminum foil (left) [189]. The aluminum foil from some sensors was removed for the measurements (right).

### **The building ventilation system (5701) control**

Different monitoring sensors were used to measure the temperatures of the cavity and thus control the operation of the building's ventilation system (5701) and the cavity cooling unit (5702). The sensors for monitoring the four main operation modes are shown in Figure 27. The idea of the building ventilation system (5701) control is that when the supply air needs heating, the outdoor air is passed through the cavity before it is supplied to the ventilation unit. The different modes have been defined in the system so that when the temperature of the sensors GT31 and GT32, located on the south façade of the cavity, exceed 20 °C the outdoor air is taken directly from the north façade. When the same temperature points drop below 18 °C, the outdoor air is once again passed through the cavity before entering the ventilation unit.

Heating period (winter case) - system 5701  
 If the temperature of two south cavity sensors (GT31, GT32) is below 20 °C, supply air to building comes through the cavity.

Non-heating period (summer case) - system 5701  
 If the temperature of two south cavity sensors (GT31, GT32) is above 20 °C, supply air comes directly from outside.



Heating period (winter case) - system 5702  
 If the mean temperature of two south cavity sensors (GT21:1, GT21:2) are above east (GT31:1, GT31:2) or west (GT32:1, GT32:2) cavity sensors mean value, the air circulation starts (fan 5702-FF1).

Non-heating period (summer case) - system 5702  
 If the mean temperature of two south (GT21:1, GT21:2), east (GT33:1, GT33:2) or west (GT34:1, GT34:2) cavity sensors are above 20 °C, the supply (5702-TF1) and exhaust (5702-FF2) fan starts. If the sensor GT41 temperature is above 23 °C, cavity windows also open.

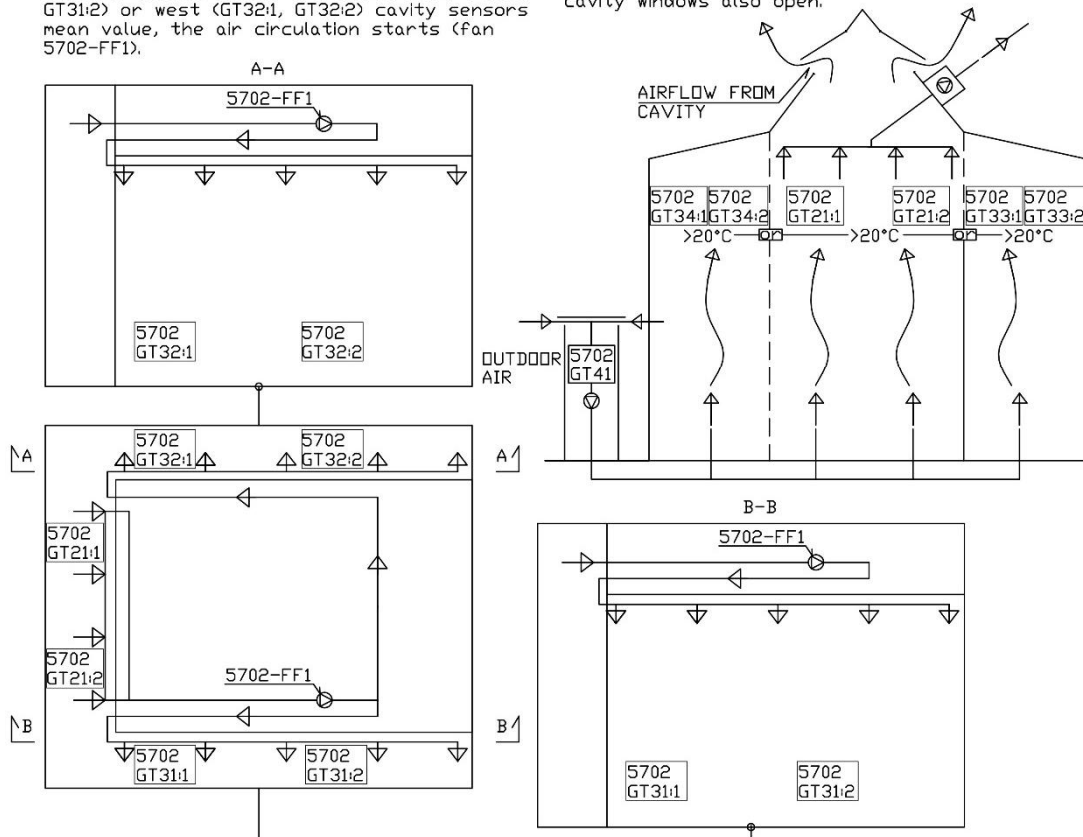


Figure 27. Connection diagram of the detailed monitoring in Malmö case building.



### **The cavity ventilation system (5702) control**

The second ventilation system, 5702 also has different modes for heating and cooling purposes (Figure 27). During heating periods, whenever the south facade has a higher temperature than either of the other two facades, the facades' temperatures are stabilized by moving the air from the south-facing cavity to the other two cavities with a fan (5702-FF1). The fan is switched on when the mean value of two temperature sensors in the south cavity (GT21:1 and GT 21:2) is higher than the mean value of the two sensors in the east or west cavity. (Article V)

During cooling periods (summertime), a fan (5702-TF1) located at the top of the vertical concrete duct (Figure 22) starts to cool down the cavity when the mean temperature in the upper part of any of the cavities is above 20 °C. It does this by passing the outdoor air through the ground duct system before supplying it to the cavity. The fan stops when the temperature drops below 18 °C. The supplied air passes through the cavity and leaves through an exhaust fan (5702-FF2) or through the two cavity windows at the top of the south façade, so it is not supplied to the building. The windows (Figure 22) open when the outdoor temperature sensor located at the mouth of the concrete air-intake duct is above 23 °C, and closes again when the temperature drops below 20 °C. The outdoor air used in the building during the cavity cooling mode is supplied to the building via the north façade (Figure 21). The temperature and relative humidity sensors and their accuracy are shown in Table 11. (Article V)

Table 11. Measurement instruments with range and accuracy

Company	Measurement points	Properties	
<b>Temperatures</b>			
Produal TEU PT1000	In the cavity/outdoor: 14 points	Range	-50°C to +50°C
	Sensors: 5701-GT31, 5701-GT32, 5701-GT33, 5702-GT31:1, 5702-GT31:2, 5702-GT32:1, 5702-GT32:2, 5702-GT33:1, 5702-GT33:2, 5702-GT34:1, 5702-GT34:2, 5702-GT35, 5702-GT36, 5702-GT41	Accuracy	±0.3°C (at 0°C)
Produal TEKY PT1000	In the ventilation unit: 4 points	Range	-50°C to +80°C
	Sensors: 5701-GT11, 5701-GT12, 5701-GT21, 5701-GT22	Accuracy	±0.3°C (at 0°C)
Produal TEK PT1000	In the cavity/in the ventilation ducts: 4 points	Range	-50°C to +70°C
	Sensors: 5701-GT13, 5702-GT21:1, 5702-GT21:2, 5702-GT22	Accuracy	±0.3°C (at 0°C)
<b>Temperatures and relative humidities:</b>			
Thermokon LC-FTA54/VS	In the ventilation unit: 4 points	Range	0 to 100 % RH
	Sensors: 5701-GT/GM11, 5701-GT/GM13, 5701-GT/GM21, 5701-GT/GM22	Accuracy	±3 % between 20 – 85 % RH
		Range	-20°C...+80°C
		Accuracy	±0.5°C (at 25°C)
Thermokon FTK/VS	In the ground duct system: 1 point	Range	0 to 100 % RH
	Sensor: 5702-GT/GM11	Accuracy	±2 % between 15 – 95 % RH
		Range	-20°C...+80°C
		Accuracy	±0.5°C (at 25°C)
<b>Relative humidities</b>			
Schneider Electric SHO100	In the cavity/outdoor: 4 points	Range	0 to 95 % RH
	Sensors: 5701-GM33, 5702-GM21, 5702-GM31, 5702-GM32	Accuracy	±2 % RH (at 20 °C)
<b>Airflows</b>			
Calectro PTH-3202-DF	In the ventilation ducts: 2 points	Range	-50 to +50 Pa
	Sensors: 5701-GF11, 5701-GF21	Accuracy	±1 % > 300 Pa, ±4 Pa < 300 Pa

Before the modelling and calibration of the computer model, it was first verified that the system was working according to the identified control modes of the studied building. This was confirmed by comparing the temperatures measurements at the different locations. Also, building features like the envelope structures and the heating system operation modes were evaluated on the spot. Some of these issues have been documented in the following publications [190, 191, 189].

### 3.3 IDA-ICE simulations

In this study, the simulations were used to assess the energy-saving potential of glazed balconies. The starting point for the simulations was a detailed, level 5 (Table 2) calibration arrangement with audited information and long-term monitoring data. Based on these input data, the simulation model was calibrated using manual and graphical calibration methods as described above in section 2.3.2. The energy-saving simulations with the glazed balcony model consist of the model calibration (Article I), sensitivity

analysis (Article II) and a reliability analysis of the simple method (Article IV). The sensitivity analysis and the reliability analysis of the simple method were themselves like 'parametric studies', whose prime objective was to demonstrate the key performance indicators of the glazed balcony model, and their interdependencies. The subsequent process of model calibration, a sensitivity analysis and a reliability analysis of the simplified method was repeated three times, and each of these three models were upgraded after each step. At the end of this process, the final models were formed and their input parameters documented. In addition, calibration, sensitivity analyses and reliability analyses with the simplified method were conducted with the models.

Due to the complexity of the Malmö building, there was no benefit to be gained from performing a very detailed calibration. Nevertheless, in a technical sense, the Malmö building has many similarities to a glazed balcony and is thus a good complementary investigation for the glazed balcony studies carried out in Tampere. The meaningfulness of the Malmö building simulation as an additional study to the glazed balcony simulation lies in the totally different overall solution (mechanically controlled DSF solution) compared to the glazed balcony solutions used in the Tampere studies (passively controlled glazed balconies). The glazed balcony is, for example, occupied space, but the cavity of the DSF in Malmö is used only for service purposes. The facades of the Malmö building are also totally covered with glazing, whereas the glazed balconies cover only part of the building facades. In addition, the cavity of the DSF in Malmö is connected to the building's ventilation system (the ventilation supply ducts are connected to cavity). In the Tampere study, the balconies are separate from, or only slightly connected to the flat's ventilation system (in some cases the inlet vent of the mechanical exhaust ventilation is also in the partition wall between the living room and balcony). Despite all these differences, the same simulation software and similar modelling methods of the cavity spaces have been used for both buildings.

The  $R^2$ , MPE and MAPE indicators have been used as statistical indices in the model calibration, and ASHRAE Standard 14 [116] calibration criteria (Table 4) for MBE and CV(RMSE) are set as a 'goodness of fit' indicators for the simulation. This means that less than  $\pm 10\%$  mean bias error and  $< 30\%$  error of variation of the root mean squares are allowed. This thesis also utilises the SI indices calculated in connection with the Article II sensitivity analyses, and the statistical analysis for the meaningfulness of the balcony temperature as a balcony performance indicator analyzed in connection with Article III.

### 3.3.1 The balcony glazing simulations

The building subjected to the simulations (building F) is a typical Finnish, 1970s, 1+6 storey, prefabricated concrete block of flats. It has 3 stairwells and 54 flats (Figure 13). Its construction is typical of 1970s blocks of flats in Finland [5] and is based on the open-source panel system called BES [1]. The building is connected to the district heating network and ventilated by a mechanical-exhaust ventilation system. The heating water is delivered to the building through hot water pipes, and the heat is distributed with the help of free-standing radiators. The facades of the building were renovated in 2004, during which the windows and doors were replaced and glazing was installed on approximately 50 % of the balconies. At the same time, the condition of the HVAC system was checked and the ventilation system and radiator network were balanced. The exhaust ventilation machine itself remained the same, but was equipped with a modern timer control. (Article I, Article II)

Table 12. The building-specific information about the simulated block of flats (Article III).

Location	Building type, construction year, external wall structure and U-value [W/m <sup>2</sup> °C]	Balcony type, dimensions (Number of glazed sides informed in parentheses)	U-values of windows and doors [W/m <sup>2</sup> °C]	Balcony material (parapet material informed in parentheses)	Heat transfer by conduction ( $\sum U \cdot A$ ) from adjacent flat to balcony [W/°C]	Solar absorption level of balconies (External obstruction informed in parentheses)	Overall tightness of the balcony (after user effect)
Her- vanta	precast concrete, 1979, concrete sandwich panel, U=0.29	Protruding, w=4.0m, d=1.5m, h=2.6m (1)	U=1.2 (windows), U=1.2 (doors)	concrete balcony, (concrete parapet)	Low, 7.7	Very low (dense forest in front of facade)	Very high

The U-value of the sandwich-type façade panels is 0.29 W/m<sup>2</sup>°C and that of the windows and doors is 1.2 W/m<sup>2</sup>°C (Table 12). The total heat transfer by conduction from the flat to the adjoining balcony is actually relatively low (7.7 W/°C) compared to the other monitored flats (Figure 13). The building's exterior wall is dark red, the balcony structures are mainly white but the back wall and floors are light grey. It is surrounded by tall birch trees, which reduce the wind pressure and, most importantly, protect the building's southwestern balcony facade from the sun's radiation. The overall tightness of the glazed balcony is very high compared to the other monitored balconies. Other building-specific information is described in Table 13. (Article I and II)

Table 13. Apartments and balconies parameters.

Flat area	64m <sup>2</sup>
Number of inhabitants	2 pc.
Measured 'normal' flow rates through ventilation vents (mostly)	Storeroom: 0.0017 m <sup>3</sup> /s, WC: 0.0047 m <sup>3</sup> /s, Kitchen: 0.011 m <sup>3</sup> /s
Measured 'enchanced' flow rates through ventilation vents (Mo-Su: 6 - 9 AM, 11 AM-1 PM and 4-6 PM)	Storeroom: 0.0032 m <sup>3</sup> /s, WC: 0.0083 m <sup>3</sup> /s, Kitchen: 0.0223 m <sup>3</sup> /s
Location(climate condition)	Tampere( 61° 29' 53" N, 23° 45' 39" E), Finland
Orientation	South-West
Wind profile	Suburban
Balcony façade distance from the building in front	Mixed forest in front of the balcony facade
Apartment size (A <sub>APARTMENT</sub> )	Two-room flat, A <sub>APARTMENT</sub> =64 m <sup>2</sup> and V <sub>APARTMENT</sub> =166 m <sup>3</sup>
Balcony size (A <sub>BALCONY</sub> )	A <sub>BALCONY</sub> =6 m <sup>2</sup> and V <sub>BALCONY</sub> =16 m <sup>3</sup>
Apartment inside air temperature	23.3 °C
Standard of equipment, number of residents and apartment usage habits	According to the real situation inside the apartment (two residents, electricity consumption 1,500 kWh/year)
Apartment type	Apartment runs from front to back of a building
Balcony type	Extended concrete balconies supported on frame walls
Building air change rate	Mostly 0.35 ACH, between 06:30-09, 11-13 and 16-18 0.7 ACH
Supply air inlet vents position	Two window vents
Glazed space unintended ventilation	1.1-2.2 ACH (monthly average)
Building air leakage coefficient (at 50 Pa pressure difference)	0.88 ACH (at 50Pa pressure difference)
Heating capacity design of hot water radiators	According to current design in 1979
The heating system control curve position	According to current settings in the building
The heating system summer shut-off	No summer shut-off
Surfaces absorptivity (Balcony and external wall)	Mostly 0.22 (Balcony slab top side and external wall outer side 0.3, balustrade outer side 0.4)
Surface emissivity (Balcony and external wall)	0.9
Specific heat capacity of balcony structures	900 J/(kg*K)
Lambda value of balcony structures	1.35 W/(m*K)
Density of balcony structures	2300 kg/m <sup>3</sup>
Window or balcony glazing blinds placement position	No blind
Wall properties (wall between apartment and balcony)	A <sub>WALL</sub> =5.2 m <sup>2</sup> and U <sub>WALL</sub> =0.3 W/m <sup>2</sup> °C
Window properties (wall between apartment and balcony)	A <sub>WINDOW</sub> =3.3 m <sup>2</sup> , U <sub>WINDOW</sub> =1.4 W/m <sup>2</sup> °C, g <sub>WINDOW</sub> =0.55
Balcony door properties	A <sub>DOOR</sub> =1.9 m <sup>2</sup> , U <sub>DOOR</sub> =1.2 W/m <sup>2</sup> °C, g <sub>DOOR</sub> =0.55
Balcony glazing properties	A <sub>GLAZING</sub> =6.3 m <sup>2</sup> , U <sub>GLAZING</sub> =5.8 W/m <sup>2</sup> °C, g <sub>GLAZING</sub> =0.82
Glazing-to-floor area ratio(A <sub>GLAZING</sub> / A <sub>BALCONY</sub> )	1.05
Window and door-to-floor area ratio ((A <sub>WINDOW</sub> +A <sub>DOOR</sub> ) / A <sub>BALCONY</sub> )	0.87
Glazing-to-balcony glazing eligible area ratio (A <sub>GLAZING</sub> / (A <sub>BALCONY WALL</sub> +A <sub>BALCONY SIDE WALLS</sub> +A <sub>BALCONY FRONT WALL</sub> ))	0.26

The calculations for the two 64 m<sup>2</sup> flats of building F (Figure 28) included calculation model verification and a case-specific evaluation of energy efficiency impacts by variation. The first phase involved comparing field measurements and simulation results and its aim was to prove that the calculation accuracy of the IDA-ICE software is sufficient for evaluation of the energy efficiency impacts of the balcony glazing. The second phase included the evaluation of balcony type (integrated vs. extended balcony), orientation, structures (especially balcony door, wall and window), and size, etc. and their influence on the balcony glazing-related energy economy benefits.

### 3.3.1.1 Validation study

Two vertically adjacent flats located in the middle part of the building, one of which has a glazed balcony, were simulated by the IDA-ICE software. The data for the building in the simulation were acquired from the architectural and structural drawings, one-off measurements of the ventilation system operation and the flat's air-tightness, as well as interviews with the residents. The location of the electrical equipment and the electricity consumption were determined by site visits. The investigations were carried out in the flat with the glazed balcony, and the corresponding data for the other flat was assumed to be the same, in order to standardize the indoor atmosphere conditions and the use of the premises in both flats. For source information regarding the flat and use thereof, see Table 13 and Figure 28. (Article I)

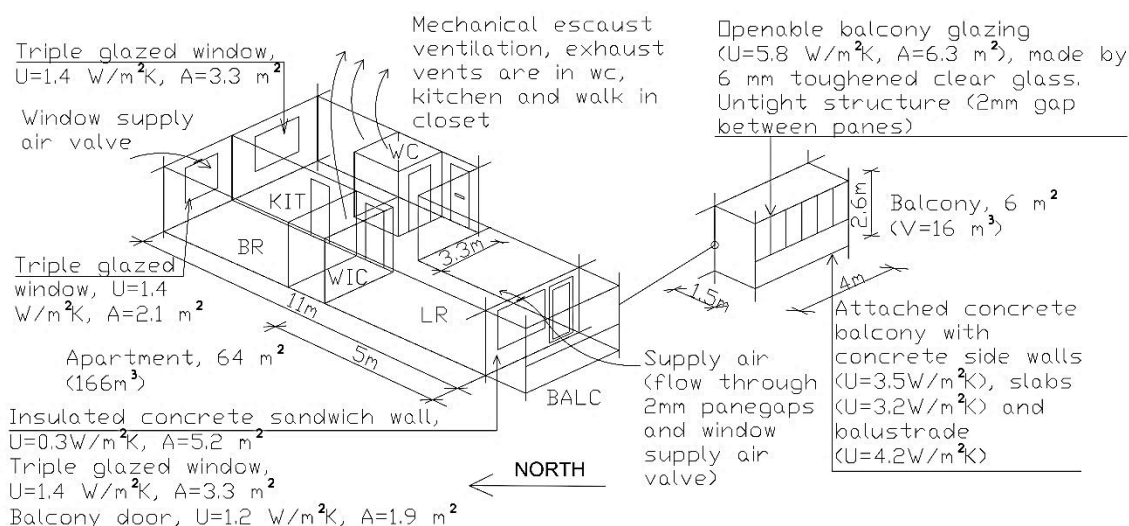


Figure 28. Illustration of the simulated apartment. (Article I)

The flats consisted of a living-room, bedroom, kitchen, indoor storage cupboard, toilet, and entrance hall (Figure 28). They have been modeled in the same simulation model, but separated thermally from one another by moving them apart (Figure 29). All the rooms and balconies have been modeled separately with a detailed zone model (climate model) and the windows and balcony glazing with a detailed window model. In this way, the IDA-ICE identifies the balcony front as an external wall and the partition wall between the balcony and the living room as an internal wall. This means, in practice, that the wind pressure is directed at the external wall i.e. the front edge of the balcony, and not to the partition wall between the balcony and the living room, as it is in reality for an unglazed balcony.

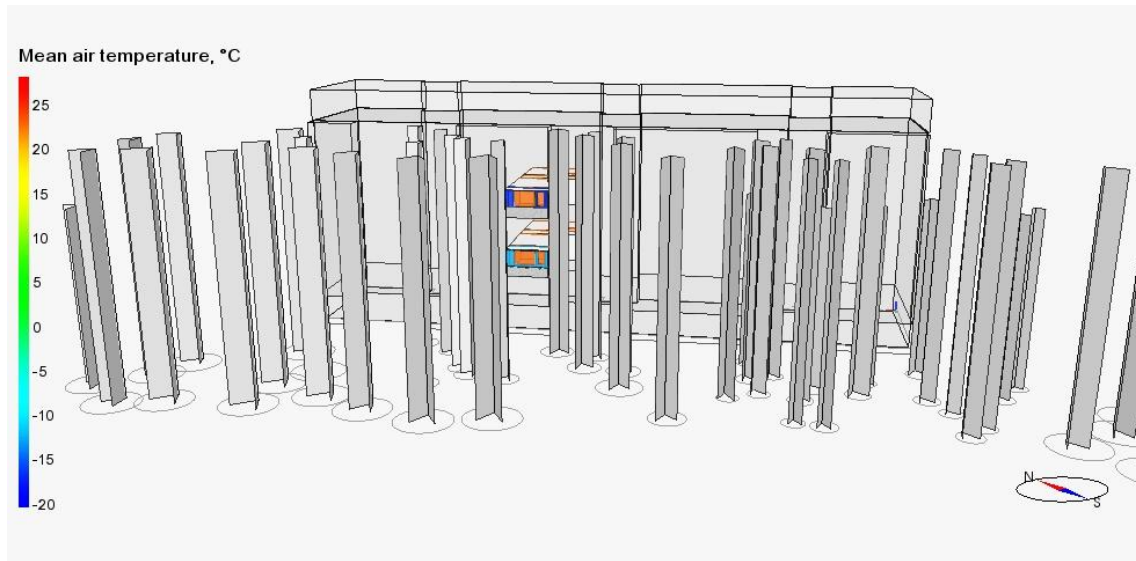


Figure 29. Simulation model of the building with trees represented by bars of different length.

The open section of the unglazed balcony and the openings of the balcony glazing system (2-3 mm gaps between panes) were measured on site and modelled as openings in IDA-ICE. The doors between the rooms were also modeled as openings (Figure 30), but the air inlet valves of the windows were modeled as an air leakage path. The difference between the flow through an air leakage path and an opening is that the flow through a leak only goes in one direction (outwards), whereas the flow in an opening can go in two directions (inwards and outwards).

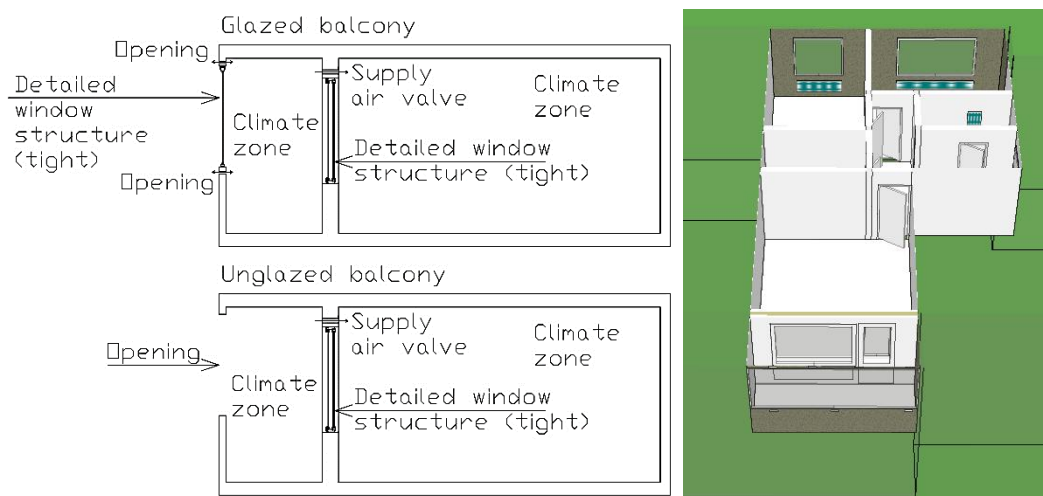


Figure 30. Modeling of the balconies in IDA-ICE (left) and model view from the flat with glazed balcony.

The building has a hot water radiator system, which adjust the water temperature according to outdoor temperature using the control setpoints of the building user (adjusted according to a real control curve). The radiators sizes were measured on site, and their power and flow rates calculated in accordance with the building's power demand when it was built. The building has an exhaust ventilation system, whose airflow was measured on site and whose operation was scheduled according to known control setpoints. Internal thermal loads and schedules as well as radiators dimensions, flow rates, and power requirements during the winter season are shown in Table 14.

Table 14. Internal thermal loads and schedules as well as radiators dimensions, flow rates, and power requirements during the winter season.

Premise, heat source	Schedule (winter period)	Thermal load	Unit
<b>Bedroom</b>			
people	Mo–Su 10 PM–7 AM	0.7	met/person (met=activity level)
lighting	Mo–Su 7-8.30 AM and 8.30-10 PM	60	W
equipment	Mo-Su 7-9 AM and 4-10 PM	15	W
<b>Living-room</b>			
people	Mo–Su 8-9 AM and 2-9 PM	1	met/person
lighting	Mo–Su 8-9 AM and 4-9 PM	60	W
equipment	Mo–Su 8-9 AM and 2-9 PM	150	W
<b>Kitchen</b>			
people	Mo–Su 7-7.30 AM, 12 noon-12.30 PM, 2.30-3 PM, 5.30-6 PM, 9.30-10 PM	1	met/person
lighting	Mo–Su 7-9 AM and 6-10 PM	25	W
equipment	Mo–Su, 24 h	100	W
<b>WC</b>			
people	Mo–Su 8-9 AM and 9-10 PM	1	met/person
lighting	Mo–Su 8-9 AM and 9-10 PM	25	W
<b>Entrance hall</b>			
lighting	Mo–Su, 12 noon-6 PM	25	W
equipment	Mo–Su, 12 noon-6 PM	15	W
<b>Storeroom</b>			
people	Mo–Su 7-7.30 AM and 9-9.30 PM	1	met/person
lighting	Mo–Su 7-7.30 AM and 9-9.30 PM	60	W
<b>Radiators dimensioned according to norms valid in 1979</b>			
<b>Location</b>	<b>Flow rate, L/s</b>	<b>Size, m2</b>	<b>Power, W</b>
<b>Living-room</b>	0.0067	450x1,200	850
<b>Bedroom</b>	0.0059	450x1,200	740
<b>Kitchen</b>	0.0067	450x1,200	850
<b>WC</b>	0.0016	300x700	200

The temperature and humidity data measured at the site during the period from 17<sup>th</sup> July to 31<sup>st</sup> December, 2009 (approximately 5.5 months) were used in the simulation. Any missing temperature, relative humidity and wind speed/direction data were obtained from the Tampere/Pirkkala airport weather station and the solar radiation data from the Jokioinen Meteorological Observatory.

The simulation studies were performed by comparing the actual air and surface temperature values to the simulated ones using four different levels of detail in the model.



The most detailed one was the simulation model with a detailed window (Detwind) and a zone (Climate) model, while the most simplified one merely used a simple window structure and a zone (Energy) model. The objective of the modelling was to make sure that the difference between the simulated values and actually measured temperatures does not exceed the MBE and CV(RMSE) criteria set by ASHRAE [116].

During the simulation, different error sources such as scenario error, building physical/operational uncertainty, model inadequacy and observation error were analyzed, and the modeling method was further developed by 'trial and error'. Scenario error included an estimation of the errors in the outdoor weather conditions and building usage or occupancy schedules. The analyses of the building's physical/operational uncertainty included an estimation of the errors in the building envelope properties, internal gains and HVAC systems as well as operation and control setpoints. Model inadequacy included estimation of errors in the modeling assumptions and in the simplification of the model algorithm. The observation error was the final phase, and included an estimation of the metered data accuracy. The analyses which were made during the model's development by 'trial and error' are described in detail in the results section of this thesis.

### **3.3.1.2 Sensitivity analysis**

After the model had been successfully validated, a starting point for the calculations was made, named the 'base case' (Figure 31). It was produced by making slight changes to the validated model and modifying its input parameters to represent a typical block of flats in Finland (Table 15). The 'base case' model (Article II) and the simplified calculation (Article IV) were made simultaneously with the building of the calibration model (Article I) so that the specific needs of all three reviews could be taken into account during the calibration. It was also noticed that the sensitivity analysis and the error analysis of the simplified calculations turned out to be an effective model development method, as these analyses pointed out many inaccuracies arising from the model having the wrong structure, or by a lack of modeling expertise on the part of the users. Those evaluations are discussed in more detail in the results section.

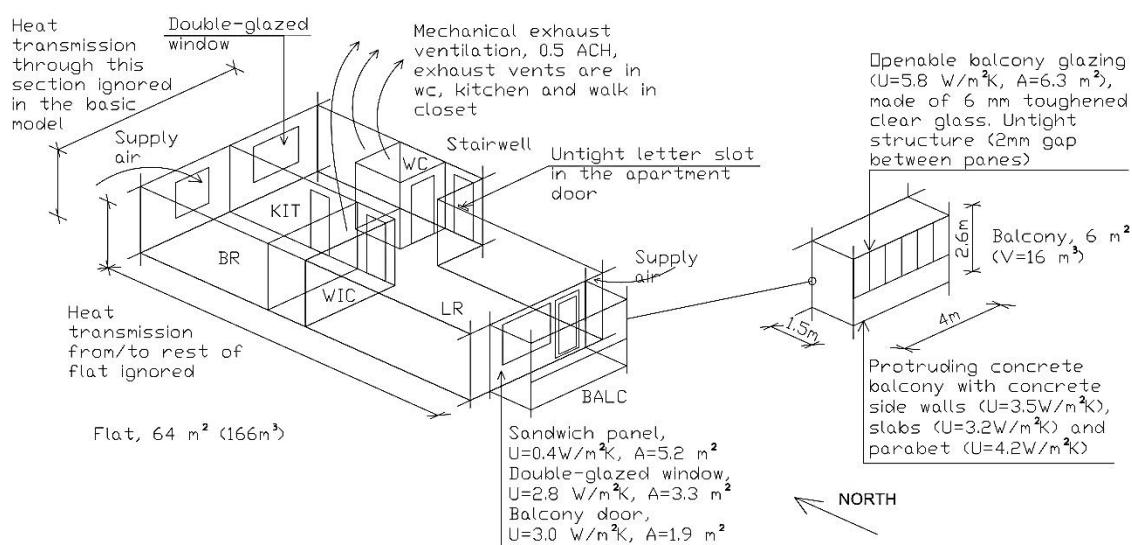


Figure 31. Illustration of the simulated flat called 'base case'. (Article II)

The simulation with the 'base case' model began with the assumption that the building lies on open terrain in a typical Finnish suburb in Helsinki. This was because new building appears to be concentrated increasingly on centres of urban growth, most of which are in southern Finland [192]. The flat is a typically sized Finnish apartment [193], with the most typical ventilation system (mechanical exhaust ventilation) [194, 195] and is located in the middle part of the building. The chosen room temperature also represents the accepted design value, i.e.  $21 \text{ }^\circ\text{C}$  [196]. (Article II and IV)

The type of electrical equipment in the apartment, the inhabitants' lifestyle habits and the operation of the HVAC systems were adjusted to correspond to the Finnish national calculation guidelines. The values in the guidelines are based on the number of residents ( $0.0357 \text{ pc./m}^2$ ); lighting ( $11 \text{ W/m}^2$ ); electrical equipment ( $4 \text{ W/m}^2$ ); the hours the residents spend in the flat; and the hours the lighting and electrical equipment are used [196]. Thus, the values of the base case simulation correspond to the typical usage of a flat in Finland [197]. The balcony structural solutions are typical for the concrete element structures of 1970s block of flats while the openings of the balcony glazing are adjusted to correspond to the typical opening levels of the systems installed in such balconies. Other input data can be found in Table 15. (Article II and IV)

Table 15. Base model input data table (bold text) and calculation variables of the sensitivity analysis. (Article II)

1	Geographical location(climate condition)	<b>Helsinki</b> , Tampere, Turku, Seinäjoki, Jyväskylä, Kuopio, Oulu, Sodankylä, Stockholm, Gothenburg, Copenhagen, Oslo, Bergen, Reykjavik, Moscow, Saint-Petersburg, Munich, Frankfurt, Hamburg, Stuttgart, Berlin, Madrid, Barcelona, Geneva, Marseille, Paris, Dublin, London, Shanghai, Ottawa, Toronto, Winnipeg, Vancouver, New York, Chicago
2	Orientation of balcony facade	<b>South</b> , South-West, North-West, North, North-East, East, South-East
3	Wind profile	<b>Suburban</b> , City center, Open country
4	Balcony façade distance from the building in front	<b>No building in front</b> , 15 m, 60 m, 100 m
5	Flat size (room number)	<b>Two (64 m<sup>2</sup>)</b> , One (45 m <sup>2</sup> ), Three (83 m <sup>2</sup> )
6	Room temperature	<b>21 °C</b> , 20 °C, 19 °C, 22 °C, 23 °C
7	Standard of equipment and number of residents	<b>According to Finnish building regulations</b> , Regulation level -20 %, Regulation -40 %, Regulation level +20 %, Regulation +40 %
8	Balcony window U-value (A=3.3 m <sup>2</sup> )	<b>2.8 W/m<sup>2</sup>°C</b> , 2.1 W/m <sup>2</sup> °C, 1.8 W/m <sup>2</sup> °C, 1.2 W/m <sup>2</sup> °C, 1.0 W/m <sup>2</sup> °C
9	Balcony door U-value (A=1.9 m <sup>2</sup> )	<b>3.0 W/m<sup>2</sup>°C</b> , 1.9 W/m <sup>2</sup> °C, 1.4 W/m <sup>2</sup> °C, 1.2 W/m <sup>2</sup> °C, 1.0 W/m <sup>2</sup> °C
10	Balcony wall U-values (A=5.2 m <sup>2</sup> )	<b>0.4 W/m<sup>2</sup>°C</b> , 0.29 W/m <sup>2</sup> °C, 0.28 W/m <sup>2</sup> °C, 0.24 W/m <sup>2</sup> °C, 0.17 W/m <sup>2</sup> °C
11	Balcony type (including depth change)	<b>Protruding balcony (1.5 m)</b> , Protruding balcony (3.0 m), Recessed balcony (1.5 m), Recessed balcony (3.0 m), Semi-recessed balcony (1.5 m), Semi-recessed balcony (3.0 m)
12	Width of balcony	<b>4 m</b> , 3 m, 5 m, 6 m, 7 m, 8 m
13	Amount of glass in the parapet and balcony glazing	<b>One side glazed (concrete balustrate)</b> , Two side glazed(concrete balustrate), Three side glazed(concrete balustrate), One side glazed(glass balustrate), Two side glazed(glass balustrate), Three side glazed(glass balustrate)
14	Glazing type (single, double, triple glazing)	<b>Single clear glass (untight structure)</b> , Single clear glass (airtight structure), Double clear glass (untight structure), Double clear glass (airtight structure), Triple low-e glass (untight structure), Triple low-e glass (airtight structure)
15	Thickness of glazing	<b>6 mm</b> , 8 mm, 10 mm, 12 mm
16	Balcony's relation to exterior wall	<b>Balcony covers the flat's exterior wall completely</b> , Balcony covers one-third of the flat's exterior walls
17	Balcony vertical position of the building	<b>Middlemost</b> , Highest, Lowest
18	Balcony horizontal position of the building	<b>Middlemost</b> , Outermost
19	Building ventilation type (air change rate)	<b>Mechanical exhaust (0.5 ACH)</b> , Mechanical exhaust (0.4 ACH), Mechanical exhaust (0.2 ACH), 50 % heat recovery ventilation, 75 % heat recovery ventilation
20	Supply air intake solution	<b>Directly from the outside</b> , Through the glazed balcony
21	Unintended ventilation rate through balcony glazing	<b>1.5-2.6 ACH</b> , 2.8-4.9 ACH, 3.7-6.5 ACH
22	Openness of the balcony glazing	<b>Completely closed</b> , 1 % (airing position), 2 % open, 8 % open, 15 % (one pane open)
23	Building air leakage coefficient (at 50 Pa)	<b>1 ACH</b> , 0.5 ACH, 2 ACH, 4 ACH
24	Designed heating capacity of hot water radiators (at Sodankylä design condition)	<b>Oversized 40 %</b> , Oversized 20 %, Exactly sized, Undersized 20 %, Undersized 40 %
25	Heating system control curve position (at Sodankylä design condition)	<b>Initial settings</b> , Bottom value increased +4 °C, Increased +8 °C, Bottom value decreased -4 °C, Decreased -8 °C
26	Heating system summer shut-off	<b>June - August</b> , No shut-off
27	Building's heat delivery system	<b>Hot water radiator heating system</b> , Ideal heater, Underfloor water heating system, Electric underfloor heating system
28	Heat losses from the heat delivery system to the flat	<b>No heat loss</b> , 10 % heat loss, 20 % heat loss, 30 % heat loss, 40 % heat loss
29	Specific heat capacity of balcony structures (J/kg°C)	<b>880</b> , 800, 1000, 1200, 1400, 1600
30	Lambda value of balcony structures (W/m°C)	<b>2.5</b> , 0.5, 0.9, 1.3, 1.7, 2.1
31	Density of balcony structures (kg/m <sup>3</sup> )	<b>2300</b> , 500, 1000, 1500, 2000, 2500
32	Surfaces absorptivity (Balcony and exterior wall)	<b>0.95</b> , 0.9, 0.8, 0.6, 0.4, 0.2
33	Surface emissivity (Balcony and exterior wall)	<b>0.95</b> , 0.9, 0.8, 0.6, 0.4, 0.2
34	Blind in balcony glazing or window	<b>No blind</b> , Window external blinds, Window blinds between panes, Window internal blinds, Balcony glazing internal blinds, Balcony glazing external blinds

A sensitivity analysis was conducted by making successive changes to the base case (Figure 31), performing re-simulations and calculating SI indexes after each step. The analysis was used to determine the relative effect of each individual parameter on the building's heating-energy consumption and the balconies' interior temperatures. The analysis included 34 calculation variables, with from 2 to 35 calculation cases each. The total number of calculation cases was 156 (Table 15). The variables were chosen from parameters found in the literature review, which have an impact on the heating energy-savings achieved by balcony glazing. The base case and the results of the sensitivity analysis were used for the simplified method presented in Section 3.3. (Article II)

### **3.3.2 Added glazing simulation in Malmö**

The building under study is a two-storey student house with four flats on the first floor, where there also is a communal kitchen and a storage facility (Figure 32). The building's floor area is 251 m<sup>2</sup> (V=565 m<sup>3</sup>) and the flats vary in size from 16.7 m<sup>2</sup> to 27.9 m<sup>2</sup>. The floor area of the cavity space is 28 m<sup>2</sup> and the air volume is 107 m<sup>3</sup> (glazing to floor area is ~1.8). The U-value of the added vertical single glazing is 5.8 W/m<sup>2</sup>°C (g=0.82) and that of the horizontal double glazing is 2.6 W/m<sup>2</sup>°C (g=0.62) (Table 16). The red brick wall's U-value is estimated to be U=1.35 W/m<sup>2</sup>°C and its solar absorptivity  $\alpha=0.75$ . The time period used in the annual simulations is the year of 2014; from 1<sup>st</sup> of January, 2014 to 31<sup>st</sup> of December, 2014 with hourly values. The climate files used in the simulations are described in Section 3.1.2. (Article V)

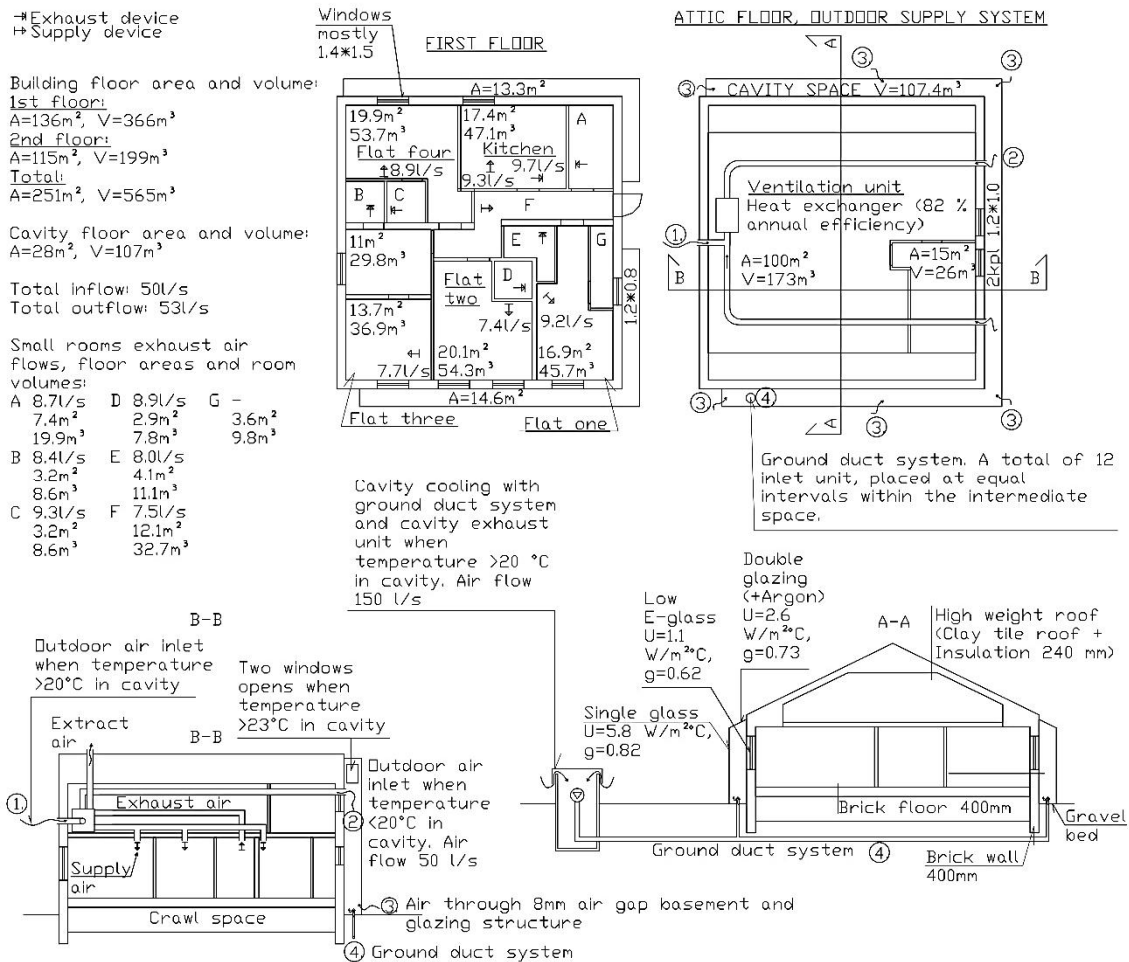


Figure 32. Illustration of the simulated building. (Article V)

The building's dimensions and technical characteristics have been estimated by using old and new drawings and verified by site inspection and supplementary measurements during the previous [191] and current study. The ventilation airflows were measured with maximum, normal and minimum ventilation modes during the previous study [189], and adjusted to correspond to the minimum ventilation mode, which was in use during the monitoring period. If some parameters were difficult or impossible to verify on site, the typical values presented from sources in the literature were used. The used airflows are shown in Figure 32 and other key input parameters in Table 16. Additional information about the building, the measurement arrangements and the monitoring results can be found in the following publications [190, 191, 189]. (Article V)

Table 16. Simulation model key input parameters. (Article V)

<b>Location (climate condition)</b>	Malmö, Sweden
<b>Orientation</b>	SE (30° from South)
<b>Wind profile</b>	City center
<b>External obstruction</b>	Some trees and buildings (see Figure 21)
<b>Building size</b>	A=251 m <sup>2</sup> and V=565 m <sup>3</sup>
<b>Size of the cavity space</b>	A=28 m <sup>2</sup> , V=107 m <sup>3</sup> and mean depth 0,75m
<b>Air temperature inside flat</b>	21 °C (system set point i.e. mainly during heating season)
<b>Lighting and equipment</b>	Lighting 11 W/m <sup>2</sup> and equipment 4 W/m <sup>2</sup> (in the first floor)
<b>Number of occupants</b>	0.0357 no./m <sup>2</sup> (totally 4.7 people), activity level 1.2 and clothing 0.85 (in the first floor)
<b>Building ventilation type (air change rate)</b>	Mechanical supply and exhaust ventilation with 82 % heat recovery (0.5 ACH)
<b>Supply air to ventilation unit</b>	From the cavity or directly from outside (See Figure 24)
<b>Building windows properties</b>	U=1.1 W/m <sup>2</sup> °C, g=0.62, internal venetian blinds (g <sub>shading</sub> + window=0.2)
<b>Cavity glazing (vertical)</b>	Single clear glass, 8 mm, U=5,8 W/m <sup>2</sup> °C, g=0.82
<b>Cavity glazing (horizontal = ceiling)</b>	Argon-filled double glazing, U=2.6 W/m <sup>2</sup> °C, g=0.73
<b>Air gaps of the glazing structure</b>	Air gaps between glazing frames and basement as well as between vertical frame structures and brick wall; mean distance 6.5 mm. Correspond to 1,6 air change per hour (ACH) in average (fluctuation 1.3-2.5 ACH)
<b>Building air leakage coefficient (at 50 Pa)</b>	1 ACH
<b>Heating system and heat delivery</b>	District heating connected to hydronic heating system with radiators (60/40 system)
<b>Control curve position of the heating system</b>	According to current settings in the building [191]
<b>Summer shut-off; heating system</b>	No summer shut-off
<b>Heat gain to zones from the heat distribution system losses</b>	5 %
<b>Properties of the brick wall</b>	Density= 2300 kg/m <sup>3</sup> , Lambda=0.7 W/m°C, Specific heat = 1050 J/kg°C
<b>Absorptivity and emissivity of the brick wall surface</b>	Emissivity=0.9, Absorptivity=0.75
<b>Summer cooling air flow through cavity</b>	150 l/s, both supply air via ground duct (TF1) and exhaust air via roof fan FF2
<b>Blinds of the added glazing structures</b>	No blinds in the basic case
<b>Used weather file</b>	Available climate information about the Malmö/Lund from the year 2014. Assembling method is described in section 3.1.2.

The calibration simulation was done with the actual implemented solution during measurement i.e. building occupancy and system control were set as in the real building used in the study (without occupancy and with ventilation units shut down at night). The locations and dimensions of the external obstructions such as trees and other buildings were measured on site as accurately as possible. They were modeled as precisely as possible (within the limits of accuracy set by the author's on-site evaluation and the simulation model) to allow accurate prediction of the building's external shading in the calculation. These obstructions are shown in the model view of the Malmö case building (Figure 33).

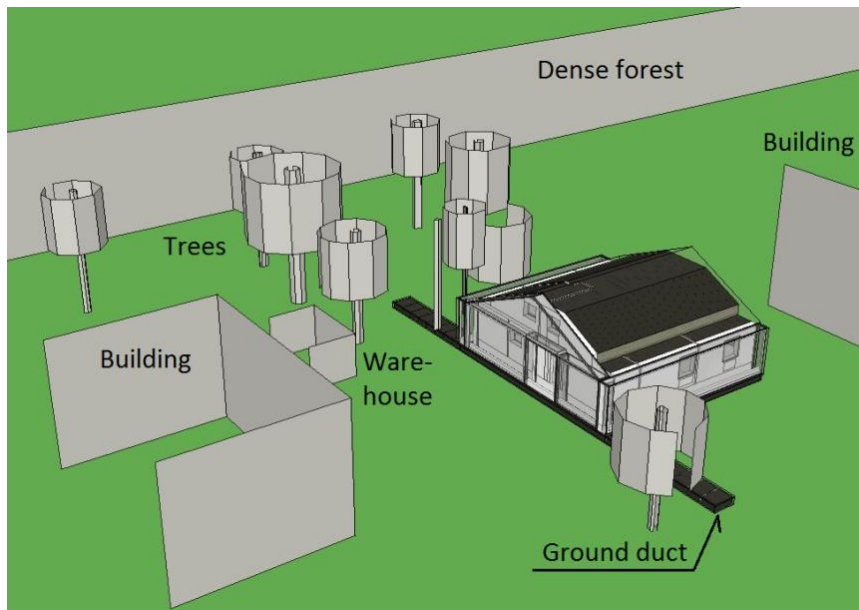


Figure 33. Outside view of the simulation model with external obstruction.

### 3.3.2.1 Calibration study

The suitability of the program for the simulation study was evaluated by comparing the field measurement results to the simulations over three weeks, one in winter, one in the summer and one in the spring. The temperatures in the cavity were used, as the cavity was the most interesting part of the building for our purposes, and also the most difficult one to model. The purpose of the winter-week calibration was to adjust the heating mode correctly, that of the summer week was to verify the operation of the cooling mode, while the spring-week simulation demonstrated the overall behavior of the model. The cavity control mode changed many times from winter mode (air supply through the cavity) to cooling mode (air supply from outside) during this spring-week simulation. The purpose of the calibration was to ensure that the IDA-ICE model behaved in a qualitatively realistic way compared with the actual building. (Article V)

The model calibration was performed in the same way as for the balcony glazing studies, although it was not, in reality, as comprehensive because the results of the balcony glazing studies were already available for some parameters (for example, the calculation time step, the zoning structure, the DSF modelling, etc. were done as in the balcony study). A qualitative validation exercise (Article V) was designed primarily to supplement the previous suitability analysis of the IDA-ICE software, and to expand the simulations to capture the more complex renovation solution for the Malmö building. This process furnished a much broader view of the subject matter. The parameter fit was not made in connection with the calibration, but the overall level of the model's

accuracy was evaluated with ASHRAE calibration criteria [116] and its 'goodness of fit' confirmed with monitored and simulated temperature results. One striking challenge when doing the IDA-ICE modeling in this study occurred when it was found that the current software package did not include the possibility to connect an adjacent zone to the ventilation unit (air supply from the cavity), nor was there any model to handle the existing ground duct system. This meant that the air supply through the cavity was captured by placing an extra exhaust ventilation unit inside the cavity space and connecting it to the attic ventilation unit. The ground duct system, in turn, was modeled as nine small underground zones connected to each other (Figure 33). By doing this, the real impact of the ground duct system could be treated to some degree.

The Malmö building was modeled with IDA-ICE 4.6 software and the double skin façade was modelled using a detailed window structure (Detwind) and a simplified zone model (Energy). It was not possible to use the detailed climate model because the façade's geometry was too complex. There is also a specially made DSF model in the current standard IDA-ICE version 4.7 (it was previously available only in the expert edition). This means that it is now simpler to implement a DSF in the building in the further studies than it was with the method used in this study. There are some differences between the 'manually made DSF' and IDA-ICE DSF model. One is that the air flow model is more detailed in the DSF model and that the 'manually made DSF' has edges that are not modelled in the DSF model. Other issues related to the model and the modeling of the existing DSF building are discussed in more detail in the results section.

### **3.3.2.2 Sensitivity analysis**

After the calibration, the user-related energy figures, such as the number of occupants, living habits and lighting and equipment usage were standardized using the Finnish standardized reference values [196]. A total number of 63 calculation cases with whole-year weather files (year 2014) were conducted, and the impact of the different glazing and ventilation modes on the building's energy demand and the summertime indoor temperatures were analyzed. The purpose of the investigations was to evaluate how effective the chosen renovation method was in terms of energy use and thermal comfort, and also to investigate other possible renovation choices with the IDA-ICE model. The existing building and its two operation modes, as well as the final 'developed' cooling solution with its particular properties (e.g. blinds) are analyzed further in the later studies (Figure 34).



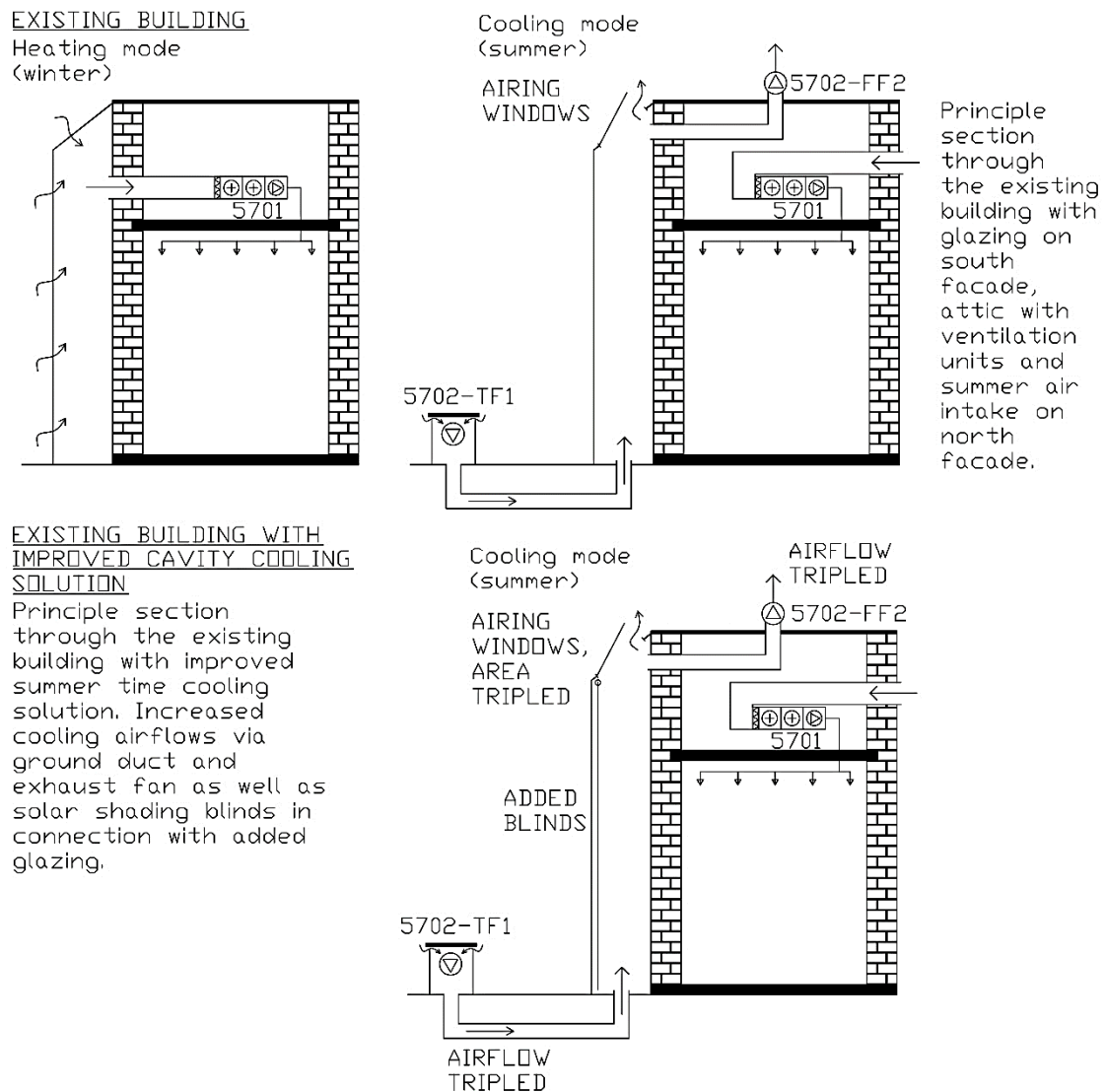


Figure 34. The principal sections of the calculation cases.

The heating energy-saving studies (winter mode) included different amounts of glazing (one, two and three glazed façades), various facade solutions (single, double and triple glazing) and two air inlet modes (through the cavity space or directly from outside). The summer-condition (cooling mode) studies included evaluations of: the cavity window ventilation, the mechanical exhaust ventilation (FF2), the ground duct system (TF1) and the internal and external blinds for the cavity glazing (shown in Figure 32 and Figure 35). The cavity cooling calculation cases were mainly chosen from the alternatives that could realistically be implemented in the real building. The controls of the systems also followed the actual designed set points, set by the building owner, and were kept unchanged throughout the study to enable evaluation of the real building, as well. The only exceptions to this principle were the blinds added to the front or back of the added

glazing to cover the whole glazed façade all the time (always down during 365 days a year) and depth variations for the ground ducts. The simulation analyses were made with standardized living habits for the tenants, which was the only difference between the calibration and simulation analyses. (Article V)

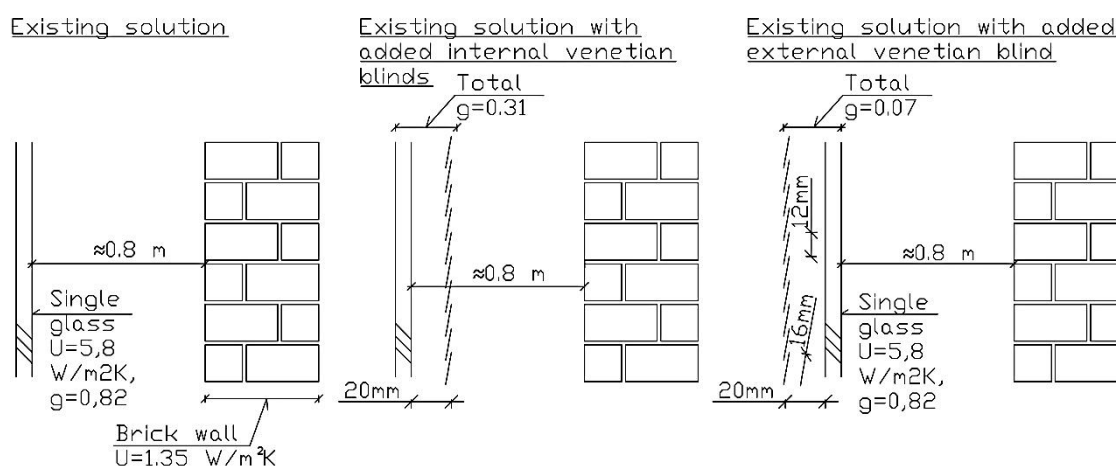


Figure 35. The principal sections of the different DSF solutions with and without venetian blinds.

### 3.4 The simplified calculation method

For the simplified method, 13 main parameters for the balcony and 5 main parameters for the flat were chosen from the sensitivity analysis (Article II). The calculation coefficients, which depict the deviation from the base case, were derived by changing the simulation parameters one at a time and by adjusting the results proportionately to those of the base case. The proposed method is intended for calculating the heating performance of individual glazed balconies during the preliminary stages of their design. It can be used for all types of glazed balconies and in all situations in which the calculation factors are present and identifiable. The method does not take cooling into account; thus the energy savings only denote the savings of heating energy. The reliability of the method is discussed in Section 4.3. (Article IV)

#### 3.4.1 The calculation procedure

The simplified calculation is performed by multiplying the factors determined from Figures 36–39 with the base case values given in Table 17. Equation 7 provides the formula for calculating the savings in heating energy and the temperatures of an individual balcony, where X depicts the chosen variable ( $E\%$ ,  $E_{kWh}$ ,  $T_{max}$ ,  $T_{min}$  or  $T_{avg}$ ). Equation 8

is used to determine the average temperature difference ( $\Delta T_{avg}$ ) as well as the minimum ( $\Delta T_{min}$ ) and the maximum temperature differences ( $\Delta T_{max}$ ). (Article IV)

$$X = \prod_i (\alpha_i) * \prod_j (\beta_j) * X_{base} \quad (7)$$

Where

X	= estimated variable in actual design situation ( $E\%$ , $E_{kWh}$ , $T_{max}$ , $T_{min}$ or $T_{avg}$ )
$\prod$	= a symbol depicting product sequence
$\alpha$	= calculation coefficient for balcony deviation (-) (section 3.3.1.1)
$\beta$	= calculation coefficient for flat deviation (-) (section 3.3.1.2)
i	= the index for balcony deviation calculation coefficients (a,b,c,...,m)
j	= the index for flat deviation calculation coefficients (1,2,3,4,5)
$X_{base}$	= the value of variable X for base case ( $E\%,_{base}$ , $E_{kWh,base}$ , $T_{max,base}$ , $T_{min,base}$ , $T_{avg,base}$ ) (Table 17)

$$\Delta T_{avg} = T_{avg} - T_{average\ outdoor\ temperature} \quad (8)$$

Where

$\Delta T_{avg}$	= temperature difference between the glazed space and outdoor air
$T_{average\ outdoor\ temperature}$	= yearly average outdoor temperature of the city (Table 18)

If the desired calculation option is not directly represented in the figures (e.g. it is between the given factors), the value can be estimated with the help of the adjacent values, i.e. it is taken to be the average of two given values. The external shading (Figure 38), which prevents the fall of solar radiation on the façades, must be estimated on the basis of the landscape in front of the balcony, i.e. a fully open terrain is represented with the obstruction level of 0 % and a fully enclosed environment has an obstruction level of 100 %. (Article IV)

Table 17. Results from the simulation of the base case. (Article IV)

Heating energy savings in base case		
Percentual ( $E\%,_{base}$ )	14.5	%
Kilowatt-hourly ( $E_{kWh,base}$ )	545	kWh
Balcony temperatures in base case		
Maximum ( $T_{max,base}$ )	41.3	°C
Minimum ( $T_{min,base}$ )	-11.1	°C
Average ( $T_{avg,base}$ )	13.4	°C

The location-based temperatures needed for the temperature difference calculations (Equation 8) are given in Table 18. All location-based weather information has been taken into account when the calculation factors were derived with the help of IDA-ICE,

even though only temperature information is used in the simplified calculation. (Article IV)

Table 18. The average, maximum and minimum temperature of the reference year in different cities. (Article IV)

	Madrid (ASHRAE IWEC2) [°C]	Frankfurt (ASHRAE IWEC2) [°C]	Bremen (ASHRAE IWEC2) [°C]	Helsinki (ASHRAE IWEC2) [°C]	Jyväskylä (ASHRAE IWEC2) [°C]	Sodankylä (ASHRAE IWEC2) [°C]	Tampere (ASHRAE IWEC2) [°C]
<b>Avg</b>	14.6	10.2	9.2	6.0	3.8	-0.3	4.6
<b>Absol. max</b>	40.0	33.6	29.1	29.0	27.5	27.6	27.0
<b>Absol. min.</b>	-6.4	-10.9	-11.8	-22.7	-31.2	-38.8	-29.0

### 3.4.1.1 Balcony deviations

The method takes into account the following differences in the balcony of the base case (Figures 36–38):

- a. Geographical location
- b. Supply air solution (through the glazed balcony or directly from outside)
- c. Balcony surface absorptivity (the balcony's ability to store solar energy)
- d. U-values of balcony window
- e. U-values of balcony door
- f. U-values of building exterior wall
- g. Orientation of balcony facade
- h. Balcony type (including depth change)
- i. Width of balcony
- j. Amount of glass in the parapet and balcony glazing
- k. Glazing type (single, double or triple glazing)
- l. Structural tightness of balcony glazing (rate of unintended ventilation)
- m. Effect of external sun protection or shading.

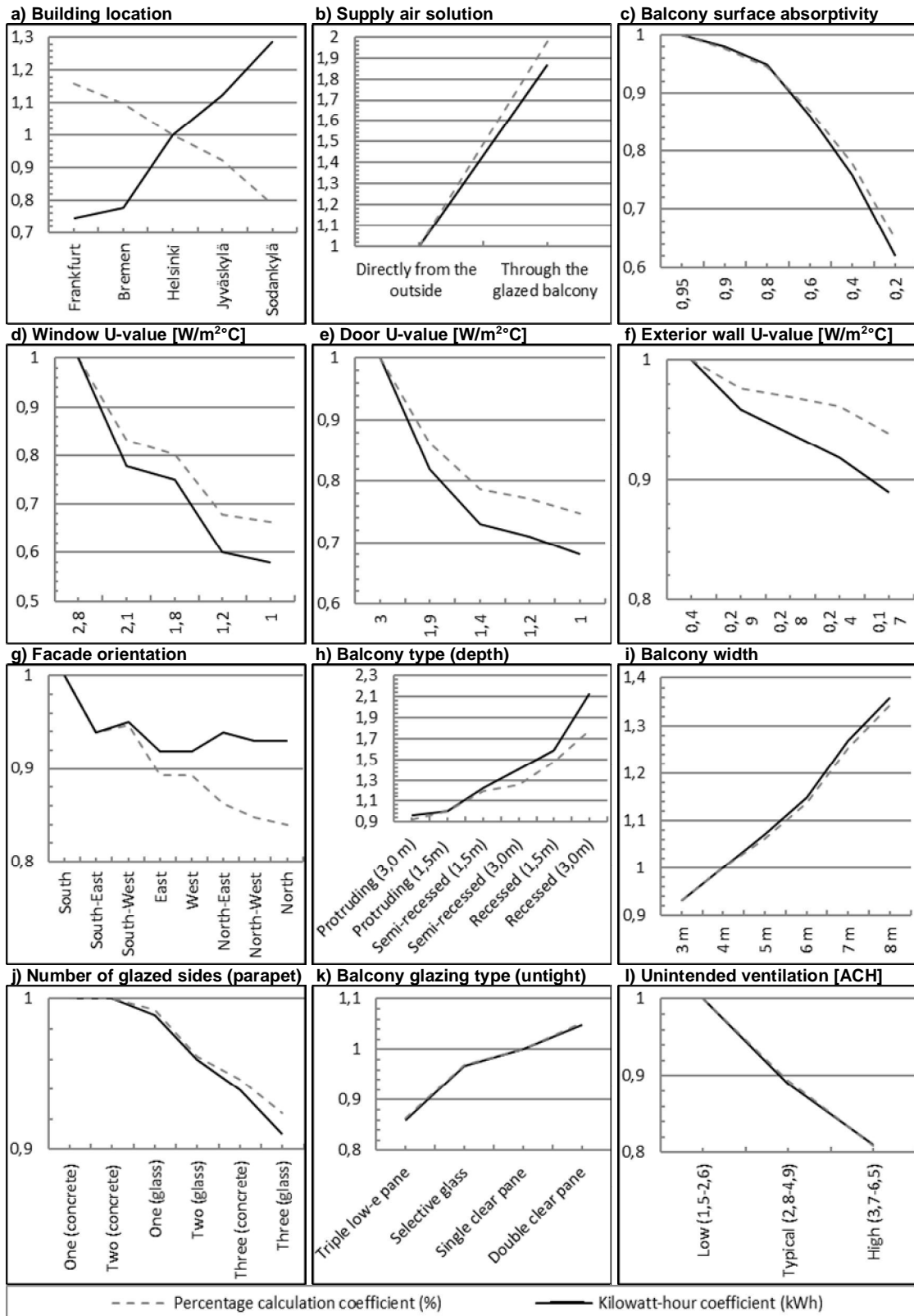


Figure 36. Graphs a-l for heating energy-saving calculations. (Article IV)

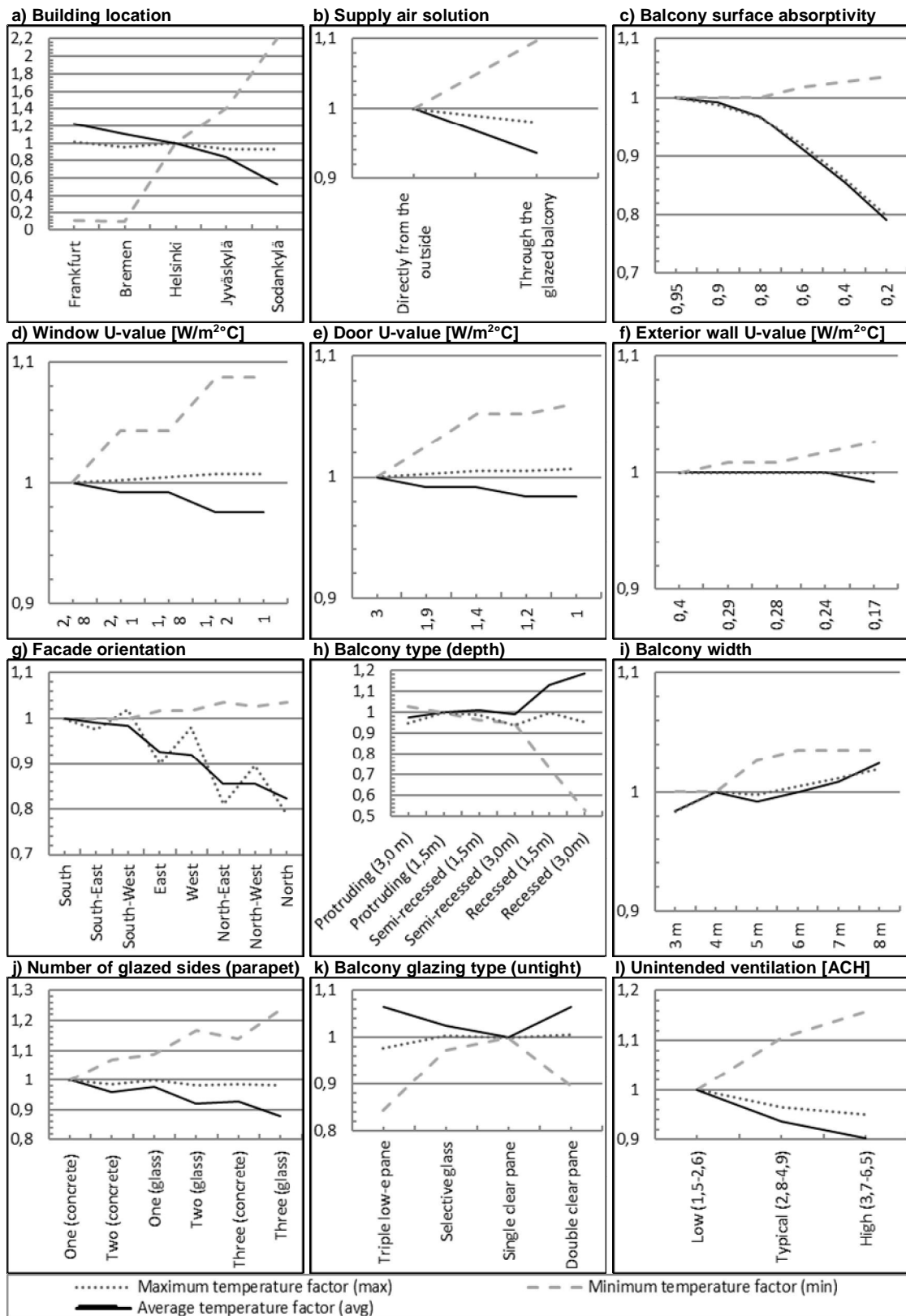


Figure 37. Graphs a-l for balcony temperature calculations. (Article IV)

m) Balcony temperature factors for shading m) Heating energy saving factors for shading

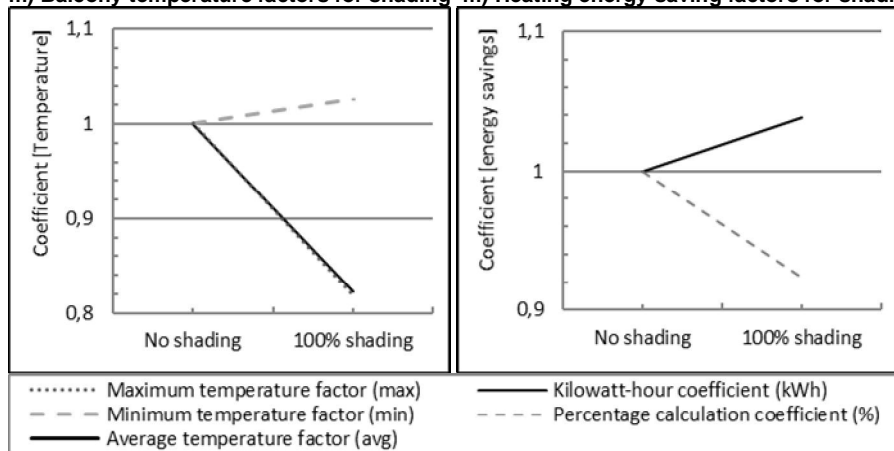


Figure 38. Graphs m for heating energy saving and balcony temperature calculations. (Article IV)

### 3.4.1.2 Flat deviation

The simplified method takes into account the following differences with the flat in the base case (Figure 39):

1. Position in the building (horizontal and vertical)
2. Size
3. Room temperature
4. Balcony's relation to exterior wall
5. Ventilation type and exchange rate

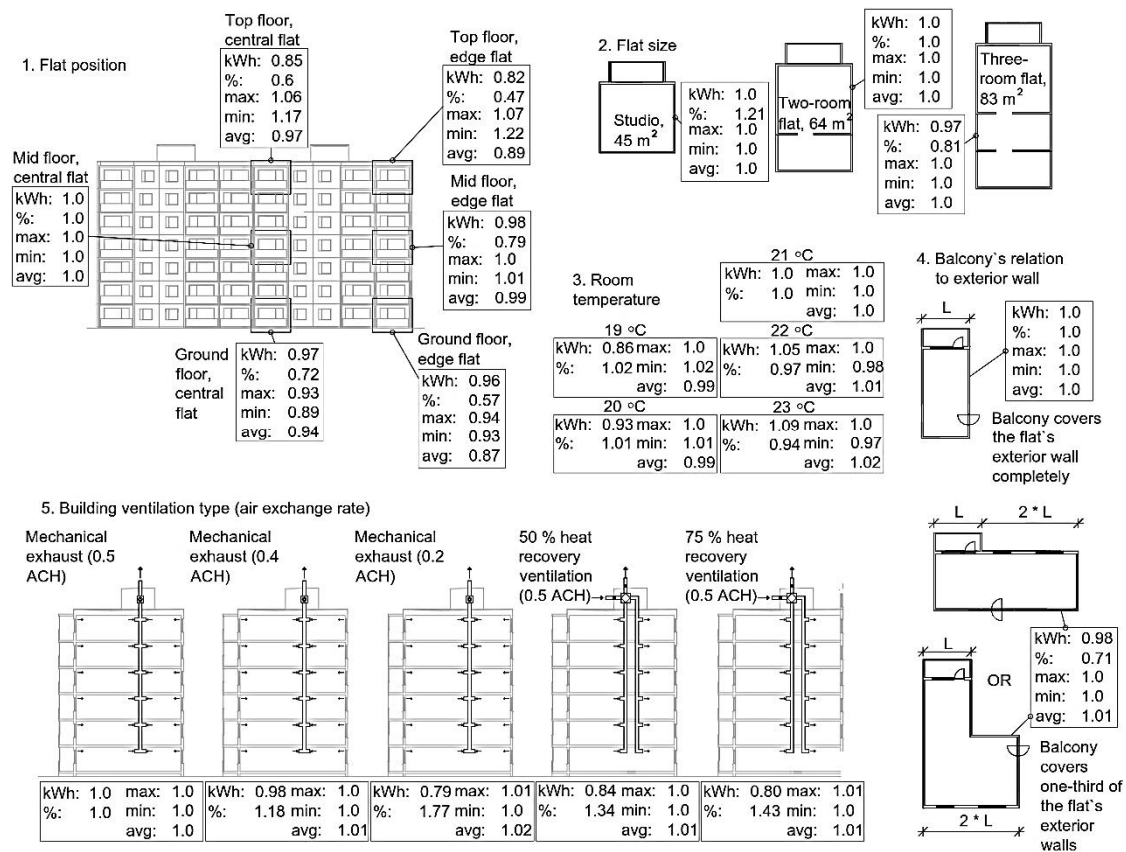


Figure 39. Flat alteration possibilities. (Article IV)



### **3.4.2 Error analysis**

In the first phase, the field monitoring results of Buildings D and F (Building 3 and 5 in article IV) were compared to the IDA-ICE simulations. The purpose of the analysis was to evaluate: a) how accurately the balcony's temperature level can be simulated with the base case model without taking into account any deviations from the base-case flat, and b) how much the inclusion of those deviations will improve the results. In the second phase, the IDA-ICE simulation results were compared to the simplified calculation in 17 different cases. In this phase, the balcony properties in the simulation model were modified to reflect the reality, but the flat was kept at default settings. The aim of this study was to give an overview of the balconies' temperature behavior and the savings in heating energy in general, rather than that of one specific balcony in a building. In the third phase, the flat's deviations were added to the IDA-ICE simulation model and a total of 17 new simplified calculations and simulations were compared. In the simulation model. The inclusion of the flats' properties meant that the model flat was adjusted to more closely match the real life situation. (Article IV)

## **4 Main results and discussion**

### **4.1 The suitability analysis of the used evaluation methods**

#### **4.1.1 Balcony air temperature as a performance indicator**

The analysis of the balconies' temperature data began by looking at how well the different temperature variables, (e.g. balcony maximum, minimum and mean temperature) and the temperature difference between the glazed and unglazed balconies correlated with the energy savings. This was accomplished by analyzing the first balcony's surface and air temperatures in mid-winter, early spring and late spring. These inspections were supplemented further by re-analysis of the simulations undertaken in the context of a sensitivity analysis (Article II). The purpose of the review was to ensure that the balcony mean temperature and the temperature difference between the glazed and unglazed balconies are meaningful energy conservation indicators i.e. those measures correlate with real energy savings in statistical analysis.

##### **4.1.1.1 Evaluation through temperature profiles**

As noted in Chapter 1, previous studies have shown that the temperatures of the glazed balconies are some degrees warmer than the outside air during winter time [13, 46]. This lowers the building energy consumption, if we can show that the increased balcony air temperature also increases the surface temperatures of the balcony's structures. If this happens, it would lead to a lower temperature difference between the internal and external surfaces of the structures, which would mean lower conduction losses and, consequently, increased energy savings for the building. This means, in practice, that the outer surface temperatures of the glazed balcony window, for example, should be higher than the corresponding window surface temperature in the unglazed balcony. This was confirmed by drawing the temperature profiles of the glazed

and unglazed balconies from the balcony wall, window and door at three different times of the year, i.e. in mid-winter (January 26th), in early spring (March 14th) and in late spring (May 16th). These 'temperature profiles' are shown in Figures 40, 41 and 42. The temperatures shown in the graphs are the average temperatures of the building elements, i.e. the window's outer surface temperature, for example, is the mean temperature of all the windows' external surface sensors (Figure 16).

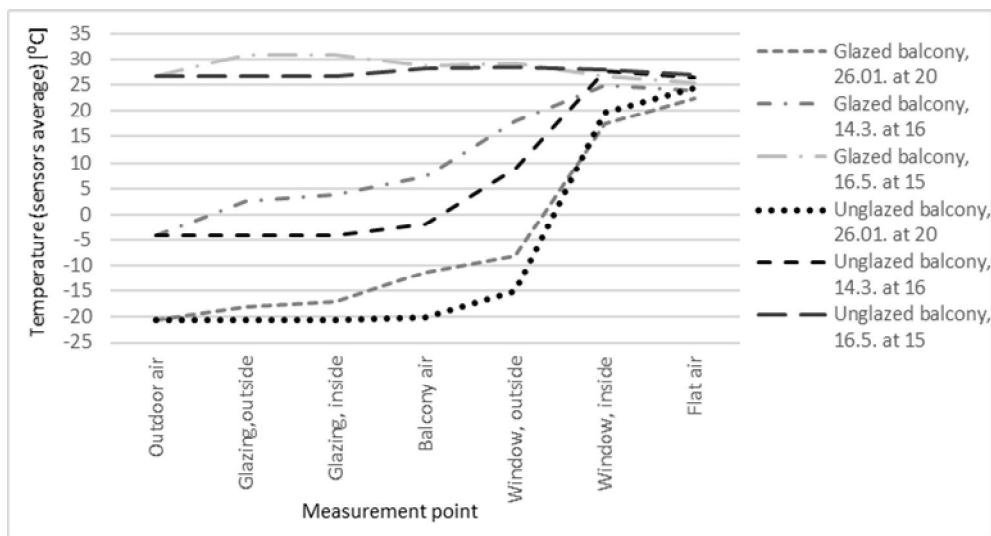


Figure 40. The balconies' temperature profiles in winter, early spring and late spring. View from the section of external window

As can be seen from the graphs, the glazed balcony was clearly warmer than the unglazed balcony in the winter and early spring, but the temperature difference was hardly noticeable the late spring. The temperature difference was most intense in mid-winter and attenuated towards the spring. This shows that the main warming factor of balconies has been the heat loss of the building, which is, in general, a fact in high latitude during the winter season, with very low solar radiation levels and sunshine hours i.e. during the Finnish winter.

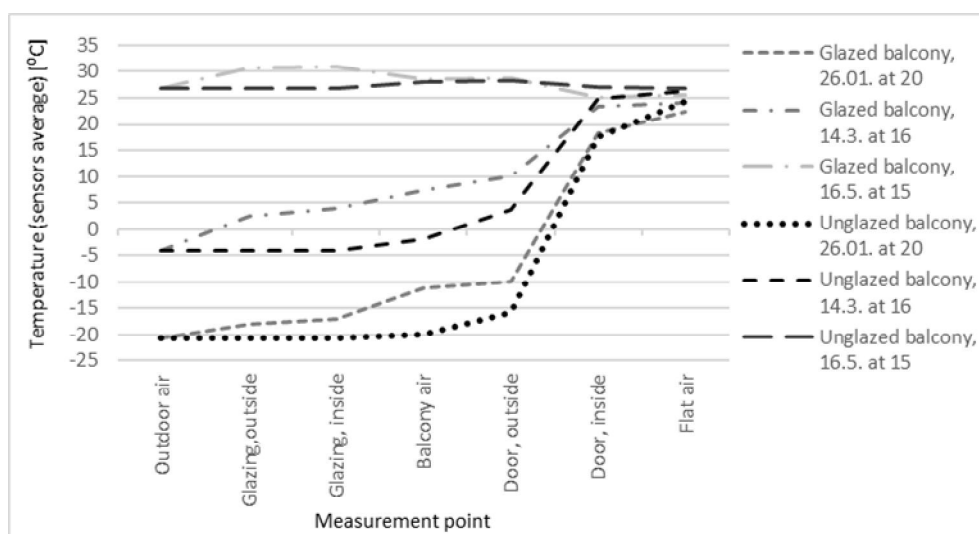


Figure 41. Balconies temperature profiles in winter, early spring and late spring. View from the section of balcony door.

The figures also show the connection between the balcony air temperature and the surface temperatures of the structures. This is clearly visible in the temperature graphs from the 26<sup>th</sup> of January; window, door and wall surface temperatures are higher in the glazed balcony than in the unglazed balcony. Graphs also show that the weaker the thermal insulation of structure, the greater the temperature difference; the windows external surface temperatures increased most with the weakest U-value from the building envelope structures and the wall surface temperatures increased least with the best U-value. It is also noticeable that the better the U-value of the main structure, the shorter the period when the effect of balcony glazing is observable i.e. the surface temperatures in the structures of the glazed balconies are higher than the corresponding temperatures in the unglazed ones. For example, the difference between the windows' external surface temperatures are also clearly visible in the early spring (Figure 40), although it is negligible between the external surface structures of the balcony walls (Figure 42). This means that although the level of heat loss through the external wall is very low in March, it is still considerable through the window.

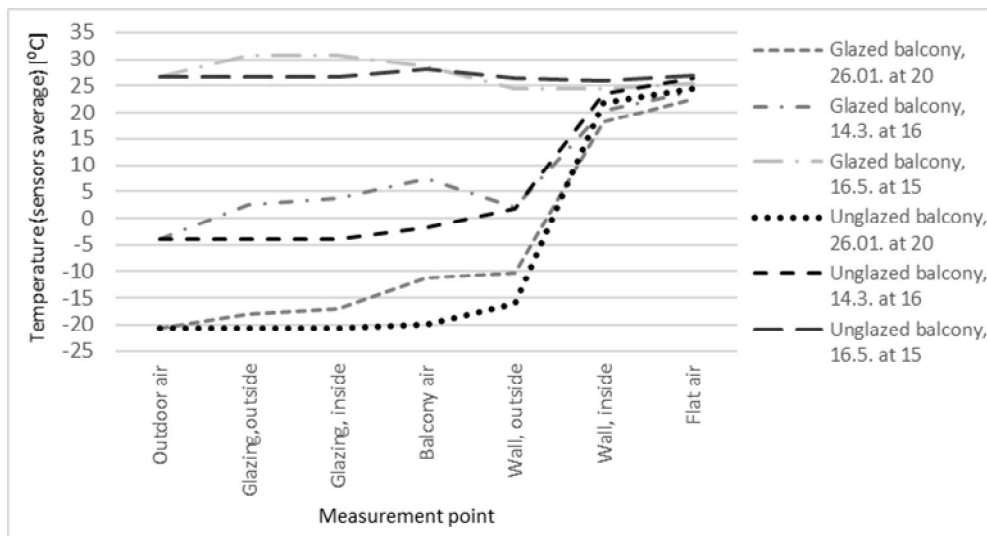


Figure 42. Balconies temperature profiles in winter, early spring and late spring. View from the section of external wall.

The graphs also show that having a glazed balcony does not automatically result in an overheating problem, because the temperature differences tail off in warmer weather, and become almost non-existent in the late spring. In fact, in late spring there were cases in which the temperatures in the flat with a glazed balcony were lower than the temperatures in the flat with the unglazed balcony. This may be due to the different lifestyle habits of the residents, i.e. the human factor. The residents of the flat with balcony glazing preferred a lower inside temperature level than the resident of the flat with the unglazed balcony, and thus set the radiator thermostats lower, which would explain the lower temperatures inside the flat with the glazed balcony.

#### 4.1.1.2 Evaluation through the temperatures of different balconies

The thermal performance analysis of all the monitored balconies confirm the findings of the detailed measurements (section 4.1.1.1); the temperature level of the balconies rise like a trend between the coldest (balcony 22) and the warmest (1 balcony) balconies in Figure 43. The trend is clearly visible in mid-winter (e.g. on January 26<sup>th</sup>) and most intense during the solar radiation in the early spring (e.g. on March 14<sup>th</sup>). In the late spring or in the early autumn, the temperature behavior was almost the same on the balconies. The temperature difference between the coldest and the warmest balcony is not as great in the summer, on average, as it is in the winter season, even though the solar radiation could easily raise the balcony's temperature uncomfortably high during the hot summer days.

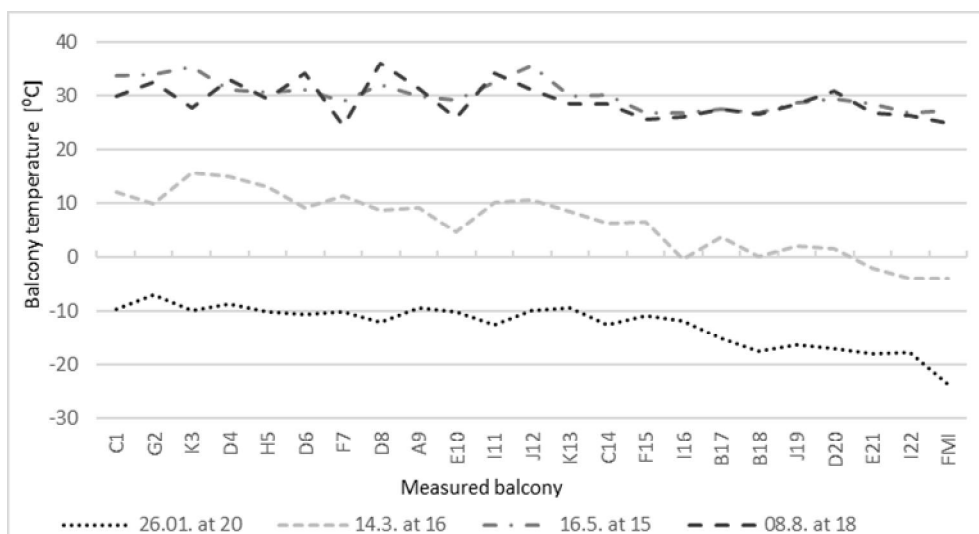


Figure 43. Balconies' measured temperatures at four different times of year. The letter code A-K identify the buildings from oldest to newest and number code 1-22 the balconies from coldest to warmest (1-17 are glazed balconies and 18-22 are unglazed balconies).

It is also interesting to see the clear connection between the balconies' temperatures and their relative humidities (Figure 44). The difference between the relative humidity level on the balconies was most apparent in mid-winter, when the temperature difference between the coldest and warmest balcony was greatest, and as could be expected, it was lowest in the summer season. For example, in January the relative humidity level of balcony 1 was slightly more than 40 % and the relative humidity on balcony 21 slightly more than 90 % (a difference of almost 50 %). There was one balcony whose performance differed from the general trend, i.e. balcony 14. However, it was established that this balcony's glazing was kept partially open throughout the measurement period, which explains the unexpected behavior.

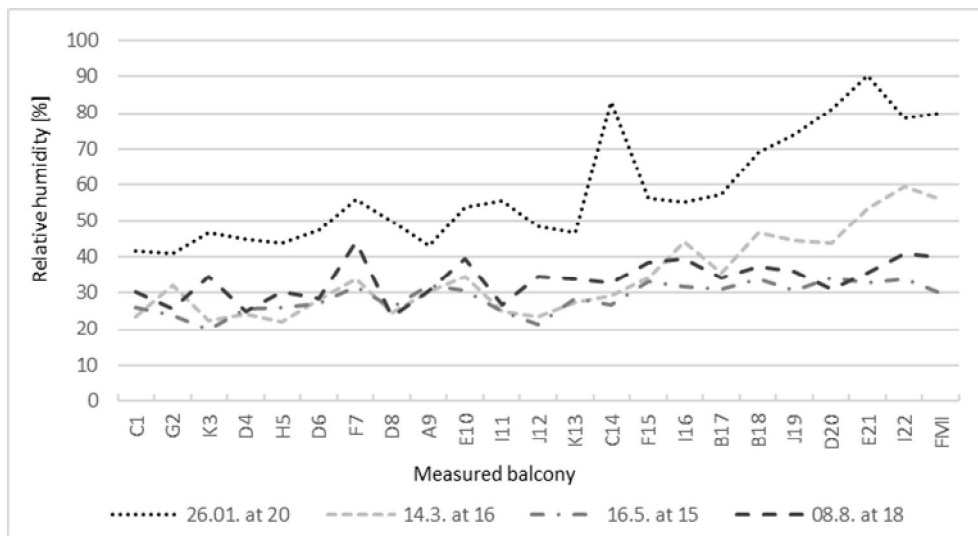


Figure 44. Balconies' relative humidity levels at four different times of year. The letter code A-K identify the buildings from oldest to newest and number code 1-22 the balconies from coldest to warmest (1-17 are glazed balconies and 18-22 are unglazed balconies).

#### 4.1.1.3 Evaluation through statistical analysis

Earlier comparisons of the balconies' air and surface temperatures clearly show that the increased air temperature of a glazed balcony also indicates higher surface temperatures inside that balcony. This, in turn, leads to the energy savings for the building, but it does not directly reveal which temperature is best used as an indicator of actual energy savings. For example, is it the balcony mean, maximum and minimum temperature? Or is it the difference between the balcony and the outside air maximum, minimum and mean temperatures? Therefore, a statistical analysis was performed with the simulation results of the sensitivity analysis (Article II), and a correlation analysis was performed between the energy savings and all of the above-mentioned temperature data. The intention of this analysis was to evaluate, for example, how well the kilowatt-hourly savings and the various temperature indicators describe the percentage energy saving. The analysis was conducted with the results of the sensitivity analysis (Article II) and included 34 calculation variables, with from 2 to 35 calculation cases for each variable. The total number of calculation cases was 156 (Table 15). The results of these statistical analyses are shown in Tables 19 and 20.

Table 19. The graph shows how well kilowatt-hourly saving and various temperature indicators describe the percentage energy saving.

INDEX (X-Y)	REGRESSION	R	R <sup>2</sup>	MBE (%)	CV(RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
kWh - %	$y = 0.0078x + 9.4018$	0.24	0.06	97.4	100.1	97	97	1133	107
Avg - %	$y = 1.4382x - 4.8253$	0.76	0.58	-5.8	22.0	-5	13	8	-19
Max - %	$y = 0.3992x - 2.9625$	0.23	0.05	67.3	68.0	67	67	37	-3
Min - %	$y = 0.5667x + 19.4381$	0.63	0.39	227.0	-229.5	199	300	-14	-38
Avg,dif - %	$y = 2.2609x + 1.6449$	0.45	0.20	-157.6	172.2	-158	158	1	-36
Max,dif - %	$y = -0.0216x + 13.6239$	0.01	0.00	-60.9	80.8	-78	79	3	-36
Min,dif - %	$y = 0.8988x + 6.8126$	0.29	0.08	-82.2	96.6	-85	86	5	-36

Table 19 shows that the correlation between the balcony temperature and the percentual energy savings was the closest ( $R^2 = 0.58$ ) of the studied correlations. There is no clear correlation between percentual energy saving and the other temperature variables. Therefore, it is clear that from the studied correlation, the average temperature of the balcony is the most suitable first indicator of percentual energy savings that can be achieved by balcony glazing. Indeed, this value is well suited for the intended purpose ( $R^2=0.58$ ), especially in situations where the temperatures of several balconies are measured or evaluated with the same method (rule of thumb: the warmer the better). Other studies have produced similar results. For example, reference [59] concludes that the space temperature is a good performance indicator, because it reveals the dominant pathways of heat gain and loss and gives an indication of the thermal buffer effects and thermal comfort.

Table 20. The graph shows how well percentage saving and various temperature indicators describe the kilowatt-hourly energy saving.

INDEX (X-Y)	REGRESSION	R	R <sup>2</sup>	MBE (%)	CV(RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
% - kWh	$y = 7.4232x + 417.6951$	0.24	0.06	-3750.8	3855.2	-3894	3894	-107	-1133
Avg - kWh	$y = -9.6524x + 640.0926$	0.17	0.03	-3975.5	4088.1	-4076	4076	-102	-1141
Max - kWh	$y = 13.9372x - 55.3513$	0.26	0.07	-1159.2	1195.5	-1159	1159	-75	-1159
Min - kWh	$y = -7.8409x + 434.5423$	0.28	0.08	4991.1	-5122.4	4660	6849	-125	-1162
Avg,dif - kWh	$y = 91.949x + 37.6599$	0.60	0.35	-9818.2	10084.7	-9832	9832	-109	-1148
Max,dif - kWh	$y = 22.5925x + 328.8344$	0.38	0.15	-6095.7	6262.3	-6588	6588	-107	-1148
Min,dif - kWh	$y = 54.8775x + 112.6227$	0.57	0.32	-6915.9	7104.4	-6954	6954	-106	-1144

However, the percentage energy savings do not directly describe the real benefits of the glazing i.e. achieved kilowatt-hourly energy savings. To determine this, the surface temperatures (to calculate the change in heat losses) or the actual heating energy consumption (to calculate real changes in energy consumption) would have to be monitored in both the glazed and unglazed balconies as well as in adjoining flats. However, such verification is often difficult and time-consuming. In addition to this, such rankings are not meaningful indicators of a balcony's 'goodness', because monitoring surface temperatures or real energy consumption is expensive, time-consuming and difficult to implement on a larger scale. Simple air temperature measurements are much more



practical in the real world. For this reason, it was decided to use the previous temperatures as the indicator of the kilowatt-hourly savings and to calculate the correlation between them. Table 20, below, shows a statistical analysis of the correlation between the measured temperatures and the kilowatt-hourly savings.

Table 20 shows that the correlation between the balcony temperatures and the kilowatt-hour savings ( $R^2=0.00-0.58$ ) is not as clear as the correlation between the balcony temperatures and the percentual savings ( $R^2=0.03-0.35$ ). This is confirmed by comparing the respective MBE (%) and CV (RMSE) (%) results in Tables 19 and 20. The balcony temperature is the only indicator which shows a strong correlation with percentual savings, and the only variable in Table 19 which fulfill the 'goodness of fit' criteria set by ASHRAE (Table 4). In contrast to this, none of the parameters even came close to the MBE and CV(RMSE) limit values ( Table 20) and neither did any of the temperature indicators show a strong statistical correlation between the temperatures and the kilowatt-hourly savings ( $R^2=0.03-0.35$ ). However, the results of this analysis do show that the strongest relationship ( $R^2= 0.35$ ) with the kilowatt-hourly savings can be found in the temperature difference between the balcony and the outdoor air (Avg,dif). However, the correlation between temperature difference and kilowatt-hourly savings is only a good indicator if it is used together with the correlation analysis between percentual energy saving and balcony temperatures. Only then will it further clarify the most energy saving balcony. However, it must be remembered that the temperature difference between the glazed and unglazed balconies is a better indicator of the real energy-saving effects of balcony glazing than the temperature difference between the glazed balcony and the outside air. However, the calculation of the temperature difference between the glazed and unglazed balconies was not possible in the field monitoring, because we could not acquire an equivalent unglazed balcony for all the glazed ones in the study in connection with Article III. As a result, we settled for using the temperature difference between the balcony and the outside air to indicate a balcony's 'goodness' in this study. These results are then complemented with the measurements of the temperature difference between glazed and unglazed balconies in those cases where we had the necessary data.

## **4.1.2 Evaluation of the glazed balcony model**

### **4.1.2.1 Calibration study**

The calibration of the simulation model was carried out in four stages. First, the uncertainty of the used climate file and flat usage was evaluated (Scenario uncertainty). After this, the input data of the simulation was evaluated (Building physical / operational uncertainty) and the simulation method was developed by 'trial and error' (Model inad-

equancy). Finally, the observation error and the overall accuracy of the model was evaluated by comparing the monitored and simulated data with each other. The results of these reviews can be found in Tables 21, 22, 23 and 24. The model was generally considered to be calibrated, when it met the ASHRAE Guidelines 14 [116] hourly calibration criteria for CV(RMSE) and MBE (Table 4). This meant a lower than 10 % ( $\pm 10$  %) deviation from zero for the MBE value and a less than 30 % deviation for the CV(MRSE) value.

### Scenario uncertainty

The outdoor weather conditions in three of the Finnish Meteorological Institute's measurement stations in Tampere were evaluated in connection with Article III. As a result of this analysis, the Tampere-Pirkkala weather station was selected as the reference weather for the study. Nevertheless, the measured temperature on site was used as much as possible (Article I). The on-site temperatures were measured with Vaisala HMT 100 type sensors (RH/T sensors), which were protected against solar radiation and precipitation by a special factory-made outdoors sensor guard (Figure 18). The temperature and relative humidity data which was missing (measurement errors from 22<sup>nd</sup> to 30<sup>th</sup> October, 2009 and from 8<sup>th</sup> November to 2<sup>nd</sup> December 2009) was obtained from Tampere-Pirkkala weather station. The correlation between the Tampere-Pirkkala reference temperature and the monitored outdoor temperature is examined in Table 21.

Table 21. Correlation between monitored air temperature on site (X) and outdoor weather condition in Tampere-Pirkkala weather station (Y).

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=REFERENCE WEATHER									
Outdoor, 101(C)	Tampere-Pirkkala (FMI)	$y = 1.0038x - 0.2238$	0.99	0.98	3	23	-6	83	8.6	-12.2

The Table 21 shows that there is a very strong correlation ( $R^2= 0.98$ ) between the temperatures, although there are still a few large deviations in the measurements (minimum difference = - 12.2 °C), as Figure 45 clearly shows. The same graph also shows that the Tampere-Pirkkala weather was generally colder and more variable than the monitored outdoor temperatures on-site. This is probably due to either micro-climatic factors, or errors in the on-site outdoor measurements (the effect of the sensor guards is unclear). Taking all the errors into consideration, the on-site monitoring seems to be more accurate for calibration than the recorded temperatures at the weather station (which is why they are also used in the model calibration).

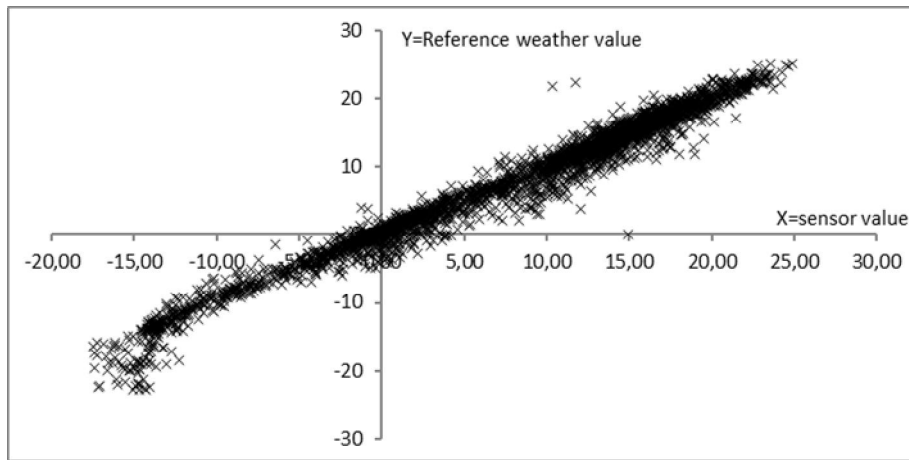


Figure 45. Correlation between monitored air temperature on site (X) and outdoor weather conditions recorded by the Tampere-Pirkkala weather station (Y).

Unfortunately there was no possibility to set up an on-site weather station to measure the solar radiation and the wind conditions within the framework of this study because it was simply too expensive. As a result, the missing wind speed/direction data were supplied by Tampere-Pirkkala airport weather station for the period in question, and the solar radiation data was obtained from the the Jokioinen Meteorological Observatory. It is clear that the Tampere-Pirkkala airport open terrain wind profile differs from the wind profile of a forest-sheltered block of flats in a suburban area. The yearly radiation level also differs between the monitoring site and Jokioinen, and this might even occur on an hourly basis, for example due to shadows cast by clouds. This means that the actual weather conditions may deviate slightly from the simulation conditions on the IDA-ICE. For example, the deviation on the yearly global radiation level is roughly  $100 \text{ MJ/m}^2$ , i.e. approximately 3 % annually. This statistic is taken from the climatological statistics of Finland from 1981 – 2010 [178].

The building usage and occupancy schedules were evaluated by occupant interviews. The flat with the glazed balcony was occupied by a retired couple who lived very regular lives and stuck rigidly to their daily/weekly routines. Despite this, the actual use of the flat may occasionally differ from the modeling assumptions, for example, when they had visitors. This building's usage is difficult to monitor. There is no certainty that the inhabitants have used the balcony glazing or the electrical equipment exactly as reported, for example, so the model also includes a degree of uncertainty with regard to the building's use.

### **Building's physical/operational uncertainty**

The factors related to the use of the building's systems and their operation were evaluated with one-off measurements. These included the internal heat loads of the flat, the airtightness of the flat, the ventilation air flows and schedules and the settings of the building's heating system. These evaluations, along with some regular remote monitoring, showed that the operational control of the flats' ventilation and the settings of the building's heating system were pretty constant throughout the monitoring period. However, one-off measurements cannot guarantee that the systems functioned in accordance with their set values or that there were no errors in the control of these systems. Furthermore, the pressure can change according to external wind and temperature conditions, which may result in errors in the flat's air change rates. These factors could not be taken into account in the model (wind conditions and the flat pressure conditions are not measured). Therefore, there is a degree of uncertainty in the modelled flat conditions.

The properties of the exterior walls were evaluated on-site and the dimensions of the concrete and thermal insulation layers were measured. However, the quality of the concrete, and the thermal insulation, are unknown. The specifications for the windows and doors were acquired from the manufacturer. These included the overall performance information about glass combinations with gas fillings, but did not include the optical and thermal properties of each separate pane. They were assessed using the Pilkington glass catalogue. However, the greatest uncertainty comes from the air gaps in the balcony glazing systems and the air flow through them. Even though the gaps were measured separately on-site and modelled as precisely as possible, the realistic behavior of the model in relation to air movement cannot be definitively confirmed, because the wind conditions and the air exchange rate between the balcony and the outside air were not measured on-site. The same uncertainty applies to the ventilation air valve in the window between the balcony and the living room. In the model, it was adjusted to the minimum flow to decrease the uncertainty of the flow between the balcony and living room, but the exact magnitude is not known. This means that there may be slight fluctuations in the air flow between the balcony and the apartment in the real flat and in the model.

### **Model inadequacy**

There are basically three kind of errors in building simulations compared to the real thing; 1) modeling assumptions, 2) simplifications in the model algorithm and 3) ignored phenomena in the algorithm. The errors in relation to the first of these are discussed in this section. The second and third error sources are related either to er-

rors in the simplifications of the model or ignored phenomena in the model. Those can be, for example, a) lack of heat transfer to and from the ground, b) wrong evaluations in leakage levels c) 100 % mixing in a zone temperatures (no temperature stratification), d) the lack of 2D and 3D heat transfer in the building envelope, etc. There are also errors due to scaling parameters, such as the calculation of the time-step, calculation of the grid size in the walls, the level of detail in the solar radiation model, the level of detail in the longwave radiation model, etc. Some of these uncertainties, which relate largely to the features of the IDA-ICE program, have already been discussed in Section 3.3.

A lot of the focus in this study has been on the IDA-ICE simulation and the choice of modeling method. In this regard, a lot of different simulations were conducted and the modeling method was carefully developed by 'trial and error'. The aim of the simulations was to evaluate the impact that increased accuracy has on the model. After each simulation, the better or best 'fitting' option was chosen as the input data or as an assumption for the subsequent simulation studies. Some of these choices are described below.

Previous studies show that knowledge of a real building's performance data is more important than the number of zones used in simulations. For example, in the simulation with actual electricity consumption and internal heat loads data, there was only a 1 % difference between the simulated and monitored energy consumptions using seven zones (one for each floor of the building) and this small difference virtually disappeared when the number of zones was increased to 37 (one zone for each flat) [198]. Despite the fairly insignificant effect it has on the simulation's accuracy (and the high impact it has on the simulation time) the flats in our study were modelled room by room. There was a practical reason for this; the room-specific zoning structure allows room-specific information to be imported into the model. The hot water radiators were also modelled separately, as suggested in [199] and the ventilation airflows were adjusted room by room.

A dynamic simulation with a 14-period start-up process in the calibration study, and a seven-period start-up process in the sensitivity analysis, were used in the simulation. The start-up-phase preceded the main simulation phase. It is a process in which the thermal mass of the building structures, for example, are adjusted to correspond the real starting point of the experiment [199]. A periodic start up process seems to be acceptable [199] for a yearly simulation, but a dynamic start-up process is recommended for shorter calibration periods. The maximum time-step in the simulation was 1h, and the results were reported in a similar manner. The number of cells in each wall was set

automatically to avoid having to use the IDA-ICE advanced level in the sensitivity analysis (it is much easier to do model changes in sensitivity analysis at the standard level).

Zoning the building began with room-by-room modelling of the building (Figure 46), but this was changed to flat-level modelling after the test simulation. This was because of the length of the simulation time, and the high number of unknown parameters (only one flat's usage was known). It was also noticed that the general accuracy of the model is better when it is limited to those parts of the building whose input data is known. This limits uncertainty about the thermal behavior between flats and errors about the flats' usage.

The final model includes one detailed flat model, where all the rooms were modeled separately (Figure 46). In this model, the heat losses are limited to the envelope structure, which is in direct contact with the outdoor air i.e. two sides of the balcony's vertical structures (glazing and parapet) and one side of the kitchen and the bedroom walls bordering the outside air (Figure 46). In other situations, it is assumed that the temperature on one side of the structure is the same as the temperature inside the structure (heat transfer does not occur). The doors between the rooms were adjusted to correspond to the most common use of the flat i.e. the walk-in-closet and toilet doors were closed and the other rooms were open (Figure 47).

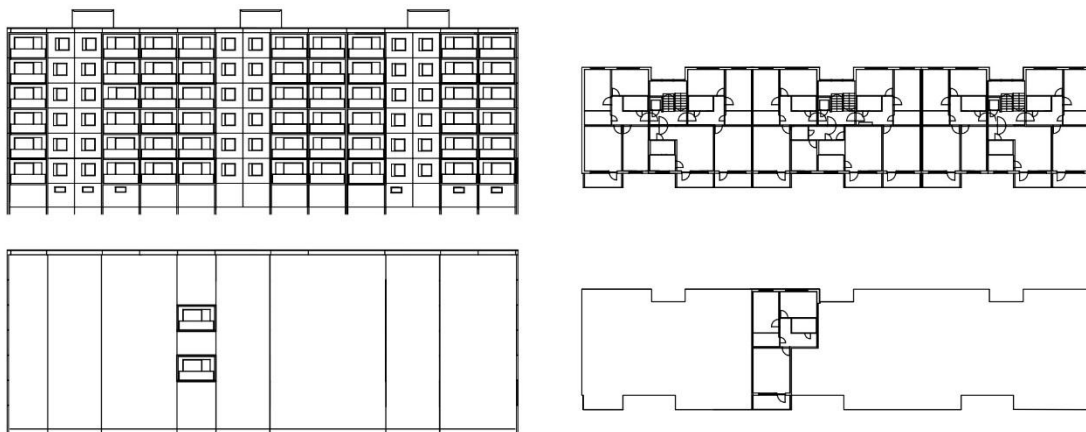


Figure 46. The building was modelled first zone by zone (higher picture), but then it was decided to limit the model to the apartment level (lower picture) after the first sensitivity analysis.

The only difference between the simulation of two studied flats and the real building situation (in addition to the identical usage) was that the flats were placed one storey apart in the simulation as this removed the heat transfer between the flats. However, the unglazed flat was not intended to represent the real flat with the unglazed balcony,

but only to act as a contrasting reference to the flat with the glazed balcony (both flat usages were adjusted according to the flat with the glazed balcony). This allowed the benefits of balcony glazing to be compared directly with the IDA-ICE.

In addition, the effect of two different window and zone models was evaluated with the IDA-ICE and the results are presented in Table 22. These show that the calibration criteria of the ASHRAE for MBE and CV(RMSE) were fulfilled with all the model combinations. The correlation between the monitored and simulated air temperatures was excellent ( $R^2 = 0.99$ ) in glazed and unglazed balconies and good ( $R^2 = 0.82$ ) in the flat with glazed balcony.

Table 22. Correlation between the measured air temperatures and those obtained by simulation with differently detailed models.

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=SIMULATION									
<b>Glazed balcony 105(C)</b>	EnergyMod, DetWin	$y = 0.9948x + 0.1027$	0.99	0.99	-1	9	0	23	8.5	-3.2
	ClimateMod, DetWin	$y = 0.9995x - 0.0709$	0.99	0.99	1	9	2	26	8.7	-3.0
	EnergyMod, SimpWin	$y = 0.9988x + 0.1257$	0.99	0.99	-1	9	0	23	8.5	-3.2
	ClimateMod, SimpWin	$y = 1.0033x - 0.0507$	0.99	0.99	0	9	1	26	8.7	-3.0
<b>Unglazed balcony 109(C)</b>	EnergyMod, DetWin	$y = 0.995x - 0.1168$	1.00	0.99	2	10	-8	28	6.0	-1.4
	ClimateMod, DetWin	$y = 0.9953x - 0.1198$	1.00	0.99	2	10	-10	30	6.0	-1.4
	EnergyMod, SimpWin	$y = 0.9956x - 0.111$	1.00	0.99	2	10	-8	28	6.0	-1.4
	ClimateMod, SimpWin	$y = 0.9959x - 0.1142$	1.00	0.99	2	10	-10	30	6.0	-1.4
<b>Flat (with glazed balcony), 107(C)</b>	EnergyMod, DetWin	$y = 0.7667x + 5.8466$	0.91	0.82	-2	2	-2	2	1.1	-1.4
	ClimateMod, DetWin	$y = 0.7846x + 5.4315$	0.91	0.83	-2	2	-2	2	1.1	-1.3
	EnergyMod, SimpWin	$y = 0.7978x + 5.1425$	0.91	0.82	-2	2	-2	2	1.1	-1.5
	ClimateMod, SimpWin	$y = 0.8147x + 4.7485$	0.91	0.83	-2	2	-2	2	1.1	-1.4

There did not seem to be any clear difference between the different models, even though the background information outlined in section 2 suggests that the most accurate results should have been achieved with the detailed window (Detwin) and zone (climate) models. There are at least two explanations for this: 1) the glazed balcony contains so little glazing on only one side of the balcony that the simple window and zone model are capable of producing as reliable results as the detailed window and zone model, and 2) there is so much uncertainty in the model that the difference between the model algorithms is lost among the other uncertainties. However, the valida-

tion studies (Table 6) do indicate that detailed models are recommended, so they are taken as a starting point for further studies.

### **Observation error**

There were visible monitoring uncertainties in the study. Most of these uncertainties were related to the solar radiation and external obstructions. There are a lot of trees in front of the balcony, and the balcony structures were relatively sheltered (only the front side of the structure between the parapet and the balcony ceiling was open), so it was decided to use unprotected temperature sensors (Figures 15 and 18). However, these were placed all over the balcony, and some of the higher ones were probably baked by the sun. Thus, it was possible to evaluate the effect of direct solar radiation by comparing the monitored temperatures between those sensors which were shaded from sun with those which were exposed to the sun. The inner surface temperature monitoring was also conducted on the same principle. In this case, the warming effect of the hot water radiator had to be avoided in the internal surface measurements, in contrast to the solar radiation which had to be avoided for the external surface sensors (the real surface temperature had to be measured without the effect of the radiator). The shadows thrown by the trees in front of the building façade were measured as accurately as possible by direct observation and placed in the model according to the architect's original planting plans, but, of course, there are some uncertainties about the shading effects of the trees. For example, the trees are not necessarily the same size as they are shown to be in the planting plan and they may not have been planted precisely in accordance with the plan, and there is also the difficulty of the trees shedding their leaves in the autumn.



Table 23. Correlation between the measured and simulated temperatures in the flat with the glazed balcony.

INDEX (X - Y)		REGRES- SION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN	
X= SENSOR	Y= SIMULA- TION										
Window, internal	upper, 111(C)	ClimateMod, DetWin	$y = 0.9918x + 0.5966$	0.96	0.92	-2	3	-2	2	3.1	-2.4
	lower, 117(C)		$y = 0.8531x + 3.7794$	0.96	0.91	-3	4	-3	4	5.3	-2.5
Win- dow,exte rnal	upper, 116(C)	ClimateMod, DetWin	$y = 0.9786x + 0.5228$	0.99	0.98	-2	11	1	10	15.8	-3.9
	lower, 118(C)		$y = 0.8993x + 2.0629$	0.99	0.97	-8	17	-3	22	16.2	-4.4
Door, internal	lower, 114(C)	ClimateMod, DetWin	$y = 1.1809x - 3.6849$	0.97	0.93	-1	3	-1	2	2.0	-2.9
	upper, 115(C)		$y = 0.912x + 2.498$	0.96	0.91	-3	4	-3	3	5.3	-2.7
Door,ext ernal	lower, 112(C)	ClimateMod, DetWin	$y = 0.8489x + 3.7756$	0.99	0.97	-23	30	-17	122	20.9	-6.9
	upper, 119(C)		$y = 1x + 0.2357$	0.99	0.98	-2	10	0	20	10.5	-4.0
Wall, internal	lower, 113(C)	ClimateMod, DetWin	$y = 0.5783x + 11.0018$	0.96	0.93	-10	10	-10	10	-0.7	-5.1
	upper, 120(C)		$y = 0.5781x + 10.7051$	0.97	0.95	-7	8	-7	7	-0.3	-3.8
Wall, external	upper, 203(C)	ClimateMod, DetWin	$y = 1.0135x + 0.8927$	1.00	0.99	-10	13	-8	19	1.5	-3.8
	lower, 204(C)		$y = 0.9795x + 1.3502$	1.00	0.99	-12	14	31	69	1.2	-3.8
Balcony glazing, internal	upper, 205(C)	ClimateMod, DetWin	$y = 1.0059x - 0.3758$	0.99	0.99	4	13	-9	77	9.3	-3.5
	upper, 217(C)		$y = 1.0033x - 0.2791$	1.00	0.99	3	12	1	54	8.5	-3.5
	lower, 218(C)		$y = 1x - 0.1794$	1.00	0.99	2	11	55	109	7.3	-3.5
	lower, 219(C)		$y = 0.9986x - 0.2083$	1.00	0.99	3	12	116	226	8.9	-3.5
Balcony glazing, external	upper, 220(C)	ClimateMod, DetWin	$y = 1.0009x - 0.1076$	0.99	0.99	1	12	-15	72	8.8	-3.6
	upper, 206(C)		$y = 1.0027x - 0.0314$	1.00	0.99	0	12	4	55	7.8	-3.7
	lower, 207(C)		$y = 0.988x + 0.301$	1.00	0.99	-3	13	-12	38	7.9	-13.0
	lower, 208(C)		$y = 0.9965x + 0.136$	1.00	0.99	-1	12	-5	57	7.1	-3.7

Despite the uncertainties, most of the sensors (18/20) in Table 23 fulfilled the ASHRAE calibration criteria for MBE and CV(MRSE). Two sensors did not meet the calibration criteria (sensors 112 and 204) but these were both external surface sensors placed to the lower part of the structures (at the bottom part of the balcony door and wall). In general, the correlation between the monitored and simulated temperatures was better with the sensors for the upper parts of the balcony structures than it was for the sensors on the lower parts. This confirms that there are uncertainties, especially with the sensors on the lower parts of structures. These uncertainties are related to the solar radiation on the external surface sensors, and the effect of the radiators on the internal surface sensors. In addition, there are uncertainties about the properties of the doors

and windows, because there was no detailed information about the structures' pane-specific properties. This is the most likely cause of the large maximum errors between the measured and simulated external surface temperatures for the doors and windows (sensors 116, 118, and 120, for example). Nonetheless, the surface temperatures of the glazed balcony and its adjoining flat correlate really strongly with the simulated values; there was  $\geq 0.97$  correlation for the external surface sensors and  $\geq 0.91$  for the internal surface sensors. The 'goodness of fit' for the monitored and simulated glazed balcony and flat surface temperatures is good overall, and the model can thus be regarded as a 'calibrated model'.

Table 24. Correlation between the measured and simulated temperatures in the flat with the unglazed balcony.

INDEX (X - Y)		Y=SIMULATION	REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR											
Window, internal	lower, 137(C)	ClimateMod, DetWin	$y = 0.4952x + 10.0843$	0.44	0.19	6	12	6	8	12.9	-3.4
	middle, 139(C)		$y = 0.8721x + 2.1421$	0.76	0.58	3	7	3	5	12.6	-3.2
	upper, 140(C)		$y = 0.9483x + 1.1424$	0.89	0.79	0	5	0	3	10.7	-3.6
Window, external	lower, 131(C)	ClimateMod, DetWin	$y = 0.978x - 0.2243$	0.98	0.97	5	19	3	26	17.0	-3.2
	middle, 132(C)		$y = 1.0159x - 0.9112$	0.99	0.97	8	18	-15	58	15.4	-2.7
	upper, 133(C)		$y = 1.0511x - 1.4274$	0.99	0.98	9	17	8	30	15.8	-2.6
Door, internal	lower, 216(C)	ClimateMod, DetWin	$y = 1.1248x - 3.6081$	0.92	0.85	4	5	4	4	4.5	-3.5
	upper, 215(C)		$y = 0.7794x + 4.9887$	0.91	0.82	-1	5	-2	3	12.0	-3.4
Door, external	upper, 214(C)	ClimateMod, DetWin	$y = 1.0447x - 1.3744$	0.99	0.98	9	17	-3	64	12.9	-3.9
	lower, 122(C)		$y = 0.8816x + 1.4582$	0.98	0.96	-5	28	-12	88	32.0	-6.0
Wall, internal	middle, 138(C)	ClimateMod, DetWin	$y = 0.6084x + 9.1706$	0.53	0.28	-1	4	-1	4	1.8	-2.6
	lower (mon.), 209(C)		$y = 0.4683x + 11.8607$	0.95	0.89	4	6	3	5	3.1	-3.6
	upper, 210(C)		$y = 0.4891x + 12.8068$	0.94	0.88	-10	11	-10	10	1.5	-5.4
	lower (rad.), 213(C)		$y = -0.4083x + 32.8326$	0.48	0.23	3	9	3	7	4.6	-3.3
Wall, external	lower, 134(C)	ClimateMod, DetWin	$y = 1.0116x - 0.4102$	1.00	0.99	4	10	30	61	7.4	-3.6
	middle, 135(C)		$y = 1.007x - 1.0045$	0.99	0.98	10	19	2	48	12.6	-2.6
	upper, 136(C)		$y = 1.0356x - 0.7636$	1.00	0.99	5	13	4	54	5.9	-18.6

Although the model of the flat with the unglazed balcony was not calibrated to match the actual internal loads of the real flat, the correlation analysis with the monitored and simulated surface temperatures of this flat confirm the conclusions drawn from the flat

with the glazed balcony. The results also worked as expected, i.e. they confirmed the previous findings. The results were surprisingly good, considering the 'false' input parameters, because all of the sensors (17/17) fulfilled the ASHRAE calibration criteria for MBE and CV(MRSE) in this case (Table 24). The weakest correlation was achieved with the sensor located on the lower part of the unglazed balcony door's external surface (Table 24), as it was in the glazed balcony (Table 23). This confirms that the thermal insulation level of the opaque part of the door is not defined clearly enough, or that the IDA-ICE does not model this part of the door correctly. Those uncertainties are also apparent when looking at the maximum errors; the highest maximum deviations are also in the door and window external surface temperatures. On the whole, the correlation between the monitored and simulated external surface temperatures was really good ( $R^2 = 0.97$  to  $0.99$ ), although the flat usage was not calibrated accordingly. Perhaps the effect of 'poor' adjustment of the internal thermal conditions was mainly limited to the internal surface sensors, because their correlation with the simulations was clearly lower ( $R^2 = 0.19$  to  $0.89$ ) than in the case of the glazed balcony ( $R^2 \geq 0.91$ ). However, the results show that even this model can be considered as a 'calibrated model', because the ASHRAE calibration criteria have been fulfilled. On the other hand, this also confirms that the calibrated model can 'tolerate' quite a lot of uncertainty.

## Conclusion

Both the theoretical and practical suitability analyses suggest that IDA-ICE 4.6.1 software is well suited for balcony glazing studies. The highest modelling accuracy can be obtained using a detailed window structure (Detwind) and a zone (Climate) model. The importance of having a detailed simulation increased when the amount of glazing increased or the amount of external shading decreased. In general, the balcony temperature was  $0.2$  °C lower with the most detailed modelling method (climate model and detailed window) than with the simplest modelling method (energy model and simplified window), which led to  $0.8$  % lower heating energy-savings for the balcony glazing. The results also showed that the wrong input parameters can have as significant, or even greater, an impact on the results than the differences between the level of detailing in the models. For example, a  $0.1$  change in the absorption coefficient has a greater effect on the calculation results (difference  $0.28$ ) than changing the model from the detailed one to the simplified one ( $0.2$ ). (Article I)

## Future work

When planning similar calibration studies, special attention should be paid to the selection of the measurement site, which should favour simple measurement cases rather than complex ones. Another valuable tool would be a small-scale weather station on

site. This should be able to measure wind speed, wind direction and air pressure as well as global horizontal radiation, direct normal radiation and diffuse radiation. One problem with our study was the degree of uncertainty caused by the weather data. For example, the solar radiation data was collected about 100 km away from the test site, while the wind data and some of the outdoor temperature and relative humidity values came from 20 km away. A third issue was the unshielded surface-temperature sensors warming up under direct solar radiation, causing errors in the calculation results. This could be avoided in future by using shielded and mechanically ventilated surface-temperature sensors. The fourth issue that arose in our study was the importance of measuring the thermal conductivity of the structures and surface absorption coefficients accurately. In this study, the material U-values were determined by measuring the thickness of the balcony structures, but then using the lambda values from the literature to calculate the thermal conductivities. The material properties of the windows and doors, and hence their U-values, were also taken from the manufacturer's product information. Therefore, there is no absolute certainty about these inputs. The fifth point is the uncertainty about the balconies' airtightness, and the real airflow through the balcony glazing and air inlet vent in the back wall of the balcony. Long-term on-site measurements need to be taken to get a better understanding of the operation of the ventilation system in different wind conditions, and a more accurate picture of the air flow from the outside to the apartment through a glazed balcony. Sixth, it was very hard to model the trees accurately in the IDA-ICE program, for example, do the shading effects of the mixed forest vary significantly in winter and summer (deciduous trees shed their leaves in the autumn). In the future, it would be better to select a more open calibration site in order to avoid uncertainties about the external obstructions in the IDA-ICE. The final source of uncertainty is, of course, the human element. It is very difficult to track the activities of the inhabitants inside the apartment, and one has to rely on their reported behaviour. Therefore, one option would be to validate the simulation model without the residents present. (Article I)

#### 4.1.2.2 Sensitivity analysis

After calibration, the focus of the simulations changed slightly. The purpose of the modelling was no longer to exactly reproduce the specific conditions on site, but rather to assess the potential of balcony glazing from an energy-saving point of view. For this reason, both the simulation model and its input parameters were slightly changed to better fit the purpose of the sensitivity analysis. In this way, the key performance indicators of the glazed balcony and their energy saving potential were analysed and compared to the outcomes of the literature review (Section 2.4) and the field monitoring results (Article III).

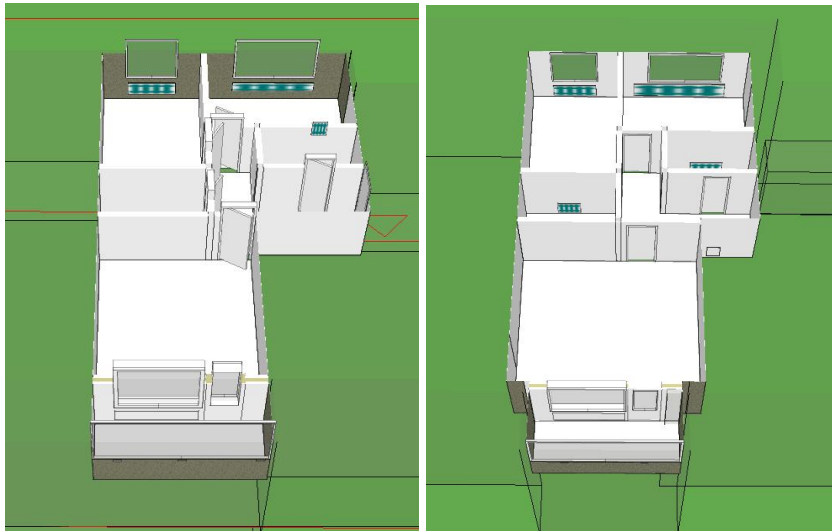


Figure 47. The simulation view of the models used in the calibration (left) and the sensitivity analysis (right). The dimensions of the living room and the openness of the internal doors were changed after the calibration, as were a few other input parameters in order to conduct simulations which were more suitable for a sensitivity analysis.

The key differences between the calibration and sensitivity analysis models related to the dimensioning of the living room (Figure 47 and 48), changing the flat's two façades exposure to one façade exposure for external climate (only the balcony is exposed to the external climate after this modification), and standardising the building's systems and their use. Other changes included relocating the building to Helsinki and placing it in an open terrain (no trees in front of the building). Also, the balcony's two-sided external climate connection was changed to three sides (as if there were no adjacent balcony) and the climate-based wind pressure was replaced with a constant airflow (the effects of the wind can be better controlled). Furthermore, the supply air valve of the building's exhaust ventilation unit was moved away from the balcony window and placed on an external wall of the building (an air inlet through the balcony would distort

the results in a sensitivity analysis). The flat's internal doors were set at closed (reduced air circulation between the rooms and speeds up the simulation) and finally, the balcony window, door and external wall properties were updated to better represent the original structures of 1970s blocks of flats. Some of these changes are shown in Figures 28 and 31, and in Tables 13 and 15.

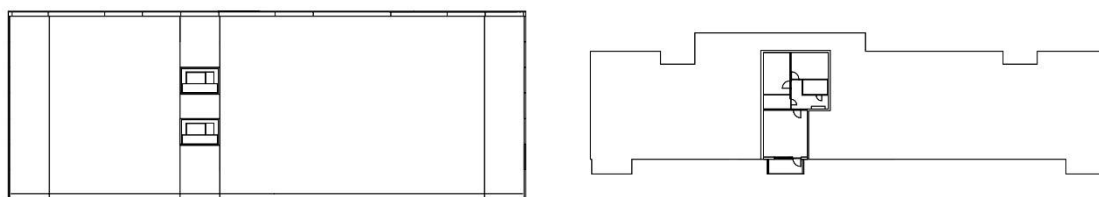


Figure 48. Simulation model in the sensitivity analysis

The above-mentioned changes were made to the model both for technical modelling reasons and to make the results more generalisable. The technical modelling reasons were, for example, to allow all the calculation cases to be done with the same model in order to better assess each parameter's impact. The reason the results had to be generalizable was because they would be used to set a calculation 'base case' for the archetypal Finnish flat. This would be useful in two ways: a) it would minimize the number of changes that would need to be made to the 'base case' in simple calculations (Article IV) and b) it would act as a 'baseline for energy saving' with respect to the ongoing renovation of Finland's late-20th-century housing stock. That is also why so much attention was also paid to the technical aspects, which have impact on the energy saving potential of balcony glazing, such as the structures having weaker U-values, tighter glazing solutions or dark paint (the 'base case' itself represents typical renovation solutions used in practice). The U-values of the structures were set to represent typical 1970s structures, the glazing tightness represents what is considered to be 'good' in a 1970s buildings (which are very good, in general) and the dark paint gave the structures a lambda value of 0.95. In this way, the base case is, in principle, a likely candidate for a Finnish balcony renovation, and therefore of interest from an energy-saving point of view. Some of those changes are also shown in Table 25.

Table 25. Changes made to the model input data and the reasons for the changes.

		Calibration model	The base case model	Reason for the change
1	Location	Tampere	Helsinki	The general focus on the construction is on the Helsinki Metropolitan Area Bottom of Form
2	Orientation	South-West	South	South-facing is also generally favoured in balcony construction. It also turned out to be the most reliable solution for simulation (all orientations analyzed). Bottom of Form
4	External obstruction	Mixed forest in front of the balcony facade	No obstruction	The facade without shading turn out to be the most reliable starting point for calculation (totally shaded facade was also analyzed)
6	Flat temperature	23.3 °C	21 °C	21 °C is general design value
7	Standard of equipment and number of occupants	Two residents, electricity consumption 1.500 kWh/year)	The number of residents (0.0357 pc./m <sup>2</sup> ); lighting (11 W/m <sup>2</sup> ); electrical equipment (4 W/m <sup>2</sup> )	Adjusted to correspond to the Finnish national calculation guidelines
8	Window U-value	1.2 W/m <sup>2</sup> °C	2.8 W/m <sup>2</sup> °C	Typical thermal insulation capacity in the 1960-1970s buildings.
9	Door U-value	1.2 W/m <sup>2</sup> °C	3.0 W/m <sup>2</sup> °C	Typical thermal insulation capacity in the 1960-1970s buildings.
10	Wall U-value	0.29 W/m <sup>2</sup> °C	0.4 W/m <sup>2</sup> °C	Typical thermal insulation capacity in the 1960-1970s buildings.
16	Balcony's relation to exterior wall	Apartment runs from front to back of a building	Balcony covers the flat's exterior wall completely	By doing this, the external wall area in relation to balcony area was in the users control.
19	Building ventilation type	Mechanical exhaust (Mostly 0.35 ACH. 0.7 ACH three times a day)	Mechanical exhaust (0.5 ACH)	Adjusted to correspond to the Finnish national calculation guidelines
20	Supply air intake solution	Two inlet vents (one in the balcony and one in the bedroom)	One inlet vent (Directly from the outside)	It was noticed that inlet vent should be outside the balcony in the base case, because the air inlets affect too much for the results in sensitivity analysis, if it is inside the balcony. Reason for the one inlet vent was that then the air inlet was totally in the user control.
21	Unintended ventilation rate through balcony glazing	1.1-2.2 ACH (monthly average)	1.5-2.6 ACH (monthly average)	Opening area is slightly increased to correspond typical 'tight' glazing solution
23	Building air leakage coefficient	0.88 ACH	1 ACH	1 ACH is better guess for general situation
24	Designed heating capacity of hot water radiators	According to current design in 1979	Sodankylä situation oversized 40 %	Reason for the oversizing of the heating capacity was that then it was sufficient for all climate situation in the sensitivity analysis
25	Heating system control curve position (at Sodankylä design condition)	According to current settings in the building	Initial settings	Adjusted to correspond to the Finnish national calculation guidelines
26	Heating system summer shut-off	No shut-off	June - August	Summer shut off is generally recommended solution
30	Lambda value of balcony structures (W/m <sup>2</sup> °C)	1.35 W/(m <sup>2</sup> K)	2.5 W/(m <sup>2</sup> K)	Lambda value of the concrete structures is highly dependent on the quality of the concrete. 1.35 is some kind of minimum estimate and 2.5 maximum estimate. 'Best guess' would be 1.8.
32	Surfaces absorptivity (Balcony and exterior wall)	Mostly 0.22	0.95	Surface absorptivity of 0.95 is almost black and 0.20 is almost white. The black was selected to the starting point for calculation. Afterwards it was noticed that 0.4 could be the 'best guess' for typical situation.

As will be clear from this thesis, the final model was constructed after numerous adjustments over a long period of time (2009 to 2014). It took thousands of re-simulations and a number of thorough comparative analyses before the final models for the calibration and sensitivity analysis were formed. As Table 25 shows, the model for the sensitivity analysis does not represent the calibration situation; it is more like a descriptive model for a typical renovation situation. By making slight changes to it, the energy-saving potential of balcony glazing can be evaluated in almost any typical Nordic situation. This is also confirmed by the error analysis of the simplified calculation method (section 4.4.2).

### **4.1.3 Evaluation of the added glazing model**

In connection with the balcony glazing studies in Finland, the opportunity arose to participate in an ongoing research project at the University of Lund, in Sweden. This meant that the research could be extended to investigate whole glazed facades of a building. Among the many interesting aspects of this project were the technical solutions which had been implemented to control the building's supply air, which came through the glazed cavity in winter, and from outside the cavity in summer. There were also a number of different methods for cooling the cavity in the summer. Also, it was a great opportunity for this researcher to perform daily site visits in an unoccupied building and to take part in a comprehensive temperature monitoring project. It was a good fit for a bit of cooperative research, so there were two longer research visits and two shorter ones amounting to a total of four and half months spent working on a glazed-in structure project in Lund. One article (Article V) about this fascinating project has already been published, and several more are in the pipeline. The author is grateful to the staff of Lund University for the field measurements that the author used for the IDA-ICE simulations described below.

#### **4.1.3.1 Calibration study**

Creating a model for the Malmö case building was helped by the experience that had been gained in carrying out the simulations of the glazed balconies in Finland. Therefore, a lot of technical choices for the modeling could be made on the basis of past experience. The main focus of the simulations was to assess the overall reliability of the model without having to make very detailed validation operations. The researchers in Sweden, Birgitta Nordqvist and Petter Wallentèn, brought their own long experience to the topic. Both of their doctoral theses 'Ventilation and Window Opening in Schools' [200] and 'Heat Flow in Building Components' [201] having familiar to researchers in this field. During the measurement period the author was privileged to meet a number of experienced and published researchers from the same field, and to benefit from their



experience and advice. In fact, the double skin façade on the building in Malmö had been the subject of previous studies which have resulted in at least two masters theses [191, 189]. Therefore, the project had a wealth of monitoring and field experience to call on for this study.

### Scenario uncertainty

Because of the uncertainty of the weather data used in the Tampere calibration, the starting point for the study was that we would have our own weather station to measure outside temperature, wind conditions and solar radiation on site. Unfortunately, this part of the project failed to materialize, so we had to use the local weather stations' information in the simulations, as was done in Tampere (described in section 3.1.2). However, the available weather data was better than it had been for the balcony studies, in that there was a nearby monitoring site for solar radiation. In fact, the 'outdoor' temperature was monitored at the two points on site, i.e. in the inlet culvert of the ground duct system and on the north facade of the building. However, these values were not used for the simulation weather, because it was noticed that the on-site sensors did not represent the actual outdoor temperature in enough detail. For example, the north façade sensor was exposed to direct solar radiation from time to time, as can be seen in Table 26; the maximum deviation between the north facade outdoor temperature and the Malmö Sturup weather station temperature was as high as 18.4 °C. However, this and other errors caused by direct solar radiation cannot entirely explain the difference between the measured sets of data ( $R^2 = 0.87$ ), so other error sources may exist. It is likely that one of the factors causing errors in the on-site sensor is the fact that it was directly mounted on to a wall and was thus exposed of the building's heat losses. In fact, there is so much uncertainty about the reliability of the on-site monitoring of the north façade that it was decided to use the Malmö Sturup airport weather information as inputs for the study.

Table 26. Correlation between monitored outdoor air temperature on site (X) and outdoor weather condition in Malmö Sturup weather station (Y).

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=SIMULATION WEATHER									
outdoor north, 5701_GT33	Malmö Sturup weather	$y = 0.8223x + 0.5222$	0.93	0.87	14	24	17	20	18.40	-5.60

Fortunately, in this study the uncertainty about the building's usage and occupancy schedules is very low, because the building was unoccupied for the whole measurement period, apart from one week in August, 2014 (from 15<sup>th</sup> to 23<sup>th</sup> of August). Human behavior has therefore not influenced the building's indoor climate or its energy bal-

ance, which makes the calibration more accurate (unlike in the balcony study). After calibration, the building's usage was standardized to represent the most likely indoor climate situation of the building in real use i.e. with occupants, lighting and electricity equipment.

### **Building physical/operational uncertainty**

Determining the dimensions and properties of the building structures, the specifications of the windows' properties and the estimation of the air gaps in the glass façade was done using the same methods as for the balcony studies i.e. primarily by direct measurement on site, and alternatively by manufacturers information and literature sources. Therefore, there are similar uncertainties in this project as there were in the Tampere one with regard to the structural properties and real airflows in the cavity. Of these, the greatest uncertainty is related to the air gaps of the glazing system and the airflow through them, as it was in the balcony glazing study. There is also a fairly high degree of uncertainty arising from the operation of the ventilation unit and the building's heating system. However, the operation of the ventilation unit and the building systems in Malmö have been regularly inspected and adjusted to follow planned control set-points in previous research studies [191, 189]. The operation of the HVAC systems in use was determined on site by following the real operation of the systems, and this was verified with the monitoring information data acquired from Malmö city during the previous studies [191, 189] and this study. Therefore, the real operation setpoints of the building's systems were used in the simulation model and its operation was verified. An important tool for this process was found to be the ability to make one's own 'customised control macro' for the systems in IDA-ICE. This allowed for flexible scheduling during the study.

### **Model inadequacy**

As previously stated, the DSF in the Malmö building was modelled in the same way as were the glazed balconies i.e. with separately-defined zones and a detailed window specifications (without using IDA-ICE's own DSF model). The reason for this was that the goal of the simulation was to make some points of comparison with the Tampere study. In the facade zone, a detailed window structure and simplified (energy) zone model was used. It wasn't possible to use a detailed (climate) zone model (as had been done for the glazed balcony study), because of the complex geometry of the double façade (the climate model only allows to use of rectangular geometries). The newest edition of the IDA-ICE (IDA-ICE 4.7 standard edition) has a separately developed double skin facade model, which seems to be more detailed and more reliable. How-

ever, this was not available in the IDA-ICE standard edition at the time of the model calibration.

With regard to the construction of the DSF zone, the effect of the convective heat transfer coefficient on the airflows and cavity temperature was assessed. All the internal surface convection models described in this thesis (see section 2.3.4) were assessed, as it had already been observed that internal surface convection is a key factor affecting the cavity temperatures. However, the simulation was conducted with the default setting, because a) the real cavity airflows were not measured on site, b) there was no certainty that the measured cavity temperatures represented the real cavity air temperature, c) it avoided having to use IDA-ICE advanced level (it slows down the computing time) and d) there was no reference information to which the default settings should have been changed. There is thus significant uncertainty associated with this issue.

The ground duct system was modelled by placing eight consecutive zones underground and connecting them with each other by the actual diameter of the opening. This described the operation of the real ground duct system, at least on some level. The correlation analysis of the measured and simulated temperature in the outdoor inlet culvert (Table 27) shows that the correlation is very good ( $R^2 = 0.89$ ), especially when 'the coarseness of model' is taken into account. Despite this, a more detailed calculation of the ground duct system is, in principle, recommended. This could be done by adding a more detailed model to the advanced-level IDA-ICE.

Table 27. Correlation between monitored air temperature inside outdoor inlet culvert (X) and simulated culvert zone temperature (Y).

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=SIMULATION									
outdoor inlet culvert, 5701_GT41	Culvert zone	$y = 0.7653x + 1.9979$	0.94	0.89	9	19	4	15	8.67	-4.60

The temperatures in the ventilation unit were also measured at various points, although their correlation with the simulations (Table 28) proved to be rather weak ( $R^2 = 0.26$  to  $0.46$ ). One reason for this is that the distances between the fans, heat exchanger and other facilities in the ventilation unit were so small that their temperatures were influenced by each other. For example, the measured temperature from the heat exchanger may not have exactly represented the correct temperature as it was also affected by the heat from the fans and the heating coil. As a result, a comparison of the monitored and simulated ventilation unit temperatures is not very meaningful. The model needs to be calibrated in more detail with accurately measured unit temperatures.

Table 28. Correlation between monitored air temperature inside ventilation unit (X) and simulated temperatures inside unit (Y).

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=SIMULATION									
supply air before heat exchanger, 5701_GT11	supply air before heat exchanger	$y = 0.7056x + 0.568$	0.68	0.46	26	38	26	29	19.17	-
supply air after heat exchanger, 5701_GT12	supply air after heat exchanger	$y = 0.2664x + 13.5441$	0.55	0.30	7	16	6	10	19.12	-4.58
supply air before fan, 5701_GT13	supply air before fan	$y = 0.1949x + 15.5382$	0.51	0.26	3	16	0	14	8.90	-

In order to model the ground duct system, the effects that the two basic ground models of IDA-ICE (ICE3 and ISO-13370:2007 [157]) have on the inside temperatures of the apartments were evaluated. The ISO model is a more complicated (and realistic) model than the IDA model, but both of them, however, only offer a simplification of the real ground performance and are intended mainly for energy simulations. A comparison of the measurements was also not reasonable because the basement model was a simplification of the real basement (which is, in reality, connection through a ground culvert to other buildings). Nevertheless, it was noticed that the ISO model always estimated higher indoor temperatures than the IDA model for the summer months. This suggests that the ISO model is better if the focus of the simulations is on thermal comfort during the summer.

### Observation error

During the analysis of monitoring data, two important issues were raised. The first concerns the cavity air temperature sensors' close contact with the brick wall of the building. The second was the solar protection of the sensors, which had been shielded with aluminum foil. Because all the measuring devices were positioned near the brick wall, they were exposed to the building's conduction heat losses. In addition to this, the most of the sensors were exposed to direct solar radiation, which caused additional measurement errors, and also interfered with the operation of the ventilation systems. The reason that sensors shielded with aluminium foil were susceptible to solar radiation is because there was no mechanical ventilation in the shielding [74], which defeated their purpose (the foil was meant to protect the east and the south facade sensors from direct solar radiation). It was also noticed that some of the sensor guards had fallen off (Figure 49). Due to these factors, the correlation analysis with the monitored and simulated cavity temperatures was conducted, but three different simulated temperatures were included in the analysis. These were the cavity mean air temperature, an internal surface temperature for the added glazing and an external surface temperature for the

brick wall. The results from those analyses are presented separately for all three glazed facades.



Figure 49. Sensors located on the west (left), south (middle) and east (right) facades. The unshielded sensors are marked by the red rectangles, and the shielded sensors by red circles.

The results from the Eastern facade (Table 29) consistently showed the best correlation between the simulated mean air temperatures and the monitored temperatures. This may be because three of the four sensors' guards (Figure 49.) were still in place at the end of the monitoring period. The effect of solar radiation was lower in most of these sensors' situations and the measured temperature was more likely to represent the cavity air temperature than the surface temperature of the brick wall. These findings are also supported by the fact that the weakest correlation between measured and simulated sensors was obtained with sensor GT31:1, i.e. the sensor whose guard fell off during the study. Nevertheless, the correlation between the measurements and the simulations is not, on the whole, optimal ( $R^2 = 0.72$  to  $0.76$  for the simulated cavity mean air temperature). In addition to the effects of solar radiation, another error source might be the conduction losses from the building.

Table 29. Correlation between monitored air temperature in the east cavity (X) and simulated cavity mean air temperature, added glazing internal temperature and brick wall external temperature (Y).

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=SIMULATION									
<b>East glazing south side (lower), 5702_GT31_1</b>	Mean air temperature	$y = 1.0048x - 1.3753$	0.85	0.72	5	17	6	15	10.95	-
	Added glazing, internal temperature	$y = 0.9754x - 2.9006$	0.80	0.63	15	24	16	23	12.58	13.19
	Brick wall, external temperature	$y = 1.0096x + 1.6139$	0.83	0.68	-8	19	-9	12	6.92	20.85
<b>East glazing south side (higher), 5702_GT33_1</b>	Mean air temperature	$y = 1.0779x - 2.629$	0.86	0.74	4	16	5	15	7.27	12.88
	Added glazing, internal temperature	$y = 1.0466x - 4.1243$	0.81	0.65	14	23	15	22	11.38	13.19
	Brick wall, external temperature	$y = 1.0792x + 0.4399$	0.84	0.70	-10	20	-10	12	3.85	21.35
<b>East glazing north side (lower), 5702_GT31_2</b>	Mean air temperature	$y = 1.0277x - 1.2935$	0.87	0.75	3	16	4	14	10.66	11.11
	Added glazing, internal temperature	$y = 1.0067x - 3.0235$	0.82	0.68	13	22	14	21	13.74	13.49
	Brick wall, external temperature	$y = 1.0484x + 1.3445$	0.86	0.73	-11	20	-11	13	6.39	19.96
<b>East glazing north side (higher), 5702_GT33_2</b>	Mean air temperature	$y = 1.0917x - 2.5266$	0.87	0.76	2	15	3	14	8.01	11.11
	Added glazing, internal temperature	$y = 1.0685x - 4.2109$	0.83	0.69	12	22	13	21	10.41	13.29
	Brick wall, external temperature	$y = 1.1101x + 0.1654$	0.86	0.74	-12	20	-12	13	4.77	20.26

The situation in the south façade is somewhat different. Three sensor guards have remained on the eastern sensors (GT31 and GT21:2), but dropped off the western sensors (GT32 and GT21:1). The usefulness of sensor guards, however, is not clearly visible in the results (Table 30), because the shielded eastern sensor GT31's accuracy is better ( $R^2=0.90$ ) than the corresponding unshielded western one (GT32,  $R^2=0.89$ ), but the accuracy of the eastern sensor GT21:2 ( $R^2=0.84$ ) is lower than the corresponding unshielded western one ( $R^2=0.87$ ). This indicates that it is not actually the sensor guard which helps to produce a more accurate correlation between the monitoring and the simulation. In fact, it seems that the south façade's sensors' correlation with the simulation is generally good ( $R^2=0.80$  to  $0.88$ ) for the simulated cavity mean air temperature and simply better than the east façade's sensors' correlation with the simulation. It also seems that the simulated external surface temperature of the brick wall correlates better with monitoring ( $R^2 = 0.84$  to  $0.90$ ) than do the simulated cavity air temperatures ( $R^2 = 0.80$  to  $0.88$ ). This supports the conclusion in Article V that the measured temperature does not actually describe the cavity air temperature, but is more likely a mixture of the cavity air and the brick wall external surface temperature.

Table 30. Correlation between monitored air temperature in the south cavity (X) and simulated cavity mean air temperature, added glazing internal temperature and brick wall external temperature (Y).

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=SIMULATION									
<b>south glazing west side (lower), 5702_GT21_1</b>	Mean air temperature	$y = 0.8132x + 1.2802$	0.91	0.83	14	20	13	17	22.33	-9.82
	Added glazing, internal temperature	$y = 0.837x - 0.949$	0.89	0.80	20	26	21	24	23.32	-9.94
	Brick wall, external temperature	$y = 0.9082x + 2.0169$	0.94	0.87	1	13	1	9	18.29	14.53
<b>south glazing east side (lower), 5702_GT21_2</b>	Mean air temperature	$y = 0.9157x - 1.3571$	0.89	0.80	14	20	14	19	14.27	10.42
	Added glazing, internal temperature	$y = 0.9304x - 3.3534$	0.86	0.74	20	26	21	25	16.13	10.54
	Brick wall, external temperature	$y = 1.0231x - 0.9383$	0.91	0.84	1	14	2	11	9.39	15.78
<b>south glazing west side (higher), 5701_GT32</b>	Mean air temperature	$y = 0.9491x - 1.5665$	0.94	0.88	13	22	16	20	15.33	11.56
	Added glazing, internal temperature	$y = 0.9296x - 2.5982$	0.91	0.83	21	29	25	29	16.32	11.70
	Brick wall, external temperature	$y = 1.0609x - 1.2275$	0.95	0.89	0	18	2	12	11.29	18.44
<b>south glazing east side (higher), 5701_GT31</b>	Mean air temperature	$y = 0.9319x - 1.088$	0.94	0.88	12	22	15	19	16.33	11.86
	Added glazing, internal temperature	$y = 0.9139x - 2.1496$	0.91	0.83	20	29	24	28	17.32	12.07
	Brick wall, external temperature	$y = 1.0431x - 0.7178$	0.95	0.90	-1	18	1	12	12.29	18.84

There were no guards on the west façade's sensors (Figure 49) but this facade was otherwise the most protected from the sun, as there were trees in front of the facade. This might explain why the correlation between the measured and simulated temperatures is the best on this façade (Table 31). The correlation between the monitored and simulated cavity temperatures was from 0.86 to 0.92, and it was even better between the monitored cavity air temperature and simulated brick wall external surface temperature ( $R^2 = 0.92$  to  $0.95$ ). This all seems to confirm the problems with sensors guards, i.e. the best results were achieved without sensor guards, but with external tree shading.

Table 31. Correlation between monitored air temperature in the west cavity (X) and simulated cavity mean air temperature, added glazing internal temperature and brick wall external temperature (Y).

INDEX (X - Y)		REGRESSION	R	R <sup>2</sup>	MBE (%)	CV (RMSE) (%)	MPE (%)	MAPE (%)	MAX	MIN
X=SENSOR	Y=SIMULATION									
<b>West glazing south side (lower), 5702_GT32_1</b>	Mean air temperature	$y = 1.2428x - 4.7041$	0.95	0.90	4	20	9	19	9.07	-9.71
	Added glazing, internal temperature	$y = 1.1997x - 5.796$	0.93	0.87	14	25	21	27	12.29	-9.19
	Brick wall, external temperature	$y = 1.3275x - 3.8483$	0.97	0.94	-10	22	-6	12	3.68	15.50
<b>West glazing south side (higher), 5702_GT34_1</b>	Mean air temperature	$y = 1.2071x - 4.6556$	0.96	0.92	6	18	12	19	8.52	-8.78
	Added glazing, internal temperature	$y = 1.1665x - 5.7709$	0.94	0.89	17	25	23	27	11.59	-8.09
	Brick wall, external temperature	$y = 1.284x - 3.703$	0.97	0.95	-7	18	-3	11	3.90	14.40
<b>West glazing north side (lower), 5702_GT32_2</b>	Mean air temperature	$y = 0.9345x - 0.3918$	0.93	0.86	9	21	12	18	18.10	-9.71
	Added glazing, internal temperature	$y = 0.911x - 1.7914$	0.92	0.85	19	27	24	27	20.34	-7.73
	Brick wall, external temperature	$y = 1.0133x + 0.4895$	0.96	0.92	-4	15	-3	8	13.44	11.39
<b>West glazing north side (higher), 5702_GT34_2</b>	Mean air temperature	$y = 1.006x - 1.4731$	0.93	0.86	8	20	12	18	16.81	-9.70
	Added glazing, internal temperature	$y = 0.9765x - 2.7726$	0.92	0.84	18	27	23	27	19.44	-7.83
	Brick wall, external temperature	$y = 1.0913x - 0.6922$	0.96	0.93	-5	16	-3	9	11.80	11.82

Looking at the results as a whole, it can be said that 83 % (10/12) of the surface temperature sensors fulfill the ASHRAE calibration criteria for MBE and CV(RMSE), as do 67 % (8/12) of the cavity mean air temperature sensors. On this basis, it can be concluded that the monitoring sensors, as a whole, represent the external surface temperature of the brick wall better than the cavity air temperature. Nevertheless, the 83 % fulfillment confirms that the model can be considered as a 'calibrated model' and the results are reliable for further analysis.

## Conclusion

The comparison of the measured cavity air temperatures to the simulated cavity air, brick wall and glazing temperatures showed that the model was good enough to be used in further studies. It might be possible, but not really worthwhile, to try to get a better fit by making a detailed model of the mounting of the sensors together with the solar shading of the aluminum foil. However, it was not the goal of this study to make a perfect parameter fit for this particular house, but to create a reasonable model that manages to capture the qualitative behavior of the complex ventilation and glazing renovation, which could then be used in further simulations. Given that there are many local phenomena not included in the model, including, for instance, the thermal behavior of the temperature sensors, the results are surprisingly good. (Article V)



#### 4.1.3.2 Sensitivity analysis

The calibration model only needed slight changes for the sensitivity analysis. The only changes were the standardization of the building's usage to match the typical use of the building and updating the simulation period to a full-year simulation. Thus, it was possible to assess the impact of modifications to the model parameters on the building's energy consumption and indoor climate on a yearly basis with the realistic use of the building (internal heat loads and their schedules have taken into account). The sensitivity analysis should be regarded more as an assessment of the existing DSF solution's usefulness and possible further development of the implemented concept, than a pure sensitivity analysis. Of course, the significant parameters are clearly brought out in the review, but they must be regarded as being more applicable to the existing building and the implemented solution rather than a generalisable fact.

The variables in the development study for the implemented concept were increased airflows through the ground duct system and the cavity exhaust fan, increasing the extent of the openable windows, and adding blinds to the cavity glazing (internal and external). The winter and summer situations were analyzed separately, and without taking the operational control of the solutions, like added blinds, into account. As a result, the sun protection, for example, is assumed to be in a lowered position all the time. This does capture the significance of the solar shading, in general, but it does not clearly define the overall yearly benefits that could be achieved if the system's combinations were modelled with realistic control options. The sensitivity analysis' main drawbacks are therefore that a) the studied apartment was calibrated only with the glazed cavity temperatures, but not with indoor air temperatures at a time of thesis publication (under construction under during spring 2017) and b) it does not take into account the operation of different combinations of the energy-saving and solar-protection options in the whole year simulations (optimized separately in this study). These factors must be taken into account in any further studies.

## 4.2 Monitored balconies and flats in Tampere

### 4.2.1 Surface temperatures

This chapter is concerned with the main results of the surface temperature measurements taken on two balconies in Tampere between 16<sup>th</sup> July, 2009 and 24<sup>th</sup> May, 2010.

#### Window surface temperatures

The external window surface temperatures on the glazed balconies varied between -13.9...42.1 °C and on the unglazed balconies between -18.8...44.8 °C. The external window surface temperatures on the glazed balconies exceeded those of the unglazed balconies by 2.5 °C on average. During the winter, the average difference between the glazed and unglazed balcony temperatures was 2.8 °C, and during the summer it was 1.7 °C. The temperature variations at the windows' bottom edges exceeded those at the top. For example, the surface temperatures of the bottom edge of the window on the unglazed balcony varied between -18.8...44.8 °C while the top edge was between -18.0...31.4 °C. On the glazed balcony, the external window surface temperatures varied between -13.9...42.1 °C at the bottom edge and between -11.4...34.3 °C at the top edge. These results indicate that the balcony glazing decreased temperature fluctuation and temperature differences between the top and bottom edges of the external window surfaces.

The internal window surface temperatures in the flat with the glazed balcony varied between 15.9...32.2 °C. In the flat with the unglazed balcony they were between 16.0...46.8 °C. On average, the internal window surface temperatures in the flat with glazed balcony exceeded those of the flat with the unglazed balcony by 1.0 °C. At the monthly level, the internal window surface temperatures were almost equal from April to September, with the closest match in July. In the winter, the internal window surface temperatures in the flat with the glazed balcony exceeded those of the flat with the unglazed balcony by 1.3 to 2.5 °C. The lower window surface temperatures in the flat with the glazed balcony are probably caused by the reduced heating need.

On average, the heat losses through the window of the flat with the glazed balcony were 22 % lower than they were in the flat without a glazed balcony. The impact of solar radiation can be estimated based on the monthly energy savings. The heat losses were reduced by 23 % in March, 25 %, in April, 34 % in May and between 18-19 % in Mid-winter. In summer, the heat losses expressed by percentages differ significantly, although the external and internal window surface temperatures differ by less than 2 °C. The reduction in heat losses has been affected both by the balcony glazing and the

lower radiator temperatures resulting from the reduced heating requirement in the flat with the glazed balcony as compared to the flat with the unglazed balcony.

### **Door surface temperatures**

The external surface temperature of the door on the glazed balcony varied between -17.4 and 56.4 °C, while on the unglazed balcony it was between -21.2...60.6 °C. On average, the temperature of the external surface of the door on the glazed balcony exceeded that of the unglazed balcony by 2.0°C. During the heating season, the average difference between these temperatures was 2.4 °C, and during the summer it fell to 1.3 °C. The temperature variations at the bottom edge of the door exceeded those at the top. For example, the door's bottom edge surface temperatures on the unglazed balcony varied between -21.2 and 60.6 °C, while on the top edge they were between -17.0...36.5 °C. On the glazed balcony, the door's surface temperatures varied between -17.4 and 56.4 °C at the bottom edge and between -12.4 and 35.1 °C at the top. These results indicate that the balcony glazing evened out the temperature variations and temperature differences between the top and bottom edges of the external door surface.

The internal surface temperatures of the door to the flat with the glazed balcony varied between 16.2 and 32.0 °C, and in the flat with the unglazed balcony it ranged between 15.5 and 40.4 °C. On average, the internal door surface temperatures in the flat with the unglazed balcony exceeded those of the flat with the glazed balcony by 0.4 °C. On average, the surface temperatures of the door of the flat with the unglazed balcony exceeded those of the flat with the glazed balcony by 1 °C in winter and by 0.3 °C in summer. The results suggest that the higher radiator temperature in the flat with the unglazed balcony did not have as much effect on the internal door surface temperatures as it did on the window surface temperatures. In the glazed balcony, the temperatures at the top edge of the door were higher than they were at the bottom edge, but this difference was lower in the unglazed balcony. It can be assumed that the hot radiator located next to the door in the flat with the unglazed balcony influences the surface temperatures of the bottom edge of the door, but has no significant impact on the top edge.

On average, the heat losses from the flat with the glazed balcony door were 15 % lower than they were from the flat with the unglazed balcony. In December, January and February, the glazed balcony flat's heat losses were 10 % lower than for the unglazed balcony. The impact of solar radiation can be seen from the monthly energy savings. In March, the heat losses were 15 % lower, in April 21 %, and in May even 31 %. In summer, the heat losses expressed by percentages differ significantly, although the

external and internal door surface temperatures differ by less than 2 °C. The reduction in heat losses was affected both by the balcony glazing and the lower radiator temperatures due to the reduced heating requirement in the flat with the glazed balcony as compared to the flat with the unglazed balcony.

### **Wall surface temperatures**

The building's external wall surface temperatures on the glazed balcony varied between -16.2 and 31.2 °C and on the unglazed balcony between -20.0 and 33.4 °C. On average, the wall external surface temperatures on the glazed balcony exceeded those of the unglazed balcony by 1.4 °C. During the heating season, the average difference between the balcony temperatures was 1.6 °C, and during the summer it was 1.0 °C. The temperature variations at the bottom edge of the wall exceeded those at the top edge. The strongest reaction to solar radiation was registered by the surface temperature sensor located in the middle of the balcony's back wall in the flat with the unglazed balcony. It can be assumed that the surface temperature sensor located at the bottom edge of the wall would have been heated even more by the solar radiation if it would not have been blocked by a chair for some time during the day. The results indicate that the balcony glazing evened out temperature variations and temperature differences between the top and bottom edges of the external wall surface.

The internal surface temperatures of the wall in the flat with the glazed balcony varied between 16.6 and 25.3°C and in the flat with the unglazed balcony between 17.1 and 28.6 °C. On average, the internal wall surface temperatures in the flat with the unglazed balcony exceeded those of the flat with the glazed balcony by 2.0 °C. In the summer, on average, the internal wall surface temperatures of the flat with the unglazed balcony exceeded those of the flat with the glazed balcony by 0.1 °C, and in the winter by 2.7 °C. The lower wall surface temperatures in the flat with the glazed balcony, are probably caused by the reduced heating need.

On average, the heat losses from the wall of the flat with the glazed balcony were 18 % lower than they were from the flat with the unglazed balcony. In December, January and February, the glazed balcony heat losses were 17-18 % lower. The impact of solar radiation can be seen from the monthly energy savings. In March, the heat losses were 20 %, in April 21 %, and in May even 26 % lower. In summer, the heat losses expressed in percentages differ significantly, although the external and internal wall surface temperatures differ by less than 1.5 °C. The reduction in heat losses was affected both by the balcony glazing and the lower radiator temperatures due to the reduced heating requirement in the flat with the glazed balcony as compared to the flat with the unglazed balcony.

Based on thermal camera imaging carried out in winter, the radiator surface temperatures in the flat with the unglazed balcony were significantly higher than the radiator temperatures in the flat with the glazed balcony. Because of this, during the heating season, the internal surface temperatures of the window, door and wall in the flat with the unglazed balcony were higher than those of the flat with the glazed balcony. For example, on March 24<sup>th</sup>, 2010, at 1 PM, at an outdoors temperature of 1.7 °C, the radiator surface temperature in the flat with the unglazed balcony was 40 °C, while in the flat with the glazed balcony, it was 31 °C.

### **Balcony glazing surface temperatures**

There were no significant differences in the balcony glazing's internal and external surface temperatures. The external surface temperatures varied between -21.85 and 36.31 °C while the internal surface temperatures were between -20.75 and 35.68 °C. On average, the internal surface temperature of the balcony glazing exceeded that of the external surface by 0.3 °C. The temperature difference between the balcony glazing's internal and external surfaces were within the same order of magnitude throughout the measurement period. On sunny summer days, the balcony glass pane surface temperatures climbed much higher than the outdoors temperature, but the difference evened out rapidly soon after sunset.

In the winter season, the variations between the balcony glazing surface temperatures and the outdoors temperatures were clearly less pronounced than in the summer. In most cases, the surface temperatures were very close to each other. However, if the weather was really cold, the difference between the outdoor air and the surface temperatures was much more noticeable.

## 4.2.2 Balcony temperatures

The monitoring results are arranged from the warmest (No. 1) to the coldest (No. 22) balconies in numerical order: 1 - 17 represent the glazed balconies and 18 - 22 the unglazed ones (Figure 50). The unglazed balconies are further defined in the diagrams by rectangles, and the glazed balconies by circles. The ages of the buildings, the orientations of the façades, the percentage of glazing openness (categorized into three groups; closed, ventilation position and one pane open) and the mean temperatures of the spaces are also shown. (Article III)

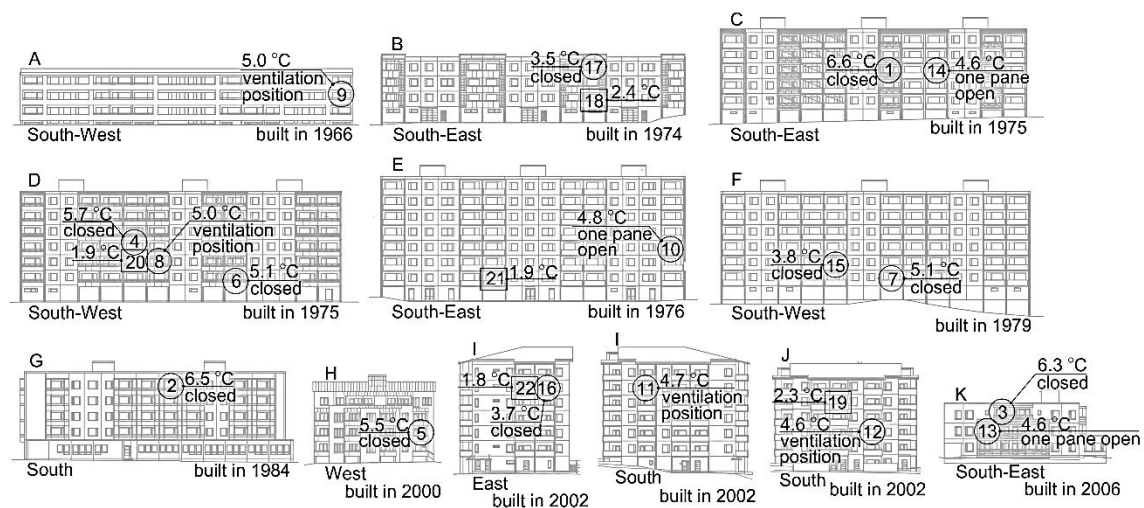


Figure 50. Studied blocks of flats from oldest to newest, in alphabetical order from the oldest, A, to the newest, K. (Article III)

### Temperatures of unglazed balconies

On average, the temperatures of the five unglazed balconies exceeded the outdoor air by 2 °C with a range of from 1.8 °C to 2.4 °C, depending on the balcony (Figure 50). Day temperatures, divided into a six-hour average, show clearly that the unglazed balconies do not cool as much as the outside air during a cold winter night and they warm up more effectively on sunny days in spring and summer (Figure 51). The intensity of the warming is highly dependent on the balcony's orientation and external obstructions. Of the studied balconies, those facing south (balcony 19) warm up most, while those facing east (balcony 22) warm up the least. (Article III)

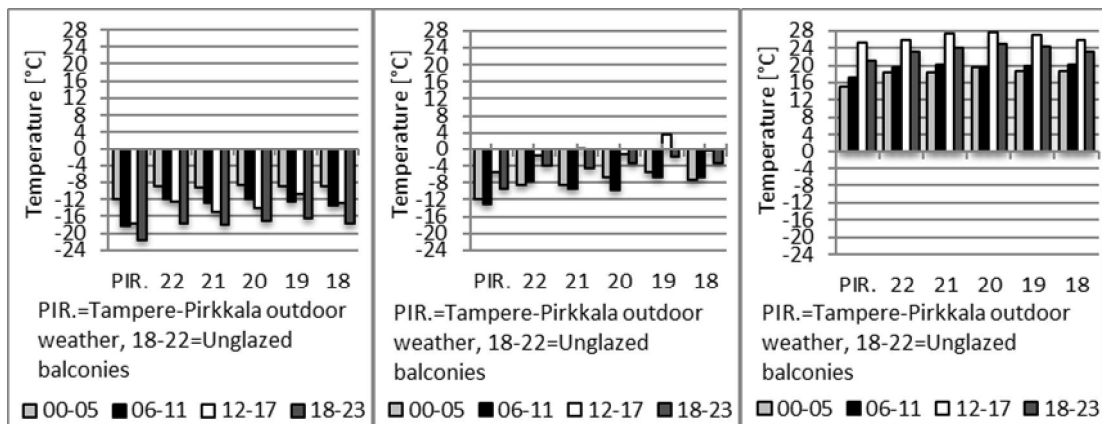


Figure 51. One cold winter day (26<sup>th</sup> January), an early spring day (15<sup>th</sup> March), and a late spring day (16<sup>th</sup> May), as well as Tampere-Pirkkala outdoor weather measurements, divided into the mean temperatures for six-hour periods. (Article III)

### Temperatures of glazed balconies

The average temperature of the 17 glazed balconies differed by 5.0 °C from the outdoor temperature, and the differences ranged from 3.5 °C to 6.6 °C, depending on the balcony. The importance of glazing for balcony indoor temperatures varied seasonally. Glazing had the highest effect in March, when the average temperature difference of the 17 glazed balconies was 6.6 °C compared to the outdoor air, while the lowest was in November with a 2.8 °C temperature difference. Calculated seasonally, the average temperature differences between the glazed balconies and the outdoor air were 4.2 °C in autumn (Sep - Dec) and 5.8 °C in spring (Mar - May). This difference of more than one and a half degrees between the autumn and spring values was caused by solar radiation, since it affected temperatures more in spring than in autumn.

The temperature in Finland can fluctuate quite dramatically, and this was reflected in the measurements for this study, which included hourly weather readings on 17 balconies over a ten-month period. During that period, the temperature differences between the glazed balconies and the outdoor air ranged from 5.8 °C below the outdoor temperature to 29.6 °C above it. The -5.8 °C difference occurred on Balcony 7 in the winter when there was a rapid increase in the outdoor temperature to which the balcony's concrete structures reacted after a short delay. The large positive temperature difference (29.6 °C) occurred on balcony 3 in spring, when there were noticeably higher temperatures during a period of very intensive solar radiation. (Article III)

### Comparison of glazed and unglazed balconies

A scatter diagram comparing a glazed and an unglazed balcony (Figure 52a and b) reveals three important observations. First, the set of points is clearly more widely spread in the glazed balcony, which shows that occasional deviations relative to the ambient air are clearly higher in the glazed balconies than in the unglazed balcony temperatures. Second, the set of points in the glazed balcony scatter diagram are more spread out from the black line (which denotes the outdoor temperature); i.e. the balcony temperatures are clearly more widely dispersed from the outdoor temperature and yet, almost without exception, higher. The balcony temperatures may momentarily drop below the outside temperature, but such moments are limited to an outside temperature range of  $-13\text{ }^{\circ}\text{C}$  to  $+18\text{ }^{\circ}\text{C}$  on balcony 1. Third, the set of plots is furthest from the outdoor temperature at the lowest and highest ends of the temperature range, which indicates that glazing has the most significant effect during very cold (outside temperature  $<13\text{ }^{\circ}\text{C}$ ) and the very warm days (ambient temperature  $>18\text{ }^{\circ}\text{C}$ ). The glazed balconies were  $3.0\text{ }^{\circ}\text{C}$  warmer than the unglazed ones, on average. (Article III)

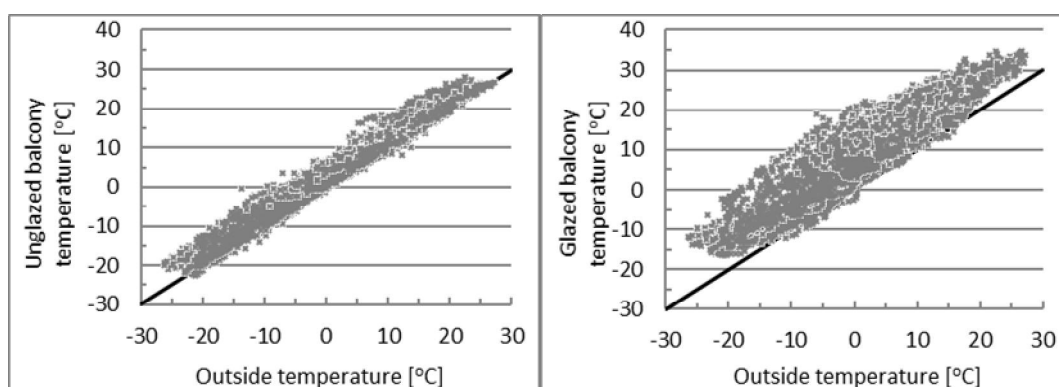


Figure 52a and 52b. Temperatures of the coldest unglazed balcony (no. 22, left) and of the warmest glazed balcony (no. 1, right) in relation to the outdoor temperature measured at the Tampere-Pirkkala weather station. (Article III)

The glazed balcony temperature exceeded  $20\text{ }^{\circ}\text{C}$  for the first time in the spring on March 9<sup>th</sup> and for the last time in autumn on October 15<sup>th</sup>. Respectively, unglazed balcony temperature exceeded  $20\text{ }^{\circ}\text{C}$  for the first time on May 12<sup>th</sup> and for the last time on September 21<sup>st</sup>. The average temperature of all the glazed balconies exceeded  $20\text{ }^{\circ}\text{C}$  for the first time on April 13<sup>th</sup> and for the last time on September 15<sup>th</sup>. The corresponding dates for the unglazed balconies were May 12<sup>th</sup> and September 15<sup>th</sup>. This means that the average usage time of a glazed balcony exceeds that of an unglazed balcony by more than a month, while in the best case scenario the usage time could even be 2.5 months longer.



### 4.2.3 Flat temperatures

The indoors temperatures of the flats with glazed balconies varied between 18.9 and 28.8 °C, while in the flats with unglazed balconies they were 19.3 and 31.6 °C. The average temperatures in the flats with unglazed balconies varied between 22.3 and 27.4 °C, in the flats with glazed balconies it was between 22.1 and 26.7 °C. The annual average temperature of all the flats with unglazed balconies was 23.8 °C and for the flats with glazed balconies it was 23.3 °C. The average difference of the temperatures measured in the flats, either with or without glazed balconies amounted to 0.5 °C for the entire monitoring period, (0.4 °C in autumn and 0.6 °C in spring). A clear connection can be seen between the balcony temperatures and the indoors temperatures measured in the flats. This was lowest in November (during the heating season), and greatest in March. The temperature difference between the flats increased as the temperature difference between the glazed and unglazed balconies increased, and it decreased as the temperature difference between the balconies decreased. This suggests that balcony glazing installation allows for a decrease in the indoors temperature of the flat without any loss in thermal comfort.

The research also included experiments to establish the connection between balcony glazing and indoors temperature reduction. The examination covered blocks of flats that included at least one flat with a glazed balcony and one flat with an unglazed balcony; the indoors temperatures measured in flats with unglazed balconies could thus be compared to the temperatures measured in flats with glazed balconies. Ten such flats were surveyed. Of these, seven had indoor temperatures which were lower than the indoor temperature of the reference flat with the unglazed balcony, while three had higher temperatures. On average, the temperature of the seven glazed balconies was 1.3 °C lower than the indoor temperature of the flat with the unglazed balcony, while the indoor temperature of three of the flats with glazed balconies was 0.6 °C higher. In most cases, the indoor temperatures of flats with glazed balconies were lower than the indoor temperatures of flats with unglazed balconies. It should be noted that the indoor temperature underruns are clearly greater than the overruns. The results suggest that balcony glazing does have a positive influence on a flat's thermal comfort and allows for a reduction of the indoor temperature in the room adjacent to the balcony without impairing thermal comfort. Accurate estimates concerning the actual temperature reduction cannot be provided with these results, since there are many other factors affecting the indoor temperature of the flat besides the glazed balcony.

#### 4.2.4 Factors affecting the balcony inside temperatures

##### Heat loss reduction

The difference in heat transfer by conduction from the building to the balcony does not seem to have much effect on the overall performance of the glazed balcony. This is because the highest average balcony temperature was in the group where the level of conduction loss was lowest. The reason for this is that the difference in the level of conduction loss between different balconies was generally quite low, and its effect on the results lower than the effect of the tightness of the glazing and the balcony's ability to absorb solar radiation, these being the most significant factors which can explain the temperature differences between all the measured balconies. On the other hand, the conduction loss level does have a significant impact on the interior temperatures of the glazed balconies during the coldest months of the year (Dec, Jan, and Feb). Because there is so little solar radiation in the Tampere region in this period, the glazed balconies gain most of their heat from the heat losses of the building. The balconies which had most of their walls within the building's 'warm' enclosing structures (e.g., integrated balconies) seem to perform better than the protruding ones. The reason is the higher heat transfer from the adjacent flat (from three sides of the balcony) and the higher overall tightness of the balcony glazing (only one glazed side) than in the protruding balconies with two or three glazed sides. However, there is no overall good solution if the glazing is not tight enough. For example, the integrated balcony (Balcony 9) shows the highest heat losses from the adjoining flat in January, but it is not the warmest balcony in this period because of the poor fit of the glazing. A better solution, for example, is balcony 2, which has typical heat loss but the most tightly-fitted glazing. (Article III)

##### Microclimate

Because the balconies chosen for the study were geographically less than 20 km apart from each other, the small local differences between the temperatures of the unglazed balconies were not caused by climate difference, but mostly stemmed from the studied balconies' different design solutions and external environmental conditions, i.e. building and site-specific factors. These affect the balconies' ability to absorb and store solar energy. For example, balconies with one open side were less exposed to changing wind conditions than those with three open sides, and an east-facing balcony with external obstruction received less solar radiation than a south-facing one in open terrain. Interestingly, the temperature difference (0.5 °C) between the two similar, but differently oriented unglazed balconies in Härmälä was greater than that between the coldest (Hervanta) and the warmest (Lielähti) area (0.4 °C). Overall, it seems that more attention was paid to the microclimate in some buildings' designs than in others. (Article III)

### **Solar absorption (orientation and external obstacles)**

The difference in the levels of solar absorption between the balcony which received the most solar radiation (very high) and the balcony which received the least (very low) was approximately 1.0 °C overall. All the glazed balconies which had a high solar absorption level warmed up strongly or very strongly in sunshine. The degree of external obstruction also seemed to affect the balcony's ability to capture solar radiation. Based on the research, a southern orientation is clearly recommended. However, this effect could not be analyzed in detail, because the sample size was not sufficient to cover a wide enough range of all the possible orientations. (Article III)

On the whole, solar absorption seems to be a more critical factor than conduction losses from the adjacent building or the balcony/building's microclimatic design. For example, the three warmest balconies over the whole year were far from the warmest in November and December, but without exception they were the warmest in spring and autumn. Solar radiation seems to start to affect the monthly temperatures as early as January. In February, the second coldest month of the year, the effect was clearly visible in those balconies which had a high capacity to absorb solar radiation. (Article III)

### **Amount of glazing**

Increasing the amount of glazing by replacing a 180-mm thick balcony side wall element ( $U = 3.5 \text{ W/m}^2\text{°C}$ ) with balcony glazing ( $U = 5.7 \text{ W/m}^2\text{°C}$ ) slightly increased the conduction heat losses from the balcony to the outside air. It also increased the balcony's unintended ventilation (convection), because a tightly sealed concrete wall structure was replaced with a leaky glazing structure. On the other hand, the increased glazing area increases the balcony's ability to capture solar energy, which compensates for the increased conduction and convection heat losses. It also seems that the temperature fluctuations are directly proportional to the amount of glazing. The optimal solution for the mean air temperature inside the balcony seems to be a balcony glazed on two sides, thus effecting a compromise between high solar absorption and the air leakage through the glazing. Indeed, the lowest mean temperatures were recorded for balconies with three loosely-fitting glazed sides, even though they had high solar energy absorption potential. This indicates that the increase in unintended ventilation had a more significant effect on the results than increased solar energy absorption. On average, the temperature difference between the balconies with two (the best solution) and three (the weakest solution) glazed sides was 0.6 °C (Figure 53). (Article III)



Figure 53. The optimal solution for the mean air temperature inside the balcony seems to be balconies glazed on two sides, as they offer a compromise between high solar absorption and the amount of air leakage through the glazing.

### Tightness of the balcony's vertical structures

In Finland, all balcony glazing structures are leaky structures because of the 2–3-mm air gaps between the glass panes, yet the air outflow can range, according to our estimate, from 1 l/s to 40 l/s depending on the overall differences in the glazed balcony solutions. The main factors affecting this are the variations in the tightness of the glazing and the balcony's heat gains from solar radiation and heat transfer from the adjacent flat (Figure 54).

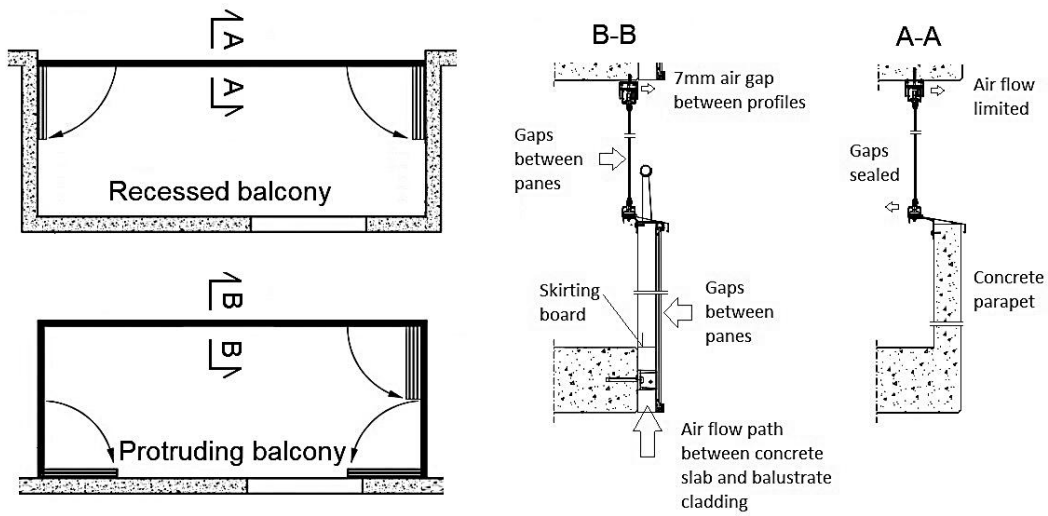


Figure 54. Examples of a very tight recessed balcony and a very leaky protruding balcony. The total areas of the gaps are 7000mm<sup>2</sup> and 154000 mm<sup>2</sup> respectively (22 times higher).

The temperature difference between the balconies with the most tightly-fitted glazing and those with the most loosely-fitted glazing was 2.1 °C, on average, i.e., clearly higher than for any of the other factors studied in the field monitoring. Furthermore, the average difference between the balconies with very high and low tightness was significant (1.0 °C). This clearly shows the importance of tightly-fitted glazing for the final result. Furthermore, the air leakage of the coldest glazed balcony (balcony 17) was the highest in the group, and the five coldest balconies included the three leakiest glazed balconies. (Article III)

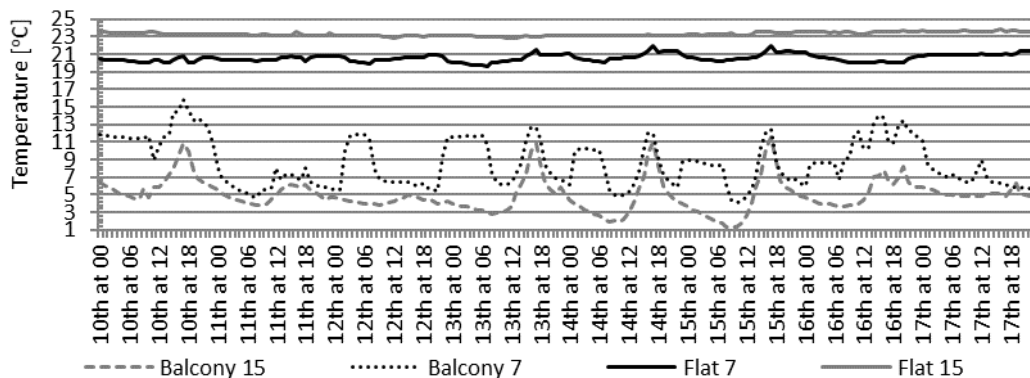


Figure 55. Temperatures of balconies 15 and 7 and of the adjacent apartments from October 10<sup>th</sup> to 17<sup>th</sup>, 2009. The figure shows how the resident of flat 7 ventilated the flat by keeping the balcony door open, especially at night. (Article III)

Surprisingly, two of the five coldest balconies were structurally very tight compared to the other balconies. However, it transpired that the glazing on these balconies had been left partly open for some reason, which explains why the temperatures on those balconies were lower. For example, in building C, the glazing on balcony 1 was kept closed, whereas on balcony 14 it was kept partly open, resulting in a 2.0 °C temperature difference between the balconies (6.6 °C and 4.6 °C, respectively). Human activity was also instrumental in another context. For example, balcony 7 warmed effectively when the door to the flat was left open for long periods during the measurement period (Figure 55), resulting in a significant difference in the average temperature of two balconies in the same building (1.3 °C between balconies 7 and 15). (Article III)

### The openness of the balcony glazing

The users of balcony glazing or balconies in general can also reduce or completely negate the energy savings achieved with the help of balcony glazing – consider the following actions, for example:

- The balcony door is left ajar. In such cases, increased use of the balcony after balcony glazing installation may even lead to increased heat losses.
- Some of the balcony glazing is left partly or completely open during the winter season. This considerably reduces the energy efficiency benefits achieved by balcony glazing.
- As a consequence of smoking, the balcony glass panes are continually kept slightly open, in order to get rid of the tobacco smell more efficiently.

Within the framework of the research, all the glazed balconies (one detailed monitoring and the 17 data logger cases) were monitored by checking the balcony glazing's openness grade from outside at least once a month. The degrees of openness were classified as follows: balcony glazing fully closed, one of the glass panes in the ventilation position, one glass pane fully open, more than one glass pane fully open.

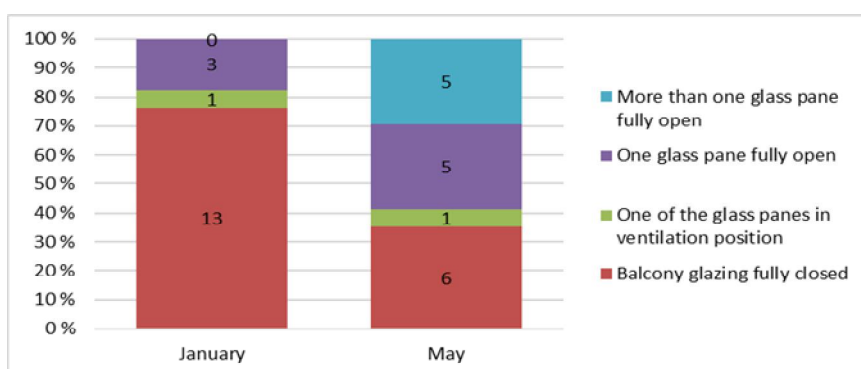


Figure 56. Use of balcony glazing at research sites in January and May 2010.

The monitoring suggested that in most cases, the balcony glazing is kept fully closed in winter, and with at least one glass pane ajar in summer (Figure 56). In January, under severe frost conditions, 84 % of the balcony panes were either fully closed or only one pane was ajar. On hot summer days, there was at least one pane fully open in 59 % of the cases. Jari Heikkilä [18] got similar results when conducting an extensive survey of the occupants of such flats. According to his data, almost 90 % of glazed balconies were kept fully closed in winter and approx. 80 % were kept partly open in summer.

In connection with the balcony glazing follow-up study, it was noticed that in flats where the balcony was used for smoking or some other quite cyclic activity, the openness grade of the glazing varied significantly during winter. On the other hand, balconies which were not used, or only used for storage purposes, remained at the same grade of openness for quite long periods of time. The residents who made active use of their balconies generally complied with the principles of energy efficiency – i.e., the glazing was fully closed at sub-zero temperatures and at least one pane was open in hot summer days. The residents' habits can be influenced by instructions, guidance and notification, which would enhance the energy efficiency benefits of glazed balconies. The user guidelines for balcony glazing should include instructions on energy-efficient use.

#### **4.2.5 Additional findings on the monitoring study**

The regular monitoring of the temperature behaviour in the balconies allowed them to be ranked from the warmest to the coolest on a monthly basis. The results of this monthly ranking could vary considerably from month to month. For example, balcony 9 was relatively cool in summer, being ranked 17<sup>th</sup> and 18<sup>th</sup> in July and August. However, it rose from being 11<sup>th</sup>, in October to being ranked the 6<sup>th</sup> warmest in December, and the warmest of all the balconies in January. Then, in February, dropped back to 9<sup>th</sup>. However, not all the results fluctuated quite so erratically. For example, in building D all the glazed balconies performed well. The reasons for the overall good results in building D were weak window insulation of the flat compared to the other reference data, insignificant external shading and relatively airtight balcony structures.

The study showed that there was also glazed balconies, whose average temperatures were only 1 - 2°C higher than the unglazed ones. There are obvious explanations for this rather poor overall performance in those glazed balconies, such as good thermal insulation of the building envelope, or very loose balcony balustrades. However, no single factor impairing a glazed balcony's energy efficiency. For example, good thermal insulation completely cancelled out the energy-saving potential of the glazed balconies. This required several factors, such as those observed building I.

From the viewpoint of energy efficiency, the poorest balconies were located in Buildings B and I. Building B was built in the early 1970s, but renovated in the 2000s. The balcony windows and doors had recently been renewed and the old balconies replaced with new ones to improve the overall appearance of the building. The new balconies had many glass surfaces, and were really loose structures. The balcony glazing in this flat was always kept closed. Although there were reasonable explanations for the poor thermal insulation of the balcony, the poor energy savings were still quite a surprise. Building I is relatively new and characterised by significantly better thermal insulation than its counterparts constructed in the 1970s. In building I, the balconies are protruding and have glazing on two or three of their sides. Balcony 16 in Building I is oriented almost directly towards the east and the balcony glazing was always kept closed. With regard to energy efficiency, the most inadequate balcony balustrades are those in Building I and J. Their corrugated sheet metal balusters were rattled by the wind, and the balconies were hot in summer, which occasionally caused significantly high indoor temperatures in the glazed balconies. Moreover, the baluster was quite cold in winter, which created an unpleasant feeling of a cold draft on the balcony during the winter months.

The openness of the balcony glazing exerted a significant influence on the indoor temperatures of the balconies. For example, in the cases of balconies 1 and 14, the balcony glazing was either kept closed (balcony 1) or a pane was kept open (balcony 14). Leaving one pane open lowered the balcony's indoor temperature by 50 %. Nevertheless, the study does show that even in glazed balconies where one glass pane is kept open, the temperatures are higher than they are in unglazed balconies both in the winter (energy saving) and in the summer (overheating). For efficient ventilation in the summer, two or more panes on two or more sides need to be opened. The resulting through-draught allows more efficient cooling of the balcony in summer. For angular or U-shaped balconies, which usually have a greater number of sides the through-draught is easier to produce than for rectangular balconies which only have one open side

## **4.3 Dynamic energy simulations**

### **4.3.1 Balcony glazing studies in Tampere**

The sensitivity analysis showed that the heating energy consumption of the flat with a glazed balcony was 3593.2 kWh, and for the unglazed one it was 4135.9 kWh. Thus, the saving in heating energy was 542.7 kWh (13.1 %), which differs only slightly from the values used in the simplified method (14.5 % and 545 kWh in Table 17). The rea-



son for the difference is the climate data which was used. The base case for the sensitivity analysis was calculated with the Helsinki-Vantaa test reference year (version 2012) and the base case for the simplified method was calculated with the ASHRAE IWEC2 weather file.

Table 32. The energy-saving variations of different calculation variables and the calculation factors are shown below, and are ranked according to their SI indices.

	Calculation variable	Percentual savings [%]	Kilowatt-hourly savings [kWh]	SI index [%]	Calculation factor
34	Blind in balcony glazing or window	2.8 - 13.1	114 - 548	79 %	Figure 59
1	Geographical location(climate condition)	10.9 - 42.2	217 - 749	74 %	a
22	Openness of the balcony glazing	6.4 - 13.1	226 - 543	72 %	Figure 60
20	Supply air intake solution	13.1 - 25.9	543 - 1015	49 %	b
11	Balcony type (including depth change)	12.1 - 23.3	526 - 1156	48 %	h
19	Building ventilation type (air change rate)	13.1 - 23.2	418 - 543	44 %	5
17	Balcony vertical position of the building	8.8 - 13.1	521 - 543	40 %	1
32	Surfaces absorptivity (Balcony and exterior wall)	8.5 - 13.1	336 - 543	35 %	c
8	Balcony window U-value (A=3.3 m <sup>2</sup> )	8.7 - 13.1	315 - 543	34 %	d
5	Flat size (room number)	10.6 - 15.9	526 - 543	33 %	2
12	Width of balcony	12.2 - 17.6	505 - 738	31 %	i
14	Glazing type (single, double or triple glazing)	11.3 - 16.0	467 - 662	29 %	k
16	Balcony's relation to exterior wall	9.3 - 13.1	532 - 543	29 %	4
9	Balcony door U-value (A=1.9 m <sup>2</sup> )	9.8 - 13.1	369 - 543	25 %	e
24	Designed heating capacity of hot water radiators	10.1 - 13.1	336 - 543	23 %	
18	Balcony horizontal position of the building	10.3 - 13.1	532 - 543	21 %	1
23	Building air leakage coefficient (at 50 Pa)	10.9 - 13.1	537 - 543	20 %	
21	Unintended ventilation rate through balcony glazing	10.6 - 13.1	440- 543	19 %	l
25	Heating system control curve position	10.9 - 13.1	423 - 543	19 %	
33	Surface emissivity (Balcony and exterior wall)	13.1 - 16.1	543 - 662	19 %	
2	Orientation of balcony facade	11.0 - 13.1	499 - 543	16 %	g
7	Standard of equipment and number of residents	11.8 - 14.1	521 - 548	16 %	
15	Thickness of glazing	11.7 - 13.1	483 - 543	11 %	
30	Lambda value of balcony structures (W/m°C)	13.1 - 14.8	543 - 635	11 %	
6	Room temperature	12.3 - 13.4	467 - 592	8 %	3
13	Amount of glass in the parapet and balcony glazing	12.1 - 13.1	494 - 543	8 %	j
27	Building's heat delivery system	13.0 - 14.1	543 - 630	8 %	
10	Balcony wall U-values (A=5.2 m <sup>2</sup> )	12.3 - 13.1	483 - 543	6 %	f
28	Heat losses from the heat delivery system to the flat	13.1 - 13.9	543 - 548	6 %	
26	Heating system summer shut-off	13.1 - 13.8	543 - 575	5 %	
4	Balcony façade distance from the building in front	12.7 - 13.1	543 - 570	3 %	m
3	Wind profile	13.0 - 13.2	537 - 543	2 %	
31	Density of balcony structures (kg/m <sup>3</sup> )	12.8 - 13.1	537 - 543	2 %	
29	Specific heat capacity of balcony structures (J/kg°C)	13.1 - 13.2	543 - 548	1 %	

As has been said, there were 34 calculation variables with from 2 to 35 calculation cases each, which meant a total of 156 calculation cases were simulated for the study (Table 15). The range of percentual and kilowatt-hourly savings, the SI indices and the calculation factors for the simplified method are shown in Table 32. The factors relating to the simplified method were chosen from the foremost variables in the sensitivity analysis, and these are also dealt with below.

#### 4.3.1.1 The selection of the key performance indicators

Table 32 shows that there are many factors affecting a glazed balcony's energy-saving potential. However, the table also shows that while some of these variables have a very significant impact on the energy savings, others are barely discernible. In addition, it is clear that some of the variables are related to the same physical phenomenon, and are therefore linked with each other. For example, the balcony's size (variable 12), its type (variable 11) and the U-values of the building envelope structures (variables 8, 9 and 10) are all affected by the level of conduction heat-loss in the building, as this controls the amount of thermal energy which the balcony gets from the flat. Therefore, the total significance of the building envelope structures is the sum of the window, door and wall, whose significances are 34 %, 25 % and 6 % respectively, making a total of 85 %. This alone is an important variable, regardless of the balcony type or size. The same phenomenon applies to types of glazing (variable 14), although in this case, the heat loss is from the balcony to the outside.

The three most significant single factors for energy saving are sun protection (e.g. a blind in the balcony glazing or the flat window), the geographical location of the building and the tightness of the balcony glazing (degree of openness). The sun protection is also associated with the variable 'Balcony façade's distance from the building in front', as this can also produce shade for the building. The balcony glazing's tightness relates to 'Unintended ventilation rate through balcony glazing'. With regard to external obstructions or shading, it should be remembered that whereas solar blinds (variable 34) mounted on the balcony glazing only shade the glazed balcony, exterior shading (variable 4) shadows the entire building, affecting glazed and unglazed balconies alike. Balcony tightness (variable 2) is actually the most important parameter in Table 32, because if all the panes are open, it almost totally negates the energy-saving effects of the glazing. The location of the building, (variable 1) is also one of the most important factors in terms of the building's heating need as Table 32 clearly shows. However, a reduction in the building's heating needs typically increases the cooling needs of the building i.e. the importance of sun protection (variable 34).

Obviously, the characteristics of the building itself, and its ventilation system also have a large impact on the energy savings. This is captured by variable 20 (Supply air intake solution) and variable 19 (type of building ventilation and its ventilation rate). These were the fourth and the sixth most significant variables in the review (Table 32). The first of these has a direct impact on the preheating of the supply air, and the second has an impact on the total energy consumption of the building. The flat's energy consumption is also affected by its size and its position in the building (The balcony's horizontal and vertical positions in the building).

Another important factor is the storage of solar radiation in the balcony structures. In this case, the key factors are the colour of the surfaces (variable 32), balcony orientation (variable 2) and the amount of glazing on the balcony (variable 13). These were the eighth, twenty first and twenty sixth most significant individual variables, respectively. Other factors, such as the heating system (variables 24, 27 and 28) and its control (variables 25 and 26) as well as the flat's indoor temperature (variable 6) and its internal heat loads (variable 7) do not seem to be directly related to the energy-saving potential of balcony glazing in themselves. However, these factors illustrate how the user can easily reduce the energy-saving potential via unacceptable system settings, etc. which lower the relative importance of balcony glazing in a building's energy use. Therefore, these variables are mostly ignored in the simple calculations (Article IV). In the next section, the results of the sensitivity analysis are discussed in more detail, variable by variable.

#### **4.3.1.2 Results from the sensitivity analysis**

##### **Exposure to solar energy and ambient environmental conditions**

The location of the building is one key factor affecting the energy-saving potential of a glazed space (key factor (a) in Figure 36). Its impact varied between 543 and 749 kWh (10.9–14.9 %) in Finland, and was even greater across the whole group of simulated cities (Figure 57). In contrast, the exposure to side winds, as well as external obstructions (key factor (m) in Figure 36) did not seem to have much impact on the end result, even though they did seem to affect the balcony temperatures in practice (Article III). The reason for this may have been the modelling choices. To model the effects of external obstructions, the studied base-case balcony was placed in the middle of the building and constructed with concrete side walls (not very exposed to wind); while the external obstruction was a similar building placed between 15 m and 100 m from the modelled building (the simulation steps were 15 m, 60m and 100 m). These obstructions did not significantly reduce the availability of solar radiation in the target flat in spring and autumn. (Article II)

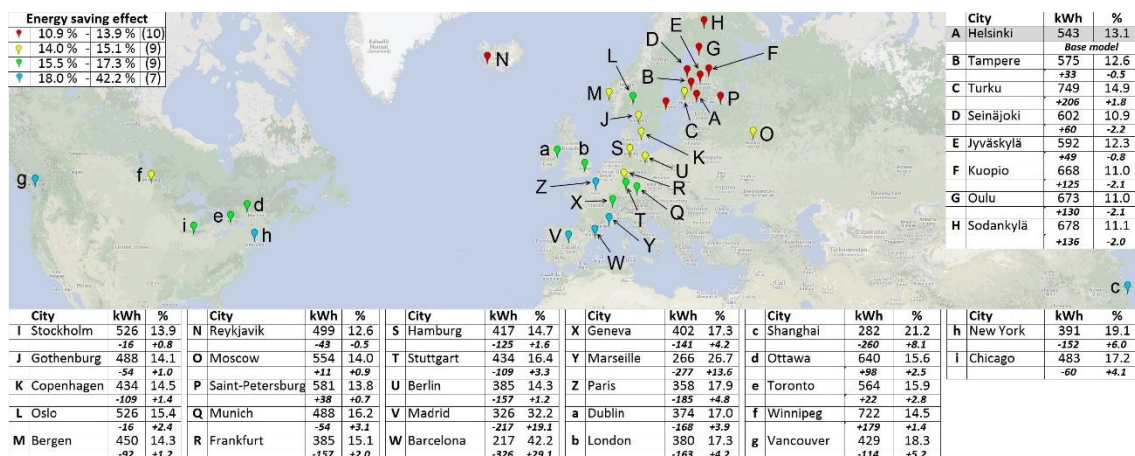


Figure 57. Impact of building's geographical position (latitude) on the annual heating energy savings achieved by a glazed space. (Article II)

Glazing seems to have the greatest effect on south-oriented balconies, and the total effect of the orientation of the glazing varied between 499 and 543 kWh (11.0–13.1 %) (key factor (g) in Figure 36). The relatively low effects of the other energy-saving measures compared to those of the location, are due to the specifics of the enclosed glazed space under analysis (only 6.3 m<sup>2</sup> of glazing on one side) and the particularly harsh conditions of the northern winters, in which hardly any solar radiation energy enters the glazed space during the winter months. It was noticeable that closer to the equator, and with a larger glazed area, the significance of glazing increases considerably in any percentage-wise analysis. For example, in Barcelona, with a balcony glazed on three sides, the heating energy-saving impact varied between 217 and 247 kWh, which in terms of percentage is 19.4 to 42.2 %.(Article II)

### Flat size and usage habits

In the analysis of the impact of flat size (key factor (2) in Figure 39), the area of the envelope (key factor (4) in Figure 39) was kept constant and only the number of rooms inside the building was varied, depending on the case. From that perspective, the heating-energy savings varied from 526 to 543 kWh (10.6–15.9 %) according to the size of the flat (from 45 m<sup>2</sup> to 83 m<sup>2</sup>). Although the savings in kilowatt hours are approximately the same, the differences in the percentage saving (as a proportion of the total heating costs) is greater, i.e. roughly similar savings in kilowatt hours are greater when expressed in terms of the percentage savings of the cost of heating a one-room flat than they are as a percentage of the total heating costs for a three-room flat. (Article II)

The temperature inside a flat (key factor (3) in Figure 39) obviously has an impact on the building's heating-energy consumption and the energy savings achieved by the

balcony glazing. On the basis of percentual savings, the balcony glazing appears to be most beneficial in buildings where indoor temperatures are kept as low as possible, and vice versa on the basis of kilowatt hours. On the whole, the results varied between 467 and 592 kWh (12.3–13.4 %) due to changes in indoor temperature. The more extensive use of the room equipment (radio, tv, etc.) and the increased usage of the flat accumulates internal heat loads, which reduces the need for heating energy. This is reflected in lower savings in kilowatt hours, but increased savings in percentage terms. On the whole, the impact of the room's interior temperature on the kilowatt-hourly results was stronger than the effects of the balcony's orientation or the presence of external obstructions. (Article II)

### **Thermal losses in the building and glazed space**

The insulation level of the structures between the building and the glazed space (key factors (d), (e), (f) in Figure 36), such as windows, doors and wall, have a decisive impact on heating energy-savings, since they largely determine how much energy the space 'receives' from the flat. The criticality of the heat losses from the flat, i.e. the denominator in variable G in Equation 3 is easy to see. By changing the insulation level of the windows, doors and the wall from the level of the 1970s building to the new construction level (year 2012) the energy saving potential with balcony glazing is reduced from 13.3 % to 3.4 %. (Article II)

Balcony type, depth and width (key factors (h) and (i) in Figure 36) also have a considerable impact on the heating energy-savings, meaning the best solution is a large recessed balcony and the poorest, a small protruding balcony. A comparison of the impact on heating energy-savings of a 3.0 m deep recessed balcony in a building with poor thermal insulation (23.3 %) and that of a 1.5 m deep protruding balcony (3.4 %) with good insulation, demonstrates the significance of the relationship between the specific losses from the glazed space to the outside and the specific gain from the building to the glazed space (variable G). The difference in the heating energy-savings in the above cases was approximately 7-fold. (Article II)

The net impact of the increased number of glazed sides in the balcony (key factor (j) in Figure 36) is slightly negative, which means that increased solar energy absorption cannot quite compensate for the increased heat loss through the looseness of the glazing structures. If the air-tightness had remained the same, the net impact of the increased glazing would have been positive. The analysis also showed that leaky low-e triple glazing (solar protection glazing) in a protruding balcony saved slightly less heating energy than leaky single glazing (key factor (k) in Figure 36), even though the improvement of thermal insulation is usually beneficial. This means, in practice, that the

most savings can be achieved with a low U-value and a high-g value. It was also noticed that relatively airtight glazing with good heat-insulation has a greater impact on recessed balconies than it does on protruding balconies. (Article II)

It is clear that how the heating energy-savings are expressed, i.e. in kilowatt hours, or as a percentage of the total heating energy consumption of the flat, is very important. For example, a flat situated in the top corner of a building consumed 1.75 times more heating energy than a flat in the centre of the same building. This was due to greater heat losses through the building envelope (key factor (1) in Figure 39). In terms of kilowatt hours, the heating energy-savings of the two flats are about the same, but when they are expressed in percentage terms, the top corner flat has only half of the energy-savings of the central flat, i.e. 6 % as opposed to 13.1 %. Therefore, an analysis based on kilowatt hours is often more useful than a percentage-wise analysis, because it captures the real heating energy-saving impact of glazing. (Article II)

### **Intended and unintended ventilation of buildings and glazed spaces**

The ventilation system and air exchange rate of a building (key factor (5) in Figure 39) have a significant impact on the heating energy-savings achieved by balcony glazing. In terms of kilowatt hours, the largest savings are attained in buildings with mechanical exhaust ventilation and a high air-exchange rate. At lower air-exchange rates, internal heat loads contribute more to heating the building, which reduces the heating need, and the energy-economy benefits that can be derived from balcony glazing. In a percentage-wise analysis, again, the lower the air-exchange rate of the building, the greater the savings attained. (Article II)

The heating energy-savings achieved by mechanical exhaust ventilation can be increased considerably by utilising the glazed balcony as a supply-air pre-heater (key factor (b) in Figure 36). Its relative significance is higher in the case of a protruding balcony than a recessed one. The amount of supply-air and the air-tightness of the balcony (key factor (l) in Figure 36) also affect the end result. Decreasing the amount of supply air taken from the balcony by a third, reduces the heating energy savings from the balcony glazing by approximately 28 %. Doubling the air leakage from a glazed balcony reduces the energy savings by 11 %, and tripling the leakage reduces them by 19 %. The air-tightness of the balcony becomes more significant when less supply air is taken from the balcony. (Article II)

The air-tightness of a building has an impact on the heating energy savings attained by balcony glazing in other ways. In the worst case scenario, the supply air does not enter the flat through the glazed space, as desired, but through an unintended leakage path

(through some leak point). This reduces the heating energy saving of the building. (Article II)

### **The building's heating system and its characteristics**

The heat distribution method, the heat losses from the heat distribution, and the heating system shutting off for the summer season do not seem to have a significant impact on heating energy-savings. However, in terms of overall economy, it is sensible to shut off the heating system for the summer if the heating is not necessary in the building. Also, the dimensioning and controls of the heating system and the settings of the room thermostats affect the achievable heating energy-savings. In the case of an undersized or improperly adjusted heating system, the occupant may have set the room thermostat to a temperature that could not be attained in the flat. Then, part of the savings attained by the installation of balcony glazing are wasted on an increased indoor temperature, so the thermostat should be reset after the installation. (Article II)

### **Glazed space construction materials and material properties**

The absorption coefficient of surfaces has a significant impact on heating energy-savings (key factor (c) in Figure 36), because it determines how much solar radiation energy is stored in the balcony and how much is reflected back to the outside (Figure 58). The impact is clearly visible even with glazing on just one side, but it is even clearer in the case of glazing on several sides. The impact of emissivity is not as high, since the emissivity of the coatings of balcony structures generally used in Finland does not vary as much as the absorption coefficients. As a rule, however, surfaces of high absorption capacity, but low emissivity, should be preferred. (Article II)

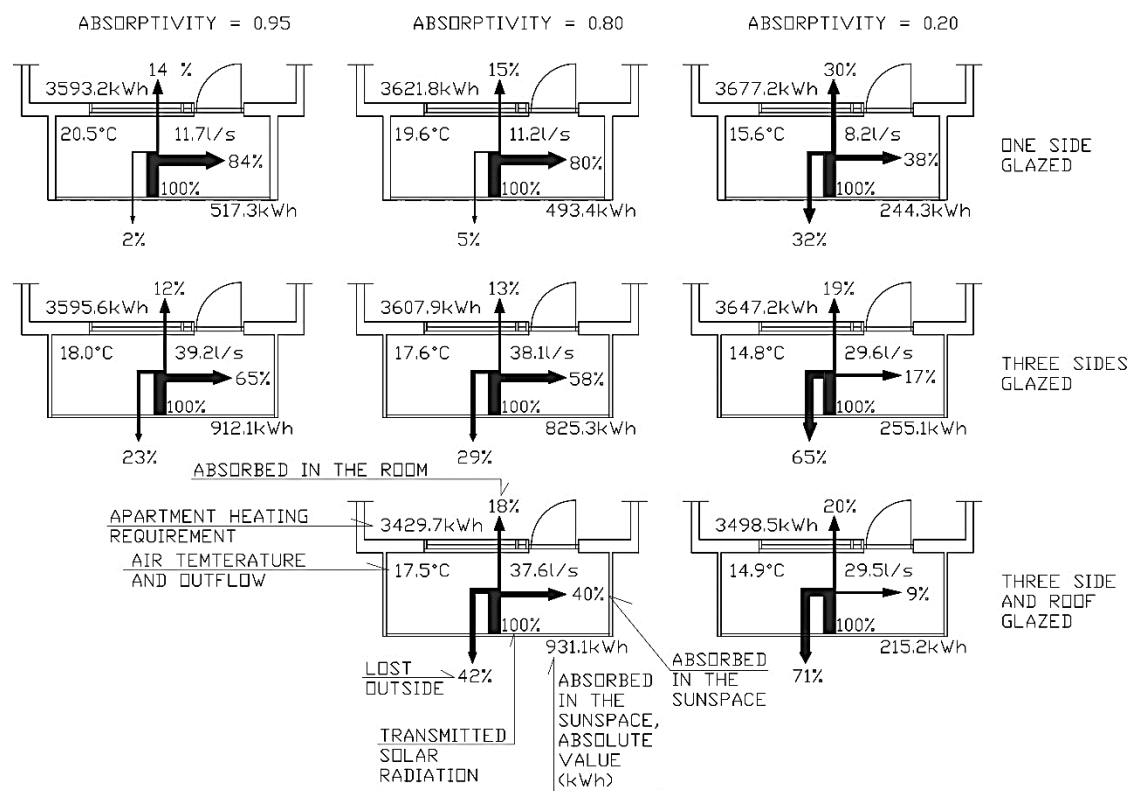


Figure 58. Solar energy absorptivity of a glazed space in relation to the amount of glazing and surface absorption coefficient (Article II).

The density and specific heat capacity of the balcony structures have no impact on the heating energy-savings achieved by glazing, even though the specific heat capacity has a clear effect on the daily temperature variation inside the glazed space. By contrast, the thermal conductivity of the structures has an impact on heating energy-savings because it improves the thermal insulation capacity of the structure. However, the effect is rather modest. (Article II)

### External obstruction and solar shading

In the window blind simulations, blinds were installed on the windows of both the flats and the glass panes of the glazed balconies. The blinds were assumed to be used throughout the year and remain always closed to facilitate the calculations. The results show that window blinds, if installed only to the flat windows, have virtually no impact on heating energy savings, although they increase the total heating energy consumption of the building in the same way an external obstruction does. By contrast, balcony glazing blinds have a large impact on heating energy-savings if they are kept closed for the entire heating season (Figure 59). This is because permanently closed blinds on balcony glazing shield the adjoining flat from solar radiation.



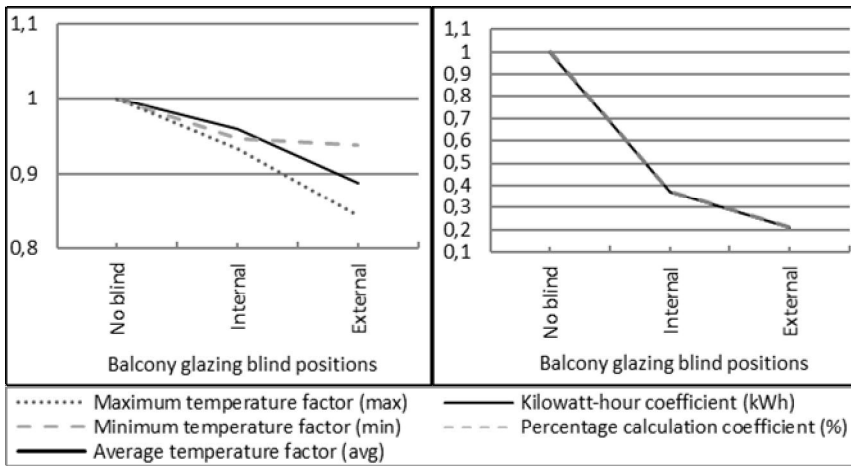


Figure 59. External and internal glazing blind factors for balcony temperatures and heating energy saving effects.

Figure 59 clearly illustrates the blinds' ability to prevent solar radiation penetrating into the glazed balcony. This cooling effect can be increased in summer by airing the balcony through the glazing. Figure 60 gives an estimate of the total cooling effect of a glazed balcony with blinds and airing in use. With a little further calculation, by adding the calculation factors from Figures 59 and 60 to Equation 7, it can easily be demonstrated that overheating problems can be handled with blinds and airing in Nordic climate conditions. (Article II)

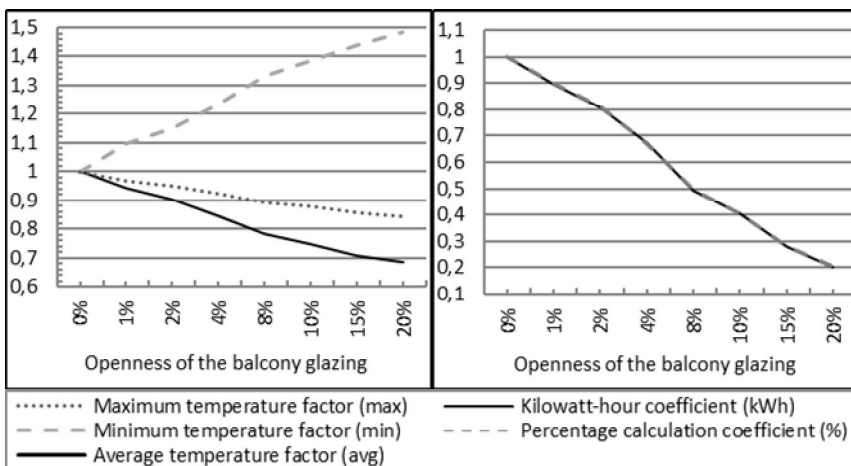


Figure 60. Openness grade factors for balcony temperatures and heating energy saving effect.

## Conclusion

All in all, the sensitivity analysis shows that the assessment of a glazed balcony's energy-saving potential must start from the type (heating or cooling demand) and size of the building's energy needs. If there is a significant heating need in the winter, as there is in Finland, the primary focus of the design is on energy-efficient technical choices for the building itself (the building must be energy efficient) and not the balcony. In such cases, the design of the glazed balcony is subordinate to the overall goal of making the building energy-efficient. This means that the building is first optimized for energy efficiency, before the balcony is designed. The later design phases can focus on the heat balance of a glazed balcony (equation 3) i.e. the relationship between the specific losses (mainly from the balcony to outside) and the specific gain (mainly from the building to the balcony in the winter when there is no solar radiation available). The main parameters for optimizing the specific gain are the properties of the building and the balcony (U-values of the envelope structures, balcony type and size, etc.). There are other factors, such as solar radiation absorption (surface colors, balcony orientation, and the amount of glazing) which also affect to the specific gains. The overall design should also take sun protection into account, even in northern climates. The ideal design solutions for balcony glazing should prevent the overheating problems in the glazed balcony, as this affects both the balcony user's comfort and building's indoor climate. Obviously, this is particularly important in southern climates, or in buildings with high cooling needs.

### 4.3.2 Added glazing study in Malmö

This section presents the results of the added-glazing simulations. The purpose was to identify the key factors which could reduce the energy demand of the building using the various energy-saving measures available. For example, the energy-saving measures may make the cavity space too hot in the summer, which would result in uncomfortably high temperatures in the student flats inside the building. In order to eliminate, or at least reduce this effect, different cavity-cooling options were adopted and their effects were evaluated.

#### 4.3.2.1 Evaluation of the different heating energy saving measures

##### The number of glazed facades

It comes as no surprise that the heating energy savings in the Malmö building were directly related to the amount of glazing. For example, the heating energy saving was 5.6 % with one (south) glazed façade, and 10.4 % with the three (south, west and east) glazed façades together. Interestingly, the average temperature of the cavity space

was highest when only the south side was glazed (6.4 °C), but was lower when three of the building facades were glazed (5.7 °C). In the summer, the temperature in the flat was closely linked to the temperature in the cavity space. Adding the glazing only to the southern side of the building increased the flat's operative temperature by 1.0 °C, from 25.7 °C to 26.7 °C (Flat 1). The temperature rose by a further 0.1 °C when the eastern façade glazing was added (26.8 °C), and by a further 0.1 °C after the western façade glazing was added (26.9 °C). (Article V)

### **Effect of the glazing's U-value**

The thermal insulation level and the g-value of the glazing structures was directly linked with the cavity space temperatures and the temperature of the flats. It was also notable that the highest temperatures in the cavity space and Flat 1 were achieved with the solution that produced the highest heating energy-saving effects. A particularly good approach to choosing the best glazing solution for a whole façade is to look for a low U-value and a high g-value. This design criterion was also found to be beneficial in Article II. In the studied cases, argon filled triple glazing ( $U=1.7 \text{ W/m}^2\text{°C}$  and  $g=0.63$ ), was the optimal heating energy-saving option (22.1 % savings). (Article V)

### **Effect of the cavity depth**

The benefit of an increased cavity depth was not clear. For example, the heating energy-savings with single vertical glazing and double horizontal glazing increased in direct proportion to the depth of the cavity, which meant that solar heat gain grew faster than the space's thermal losses as the depth of the cavity was increased. However, the effect was different with low-energy solar protection glazing ( $U=0.7 \text{ W/m}^2\text{°C}$  and  $g=0.24$ ). The optimum depth with this type of façade glazing was between 0.38 m and 1.5 m. This confirms that the optimum depth is solution-specific. (Article V)

### **Ventilation air supply from the cavity**

The results showed that taking the ventilation supply air from the cavity space was not always clearly beneficial from an energy-efficient point of view. In the case of single clear glazing (the actual implemented solution), taking the ventilation air from the cavity actually increased the heating energy demand by 14 kWh. It seems that the heat recovery efficiency of 82 % in the building ventilation unit was so high that there were only short periods during midwinter when the cavity space's 'extra preheating capacity' was needed. That being so, it seems that it may be better to warm up the incoming air with a heating coil than use cavity air, because using the cavity air has the effect of lowering the cavity temperature (by 0.1 °C during the heating season) which increases the building's conduction losses through the brick wall between the building and the

cavity. This difference, although small in terms of kWh, is interesting. Triple clear glazing, however, ( $U=1.7 \text{ W/m}^2\text{°C}$  and  $g=0.63$ ) decreased the heating energy demand by 38 kWh. These results show that optimizing the use of the cavity air for the ventilation supply air requires more detailed analysis with various glazing solutions, as stated in Article V.

When the heat recovery and the heating coil were shut off, the heating energy demand decreased clearly when the supply air was taken from the cavity. The heating energy demand decreased still further when double or triple glazing were used instead of single glazing. In conclusion, the benefits of using the cavity air for the ventilation system in connection with mechanical exhaust ventilation are strongly confirmed. (Article V)

#### 4.3.2.2 Evaluation of the different cavity cooling measures (summer situation)

All the calculation cases are shown in Figures 61 and 62, and these are discussed in more detail below. Case 1 represents the situation without added glazing, while Cases 24-63 represent different cooling options. (Article V)

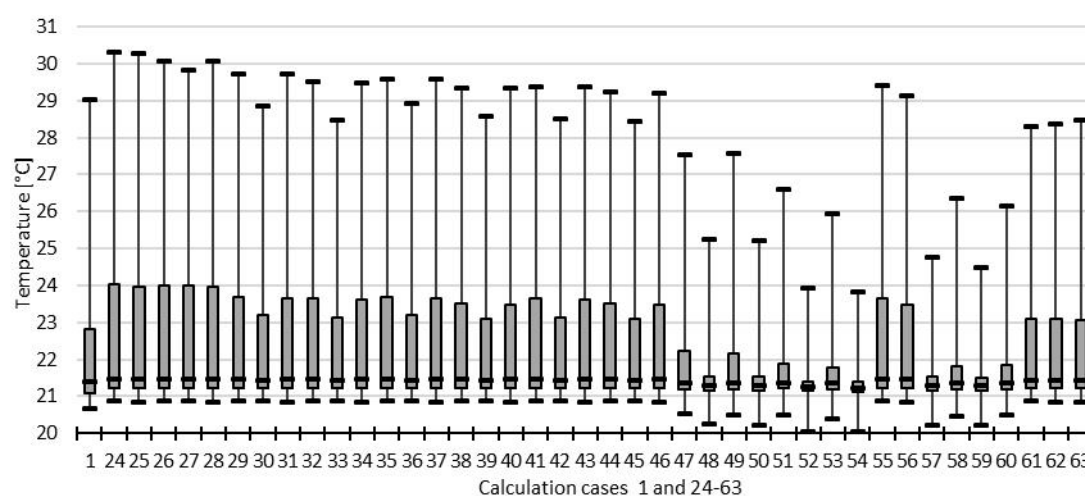


Figure 61. Boxplot graphs from Case 1 (building without added glazing) and the cavity cooling cases 24-63. The horizontal lines represent the minimum, median and maximum values (viewed in that order from the bottom to the top) of the current cases and the grey area is where 50 % of the values were concentrated. (Article V)

The results of the energy-saving studies showed that the mean and operative temperatures in Flat 1 rose during July in the majority of cases. For example, the single glazing added to the building's three facades (Case 4) raised the monthly mean operative temperature by 1.2 °C, double glazing (Case 9) raised it by 3.0 °C, and triple clear glazing (Case 15) by 3.8 °C compared to the case without added glazing (Case 1). A compari-

son of Cases 1 and 46 also shows that the overall temperature situation inside Flat 1 was poorer in summer after the renovation, even though the renovation solution included airing through the two cavity windows, the mechanical exhaust from the south façade's top gable and the air supply through the ground duct system. In the summer, the cooling solution in the Malmö building simply could not cope with the warming effect of the added insulation and the thermal storage effect of the glazing.

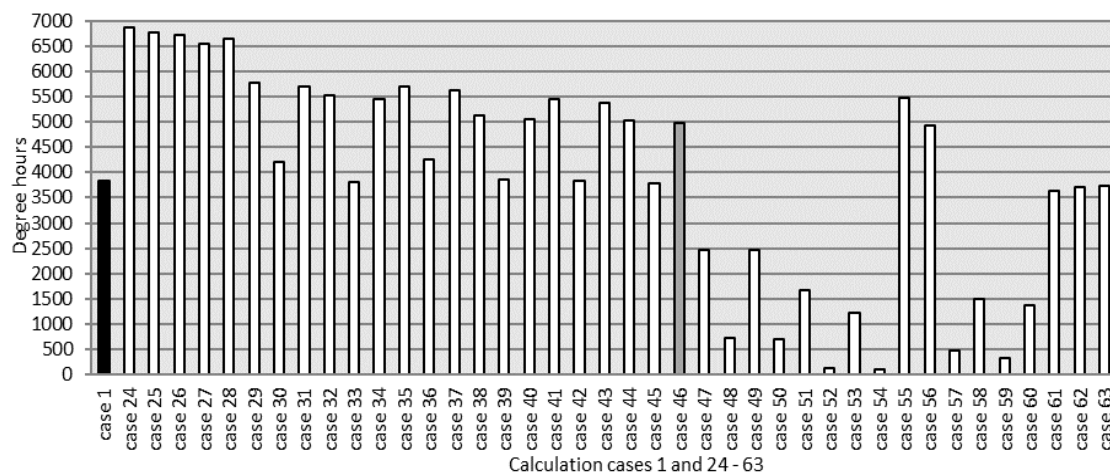


Figure 62. Calculated degree-hours over 23 °C. The degree-hour values are calculated simply by summing up the differences between the actual hourly temperatures and the reference temperature from the moment the temperature is over 23 °C (the reference temperature). (Article V)

### Individual comparisons of the cavity space cooling options

Mechanical cooling with the air supply taken through the ground duct system alone lowered the cavity temperature by 1.1 °C. Opening the vents (windows) at the top of the south cavity lowered it by 0.4 °C, and mechanical cooling with the mechanical exhaust unit lowered the cavity temperature by 1.1 °C. Improvements in each of the individual cavity-cooling methods also had an effect. Increasing the size of the windows from 0.5 m<sup>2</sup> to 1.5 m<sup>2</sup> (Case 27) lowered the cavity temperature by 0.5 °C. Speeding up the mechanical exhaust rate from 150 l/s to 450 l/s (Case 30) and increasing the air supply through the ground duct system from 150 l/s to 450 l/s (Case 33) lowered the cavity temperature by 1.6 °C and 2.7 °C respectively. When the ground duct system with the enhanced ventilation rate (Case 33) was used, the cavity space's mean temperature was 0.6 °C below the 25.5 °C room temperature and the mean operative temperature was 0.2 °C below the base-case operative temperature level. This was the first case which was better than Case 1 (Figures 62) from the overheating point of view. (Article V)

### **The effect of the combined use of cooling methods**

The most efficient combination of the two individual cooling options was a combination of the ground duct system and the mechanical exhaust ventilation with tripled supply and exhaust air flows (Case 39). In this case, the cavity space temperature was 0.4 °C cooler than when using the ground duct system with enhanced ventilation rate alone (Case 33), i.e. the combination of mechanical exhaust and the ground duct system slightly improved the situation inside the cavity. This confirms that it is possible to produce a similar or even better indoor climate for the flats with the actual implemented solution, if the cavity supply and exhaust air volumes were to be tripled. (Article V)

### **Effect of an alternative cooling solution and changing the depth of the ground duct**

The analysis showed that the use of integrated blinds added to the front or back of the glazing to cover the whole glazed façade (Cases 47-54 and Cases 57-60) considerably lowered the indoor temperatures inside the flat. Figure 62 showed that both internal blinds (Case 47), and, in particular, external blinds (Case 48) could give better indoor temperature conditions than the implemented solution (Case 46). This is due to the fact that the blinds shaded the building's external wall and windows very effectively. As said, it is the external blinds, in particular, which seemed to have the most decisive effect on the flat's temperatures. Thanks to these blinds, the cavity space's mean temperature was lowered to 22.7 °C, which is a full 6.0 °C lower than the cavity temperature of Case 24, the case without cooling. In turn, Flat 1's mean operative temperature was 2.8 °C lower than in the case without added glazing (Case 1). With interior blinds (Case 47) the difference was not so great, but still effective. Although the cavity space's temperature only dropped slightly (-0.2 °C) compared to the case without cooling (case 24), the mean operative temperature situation inside the building fell by 1.0 °C compared to case without glazing. This means that, especially if the cavity space is intended to be used as a living area, such as a summer terrace or a conservatory, (which would be possible if the cavity's depth is over 1.5 m), it would be best to use external blinds. (Article V)

The current cooling system could definitely be improved by adding blinds, and further improved by enhancing the ventilation rates, as was done in Cases 53-60. However, the ventilation effects are not nearly as significant for the flat's temperatures as are the blinds themselves. For example, with external blinds alone (Case 48) it is possible to achieve a 22.9 °C mean operative temperature inside the flat (2.8 °C lower than in case 1). Combining this with all the other cooling methods, i.e. enhanced ventilation rates and increased openable window area (Case 54) it was possible to achieve a mean

operative temperature inside Flat 1 of 21.9 °C (still 1.0 °C lower than Case 48). Interestingly, with the external blinds it is possible to achieve 20.3 °C (Case 54), 20.9 °C (Case 59) or 21.8 °C (Case 57). The mean cavity temperature had overheating levels of 94, 323 and 467 degree hours respectively, with a 23 °C overheating criterion (Figure 62). All of these cases represent comfortable living temperatures. There are other external shading cases (cases 48, 50 and 52), which also stand out clearly on the graph (Figure 62). (Article V)

Increasing the depth of the duct from 0.5 m (case 32) to 3.0 m (case 55) decreased the cavity space temperature by 0.2 °C, and the mean operative temperature in Flat 1 by 0.1 °C. By increasing the air volume passing through the deeper-set duct (Case 61) the cavity temperature was lowered by 2.9 °C, which clearly demonstrates that the air-change rate is a much more important factor than the duct depth in this situation. However, it is important to remember that the ground duct system is modeled as an underground rectangular zone group in which the different volumes are connected to each other but with a constant coupling to the ground temperature, i.e. the ground temperature is independent of the depth of the pipe. Changing the depth of the pipe in the simulation model only took into account a U-value calculation of the ground layer between the pipe and the earth's surface (the bottom and vertical sections' U-values were constant). This rather simple model treats the pipe as a number of volumes and does not model the two- (or actually three-) dimensional problem of heat transfer in the ground. Consequently, developing an accurate model of the ground duct system in IDA-ICE appears to be one possibility for follow-up research. (Article V)

## 4.4 The simplified calculation method

### 4.4.1 Accuracy of the method

The analysis showed that the simplified method can profitably be used to demonstrate the energy-saving impact and the mean, maximum and minimum temperatures for different types of glazing solutions during the preliminary design stage. The method is, in principle, intended for calculating the impact of individual glazed balconies during the preliminary design stage. It can be used for all types of glazed balconies and flats in which such calculation factors are involved. The reason for this is that the variables are selected from factors with a high tolerance of variation. Thus, the simplified calculations can reliably predict the energy-saving potential of different glazing solutions, and the effects on the indoor temperatures of the glazed space, in all situations. The accuracy of the method is, however, affected by the number of changes made from the original starting point, which was a typical 1970s apartment block in Finland. Neither does the simplified method take into account the need for, or addition of, a cooling system, as the energy savings only apply to savings in heating energy. (Article IV)

The calculation coefficients were derived by changing the simulation parameters one at a time and by adjusting the results proportionately to those of the base case. The derivation was simplified because all the possible combinations of the 13 balcony variables and the 5 flat variables would have been quite extreme to simulate, since even one simulation is pretty time-consuming. Consequently, the derived factors describe a situation where only one aspect has been changed. Their concatenation in the simplified calculation method will cause error, because some coefficients are dependent on each other. (Article IV)

As a general rule, the simplified method is reasonably reliable if it is not used for comparing balconies with different positions or flats of different sizes but is rather used to optimize the energy performance of a chosen balcony. The systemic error of the method is not too great if the total number of deviations from the base case is less than nine, and there is only one deviation for the flat. If the design includes two deviations from the base-case flat, the total number of changes to the balcony should be limited to seven, and if it has three deviations from the base case, then the balcony should have no more than 5 deviations. The method is more sensitive to deviations from the base-case flat than for the balconies: for instance, if both the flat's size and position deviate, the error is exacerbated if further deviations are made from the base-case balcony. (Article IV)



Although it was not possible to totally eliminate the variables' dependence on each other, the benefits of the simplified method outweigh its drawbacks as it is clear, easy to understand and quick to use. For example, Figures 36–39 show the effects of different variables in a very graphic manner. If they are taken into account in balcony design from the start, the number of changes required to the base case is reduced so that it rarely exceeds seven. In other words, the key factors for estimating heating energy-savings and predicting the interior temperatures of glazed spaces are easy to understand, and this information can be taken advantage of even without calculations. Furthermore, using the simplified method does not require in-depth knowledge of building physics or a deep understanding of the simulation software. Instead, any basically-trained engineer or architect can perform the calculations. This should encourage the use of the method in practical design work, allowing easy energy-engineering for glazed spaces. (Article IV)

#### **4.4.2 Error analysis**

Numerous simulations were carried out during the development of the simplified method. The challenge was to find the most suitable modelling method for the intended purpose. The aim was to make a model in which all changes could be made in such a way that: a) changes to all the parameters of the model are possible, and b) a change in one parameter does not affect the other parameters. Different balcony orientations were also examined (North and South, with or without shading). The practice showed that the calculation coefficients with the south-facing base-case gave the best correlation with respect to the IDA-ICE simulation. As a general rule, in Finland the balconies should face the south, as this is beneficial in terms of energy saving, the indoor climate and the usability of the glazed space. Therefore, the base-case's southern orientation is justified in this regard. (Article IV)

The largest relative errors of the calculation tended to occur in situations where the heating energy-savings were small, while the largest absolute errors occurred in situations where the heating energy-savings were great. In practice, this means that the larger heating energy-savings are underestimated and the smaller savings are overestimated. A similar trend was observed in the temperature results, although it is not as evident. It seems that the accuracy of the method in general is not highly dependent on the number of variables changed, but more likely, the derivation of the coefficients for the simplified method. The most accurate results were obtained in cases that deviated only slightly from the base-case. (Article IV)

#### 4.4.2.1 Balcony deviation

When only allowing deviations for the balconies, the largest error for heating energy-savings occurred in cases that had only three deviations from the base case, while the largest error for the simulated minimum temperatures occurred with five deviations. Major errors arise in situations where either the building's overall heating energy consumption level (e.g. a clearly different location than the base case) or the balcony's heat balance (increased heat loss from balcony to outside, reduced heat loss from flat to balcony and/or reduced solar energy absorption) is significantly different from the base case. In the simplified method, the heat loss level changes are examined separately for windows, doors and back walls, although observing the total heat loss levels would give more accurate results. The multiplied effects of those changes result in higher balcony temperatures than in the simulations. The combined effects can also produce errors when the size or type of balcony, or the U-values of the windows, doors or walls are changed. This is because the proportional changes of U-values are compared to the base model situation, which is a 4 m wide protruding balcony. In recessed balconies, for instance, there is a larger combined area of the flat's exterior walls, so the windows and doors represent a smaller proportion of the total heat losses. The coefficients of the simplified method cannot take these differences into account. Error can also occur if the length of the balcony differs from the base case, but the proportions of the windows and doors do not change in the same proportion. However, recessed or very wide balconies are rather rare in Finland, so the simplified method's reliability is good for most typical cases. In addition, it was necessary to provide the U-values separately for windows, doors and back walls, because these structural parts are often renovated independently of each other. (Article IV)

Variables linked to angle-dependent solar radiation, like the balcony surface absorption coefficient; the balcony orientation; external sun protection or obstruction; and the building's location, are critical. For example, the external shading and balcony orientation is the more critical, the darker the surface, and vice versa. In this case, the change in the exposure to solar radiation (either by external shading or a change of orientation), together with the change in the absorption coefficient, give a slightly distorted result. When it comes to external shading, it should be remembered that the availability of solar energy is also directly dependent on the orientation of the façade. If both factors are taken into account, for example, in a north-oriented recessed balcony case, an error occurs, because they are modelled separately and proportionally to the south-facing balconies in the sensitivity analysis. As a result, their combined effects appear to be greater than they are in reality. Due to this challenge with the assessment of the effect of the external shading and orientation, the simplified method takes shading into account as an optional parameter separated from the basic variables. Additional options

are also shown in Figures 59 and 60, which allow the evaluation of the air movement and glazing blinds to the balcony maximum temperatures in the summer. (Article IV)

Another factor in the method which causes uncertainty is the supply air inlet solution, because its proportional effect with a protruding balcony (base case) is less than that of a recessed or semi-recessed balcony. It would have been possible to rectify this effect with a correction factor, but it has not been done in order to retain the simplicity of the method.

#### **4.4.2.2 Balcony and flat deviation together**

Deviations from the base-case flat's properties do not seem to have major implications for the mean and maximum temperatures, but they do have clear impacts on the percentual and kilowatt-hourly heating energy-savings as well as on minimum temperatures. The results also show that the magnitude of the error is directly proportional to the number of deviations in the flat from the base case. The cases with only one deviation from the base-case flat's variables result in only a minor additional error, but even two and three deviations can noticeably increase the error if the balcony also deviates significantly from that of the base case. On the whole, flat deviations cause larger calculation errors than balcony deviations. (Article IV)

The results also show that some cases already have a lot of error due to the balcony's deviation, but these are even less accurate if the deviations from the base-case flat are added in. In those cases, the systemic error of the calculation method is magnified. Furthermore, the results show that changing the flat's size and the position of the facade simultaneously can also be a major source of uncertainty. In addition, major differences with regard to ventilation (e.g. supply and exhaust ventilation with heat recovery) coupled with significant deviations from the base case's heating energy consumption (e.g. location in Bremen) can cause significant errors in the results. The simplified method may even give them an incorrect ranking if, along with several balcony deviations, two or more changes are made to the flat. Three cases behaved like this. This indicates that the simplified method is not, in principle, designed for comparing the performance of balconies in different parts of the building or for flats of different sizes. However, it is good for optimizing the energy performance of a balcony, when the adjoining flat is already known. In such situations, the simplified method is capable of indicating the correct ranking of different options, even though the results do have some uncertainty. (Article IV)

## 5 Conclusion

### 5.1 Main outcomes of the research

#### Literature review

The literature review showed that in recent years there have been markedly few studies or analyses of the temperature behavior of glazed spaces and their energy-saving potential in the Nordic climate. In addition, those studies that have been carried out have usually been quite narrow in focus, and have rarely dealt with the type of frameless single glazing most commonly used on balconies in Finland. The literature review also reveals that the DSF solutions used so far in Finland and Sweden have not really been optimized either. Because of the above, and the generally poor awareness of the benefits of glazing, the construction techniques and the seasonal use of glazed spaces have not been optimized in terms of their energy-saving potential, or their tendency to cause overheating in summer. Thus, simple tools for assessing the effect of glazed balconies on energy consumption and the indoor climate in residential flats will be of great benefit to the optimal utilization of Finnish housing stock.

The glazed spaces in this study are non-heated outdoor spaces which receive their 'heating' energy from outside. The two primary heat sources are solar radiation energy, and the adjoining building's heat losses. Obviously the intensity of both heat sources varies significantly depending on the time of day and the season. The building's heat losses are the greatest during the coldest days of winter, while the solar radiation is strongest in the summer [19]. According to the literature review, the relationship between the heat losses from the glazed space to the outside and the heat gain from the building to the glazed space (equation 3) are the main factors that determine the temperature level of the space during the winter months at high latitudes [20]. This relationship includes the air leakage through the glazing, which has a marked impact on

the temperature of the glazed space. Ventilation with outdoor air removes a significant proportion of the energy absorbed and consequently lowers the temperature of the sunspace [173].

It is also important that the space is oriented towards the equator ( $\pm 30^\circ$ ) and that dark surface colors with high solar absorption [20] are used. It is also advisable to supply the inlet air through the glazed balcony in winter, and thus use the glazed balcony as a supply air pre-heater, if the building is equipped with a mechanical exhaust ventilation unit or if the building is naturally ventilated [48, 64]. However, if the air supply and the exhaust ventilation unit are linked with an efficient heat-recovery system, then it is more efficient to use that [28]. The absence of shading can lead to overheating problems in rooms adjoining the balcony, and such overheating problems can be intensified if the supply air comes from the glazed space in the summer. However, excessive indoor temperatures can be prevented by using an appropriate solar shading solution [65] and by increasing the airflow (by opening the balcony glazing) [73]. If there is a supply air inlet from the glazed balcony to the flat, it is advisable to shut it off in the summer [62].

Air temperature measurements are a useful method for evaluating the functionality of the passive solar design of a sunspace. They reveal the dominant pathways of heat gain and loss and give an indication of thermal buffer effects and thermal comfort [69, 70]. By combining those measurements with internal and external surface temperature measurement, it is also possible to reveal a structure's ability to store and release heat energy, and to get some kind of indication of the real energy-saving potential of the glazed space. However, several studies have highlighted the difficulty of taking accurate on-site measurements, and this is critical if the measurements are used as an input parameter for simulation software (indirect error) and simulation results compared with monitoring data (direct error) [75]. However, there is no formal and recognized process for calibration simulation [98]. Trial and error seems to be the most common method, so that is what had to be used for this study. The result of this kind of process is highly dependent on the user's skills and judgement [93].

In practice, the purpose, method and level of calibration depends on the intention of the project, the intended use of the model and the user's experience. It also, of course, depends on the budget. The calibration methods can be classified into the following four main categories [102]: 1) manual, iterative and pragmatic approaches; 2) graphical-based methods; 3) special test and analysis procedures; and 4) automated analytical and mathematical approaches. It is also essential to define the level of calibration needed right at the beginning of the calibration simulation study (Table 2). It is also vital to verify that the available building information is adequate for the current purpose. Once the calibration level has been defined, to the researcher should define possible

error sources and carry out an uncertainty analysis. According to the Heo [109], four main categories for uncertainties are scenario uncertainty, the building's physical/operational uncertainty, model inadequacies and observation errors (Table 3). These error sources have been evaluated in this study according to criteria in the ASHRAE Guidelines 14 [116] for building-energy simulation models (Articles I and V) (Table 4).

There are many whole-building simulation tools available on the market. One of these tools is IDA-ICE software, which has previously been validated by many accepted validation procedures. Here, its suitability for evaluating the key physical phenomena occurring in a glazed space are evaluated. Due to the proven accuracy of the software, its user-friendly interface and continuous development with Finnish technical support (developed and maintained by EQUA Simulation AB [176]), the IDA-ICE was the natural choice to be used as an analysis tool in this thesis. The IDA ICE symbolic equation structure provides a relatively easy way to extend the existing model's functionality [129] and the software can be used, for example, for complex ventilation control systems, as described in article V. The selection of IDA-ICE as the simulation tool for this study is well grounded.

### **Monitoring studies**

The monitored results of 22 balconies showed that the temperature of both glazed and unglazed balconies is above the outdoor temperature almost throughout the year. On average, the temperature of the unglazed balcony was 2.0 °C higher, and that of the glazed balcony 5.0 °C higher than outdoors. Overall, the temperature difference between a glazed balcony and the outdoor air ranged from -5.8 °C to 29.6 °C during the measurement period. The cooler balcony temperature occurred for a brief period when there was a rapid increase in the outdoor temperature in winter (balcony 7), to which the balcony with concrete structures reacted after a short delay. The dramatically higher balcony temperatures occurred after a period of very intense solar radiation in spring (balcony 3). It was also noticed that in some balconies the temperatures exceeded 20 °C for the first time in early March, and for the last time in mid-October. On average, glazed balcony temperatures exceeded 20 °C from mid-April to mid-September and unglazed balcony temperatures from mid-May to mid-September. This shows that the average usage time of glazed balconies exceeds that of unglazed balconies by a more than a month, while in the best case scenario this could be 2.5 months.

Based on temperature differences, balcony glazing had a significant influence on the structure's heat loss on the balcony side. Heat loss through the balcony window decreased by 22%, through the balcony door by 15 %, and through the balcony wall by

18 %. In the mid-winter, the decrease in heat loss for glazed balconies was lower, but still significant: balcony window, 18 to 19 %; balcony door, 10 %; and the balcony wall, 17 to 18 %. The impact of solar radiation can be seen from the monthly balcony window energy savings. In March, the heat losses of the balcony window of a flat with a glazed balcony were 23%, in April 25%, and in May 34% lower than from the flat with the unglazed balcony.

The lowered heat losses have a direct impact on the flat's indoor temperatures. On average, flats with glazed balconies were 0.5 °C cooler than flats with unglazed balconies. The temperature difference was lowest in July-August, and greatest in March. The average temperature difference of flats with glazed and unglazed balconies was 0.4 °C in autumn and to 0.6 °C in spring. The temperature difference between the flats increased as the temperature difference between glazed and unglazed balconies increased, and vice versa. It can thus be said that balcony glazing reduces a flat's heat losses and reduces the temperature in the adjacent room by 0.5-1.0 °C, with no loss in thermal comfort. The reduction in heat losses and the lower indoors temperature result in energy savings.

The field monitoring results showed that the main factors affecting the balconies' indoor temperatures seem to be the air-tightness of the glazing, the solar absorption, and the building's heat losses, in that order. Air-tightness was the most crucial factor since it affected the results all year round. Solar radiation was significant only in spring, summer, and autumn because of Finland's high latitude. The heat loss from the building to the balcony was most relevant in mid-winter, when the difference in temperature between the building and the outdoors could be as high as 60 °C. In mid-winter, a glazed balcony (as opposed to an unglazed one) brings the benefit of being able to store the heat loss from the building inside the balcony.

The use of balcony glazing also had a significant influence on the glazed balcony's indoor temperatures. For example, in the case of balconies 1 and 14, the balcony glazing was either kept closed (balcony 1) or one pane was permanently open (balcony 14). The open pane lowered the balcony's indoor temperature by 50 %. On the other hand, the study also suggests that on balconies where one glass pane is kept open, the temperatures are still higher than they are on unglazed balconies in both the winter (energy saving) and the summer (overheating). For the most efficient ventilation of a glazed balcony in the summer, more than one pane or panes on several sides should be opened.

The temperature difference between the cavity space and outside was higher in the Malmö case building than in any of the Finnish balconies. The main reason for this was

the glazing's air-tightness, which was significantly better in Malmö than it was on the Finnish glazed balconies. It is also worth noting that a carefully-designed glazed space will warm up easily when exposed to solar radiation and may consequently adversely impact on the adjacent living space's thermal comfort in summer time. However, this problem can be solved by increasing the air flow of the cavity space and/or adding new window blinds to the front or back of the glazing.

The study showed that the influence of balcony glazing is more significant in recessed balconies than in protruding ones because the former gain more from the building's heat losses, and lose less heat to the outside through the leaky glazing structures (Figure 8). It was also observed that the higher the energy-saving effect of the glazing, the greater the total heat loss reduction of the balcony door, window and back wall, which suggests it would be best to glaze the older Finnish balconies whose buildings generally have higher heat losses, than new buildings. The studies also showed that the biggest difference between glazed balcony temperatures was caused by the air tightness of the glazing, which varied considerably, particularly with regard to the balustrades (Figure 54). As a consequence, reducing the air gap is the primary energy-saving measure for existing glazed balconies. Another cost-effective action is to re-paint the balcony's inner surfaces in order to increase the balcony's absorption of solar radiation. Because of the lack of structural air-tightness in balcony glazing solutions, less attention needs to be paid to the properties of the glazing itself - particularly in the case of protruding balconies. However, if there are plans to improve the properties of the glazing, e.g. in connection with double skin facades or recessed balconies, then a good overall solution can be achieved with a low U-value and a high-g value (Articles II and V). In designing new constructions, the measurements should be more comprehensive, for example, by using the simple calculation method.

### **Simulation accuracy**

In the beginning of the simulation study, different error sources such as scenario error, the building's physical/operational uncertainty, model inadequacy and observation error were analyzed, and the modeling method was developed by trial and error. Scenario error included errors about the outdoor weather conditions and the building's usage and/or occupancy schedules. Building physical/operational uncertainty analyses included errors in estimation of the building envelope's properties, internal gains and HVAC systems, as well as operation and control set-points. Model inadequacy included errors in the modeling assumptions and in the simplifications of the model algorithm. The observation error was the final phase, and included an estimation of the metered data's accuracy.



Despite the many uncertainties, most of the sensors (18/20) in the glazed balconies fulfilled the ASHRAE calibration criteria for MBE and CV(MRSE) in the simulation. The sensors outside the calibration criteria (sensors 112 and 204) were both external surface sensors and placed on the lower part of the structures (exposed to the solar radiation). Nonetheless, the glazed balcony, and the adjoining flat's surface temperatures correlated really strongly with the simulated values; the correlation with the external surface temperatures was  $\geq 0.97$  and with the internal surfaces it was  $\geq 0.91$ . The 'goodness of fit' of the monitored balcony data and the simulated glazed balcony and their respective flat surface temperatures was good overall, and the model can be regarded as a 'calibrated model'. When looking at the results from the Malmö case study as a whole, it can be also said that calibration results are good, because 83 % (10/12) of the surface temperatures sensors fulfill the ASHRAE calibration criteria for MBE and CV(RMSE), as do 67 % (8/12) of the cavity mean air temperature sensors. In this regard, it can be concluded that the monitoring sensors on the whole are more indicative of the external surface temperature of the brick wall than the cavity air temperature. The 83 % fulfillment also confirms that the model can be considered as a 'calibrated model' and the results are reliable for further analysis.

The literature review suggest that the most accurate results can be achieved by using detailed window and zone models. However, it was found that the difference between modeling methods does not have much influence in practice. This is because of at least the following two factors; 1) the glazed balcony contains so little glazing on only one side of the balcony that the simple window and zone model are capable of producing as reliable results as the detailed window and zone model and 2) there is so much uncertainty in the model that the difference between model algorithms is 'missed' among all the other uncertainties. However, the validation studies (Table 6) do indicate that the use of detailed models is recommended and this should be taken as a starting point for further studies.

The errors and uncertainties in the monitoring and in the simulations can greatly affect the simulation results. Detailed input data and robust calibration procedures for the simulation are an essential part of any computational studies, because the wrong input parameters or inadequate calibration procedures can easily skew the results more than the choice of modelling method. The most critical parameters in the glazed space simulations were solar radiation and the window model, the longwave radiation exchange in and between the zones, the internal convection heat transfer, the air flow modelling in the cavity and the effects of the wind forces on it.

## Glazed balcony simulations

Extensive sensitivity analyses of the glazed balcony energy-saving potential with different balcony and flat properties showed that achieving heating energy-savings in practice depends not only on the glazed space features, but also the flat's HVAC-system, its set-points, and the inhabitants' behaviour. Some of the 156 parameters tested had a very significant impact on the energy savings, but there were also factors whose effect is hardly visible. In addition, a number of variables are related to the same physical phenomenon and are therefore linked with each other. For example, the balcony size (variable 12), balcony type (variable 11) and the U-values of the building envelope structures (variables 8, 9 and 10) all affect the conduction heat-loss level of the building. Of these, the total significance of the building envelope structures is the sum of the window, door and wall's significances ( $34\% + 25\% + 6\% = 85\%$ ). This alone is a very important variable, regardless of the balcony's type and size. Heat losses from the balcony to outside (variable 14) are subject to the same phenomenon, as equation 3 clearly points out. It is the twelfth variable in the list of most important single variables in this study (Table 32).

Other very significant factors are sun protection (blind in balcony glazing or window), the location of the building and the tightness of the balcony glazing, tightness (openness of the balcony glazing panes). Of these parameters, the sun protection is also affected by the variable 'balcony façade distance from the building in front', as this also shades the building. By the same token, the balcony glazing tightness is linked to 'unintended ventilation rate through balcony glazing'. Regarding the external obstruction or shading, it should be remembered that the solar blinds (variable 34) can be mounted on the balcony glazing or the flat windows, i.e. shading only the glazed balcony or the adjoining flat. Exterior shading (variable 4), on the other hand, shadows the entire building i.e. it affects all the balconies, glazed or not. Balcony tightness (variable 2) is actually the most important parameter in Table 32, because it can mean that the energy-saving effect totally disappears (all panes open). The location of the building (variable 1) is also an important factor in terms of the building's heating needs, (a flat in Barcelona needs less heat than a flat in Sodankylä) but the location can also increase the cooling demands of the building, in which case the importance of sun protection greater (variable 34).

The characteristics of the building and its ventilation system also have a large impact on energy savings. This is observed with variable 20 (Supply air intake solution) and variable 19 (Building type ventilation (air change rate)), which were the fourth and the sixth most significant individual variables in the review (Table 32). Of these, the former has a direct impact on the supply air preheating, while the latter has an impact on the

total energy consumption of the building. A flat's energy consumption is also affected by its size and its position in the building (balcony horizontal and vertical position of the building). These were the tenth, sixth and seventh most significant variables, respectively.

Another important factor is the storage of solar radiation in the balcony structures. Here, the key factors are surface coloring (variable 32), balcony orientation (variable 2) and the amount of glazing in the balcony (variable 13). These were the eighth, twenty-first and twenty-sixth most significant variables, respectively. Other factors, like the heating system (variables 24, 27 and 28) and its control (variables 25 and 26) as well as the flat's indoor temperature (variable 6) and its internal heat loads (variable 7) are not directly related to the energy-saving potential of balcony glazing. However, they do affect the energy-saving potential, and its relative importance in a building's energy use. Nevertheless, for the sake of simplicity, these variables are mostly ignored in the simple calculations (Article IV).

All in all, the sensitivity analysis showed that when assessing a glazed balcony's energy-saving potential, the starting point is always the size and type of the building's energy needs (heating or cooling demand). If there is a significant heating need in the winter, the primary focus of the design is to make the right energy-technical choices needed to design an energy-efficient building. The design of the glazed balcony must support this overall goal, which means in practice that the building is first optimized, and then the balcony. In the later design phase, the heat balance of the glazed balcony can be taken into account (equation 3) i.e. the relationship between the specific losses (mainly from the balcony to outside) and the specific gain (mainly from the building to the balcony in mid-winter). The main parameters for optimizing the specific gain are the building and balcony properties (balcony type and size, U-values of the envelope structures, etc.). There are other, external factors to consider, such as solar radiation absorption (surface colors, balcony orientation and the amount of glazing). The parameters, which affect the specific losses are mainly the U-values of the balcony structures and the overall tightness of balcony glazing itself. The overall design should also take into account sun protection in all climates, so the design solutions should avoid overheating problems inside the balcony and their effects on the building's indoor climate. This is particularly important in a southern climate and in cooled buildings.

### **Added glazing simulations**

The comparative studies in Malmö support the results from the glazed balconies in Tampere. The factors that have a significant influence on the heating energy demands of a building lie in the extent of the added glazing and its U-values and g-values, includ-

ing the values of any other features which are added to the building. The study also showed that if there is no heat recovery, e.g. a mechanical exhaust ventilation system, then it is best to pass the outdoor air through the cavity before supplying it to the building. However, if there is an efficient heat recovery system (>80 %), the effect is not so clear. The U-value and the g-value of the glazing seemed to influence the outcome. The results indicate that any combination of the U-value, the g-value and the ventilation solution should be carefully examined by simulations in the design stage.

It can also be concluded that the factors that have a significant influence on the thermal indoor climate during summer (the cooling season) are, in order of importance: external and internal shading of the cavity, a ground duct system with a fan which cools the outdoor air before supplying it to the cavity, an exhaust fan extracting the air from the cavity, and the amount of air flow in these systems.

The added glazing inhibited the building's ability to achieve sufficiently cool indoor temperatures, despite the fact that the cavity space was cooled with two openable windows, and there was mechanical exhaust ventilation and a ground duct system. However, by increasing the ventilation rate above the designed values, satisfying pleasant level of thermal comfort can be achieved. In the summer, a lower indoor temperature than before the renovation can be achieved if the air flow is increased above its current design value. This fact illustrates that simulations during the design phase can be very worthwhile. The application of several technical measures and ventilation strategies at the same time creates a complex situation which is difficult to predict in the design phase, i.e. which air flows and ventilation strategies will be the most efficient, etc? The results of this study clearly illustrate how complex a process this is. They also support the view that it's an important part of the design stage of a building project to be able to model such a complexly-controlled building with dynamic software, in order to optimize the installed systems.

In summary, it can be said that the addition of glazing in front of the brick wall reduced the heating energy demand of the building. As the temperature in the cavity was higher than the outdoor temperature, this implies that the old brick wall will now be in a warmer environment during the winter, which will have associated benefits, such as reducing the risk of freeze-thaw damage. Although the extra glazing may cause problems indoors during the summertime in terms of keeping the place cool and well-aired, it is possible to solve this by increasing the air-change rates of the cavity exhaust unit and ground duct air-supply unit. It should also be noted that the cooling solutions which can create sufficiently low indoor temperature in summertime are, to a great extent, sustainable. The shading is passive, and although the ground duct and exhaust systems

are not totally passive, no active cooling energy is needed, as opposed to air-conditioning units.

### **Simplified calculations**

It is possible to evaluate the energy-saving potential and interior temperatures of the glazed spaces with the simplified calculation method introduced in this thesis. As a result of the pre-selected variables and their pre-calculated coefficients, the method is quick and easy to use. With a few hours instruction, any architect or structural engineer can internalise the method and take advantage of it in their daily work. It is not even necessary to actually do the calculations; the user can learn a lot about the savings in heating energy and the interior temperature when designing glazed spaces simply by looking at the relevant factors in Figures 36-39, and by utilizing this knowledge in the preliminary design.

With regard to the method's accuracy, the most significant factor is not the number of deviations, but how extensive they are in comparison to the base-case. The systemic error of the method is not too great if the total number of deviations is less than nine and there is only one deviation for the flat. If the design includes two deviations from the base-case flat, the total number of changes to the balcony should be limited to seven, and if it has three deviations from the base case, then the balcony should have no more than 5 deviations. The accuracy of the method is best in Finland and in other similar climatic conditions, since the base-case is based on Finnish construction methods and Finland's northern location and climate. The method is more sensitive to deviations from the base-case flat than for the balconies.

## **5.2 The need for further research**

### **Model development**

The challenges, when doing the IDA-ICE modelling in this study, were that the current software package did not include the possibility to connect an adjacent zone to the ventilation unit (air supply from the cavity) nor any model to handle an existing ground duct system. This meant that the air supply through the cavity was modelled by placing an extra exhaust ventilation unit inside the cavity space and connecting it to the attic ventilation unit. The ground duct system, in turn, was modelled as nine small underground zones connected to each other. By doing this, the real impact of the systems could be treated to some degree. Nevertheless, the development of a more detailed ground duct model for the IDA-ICE is a possibility for a follow-up research topic.

### **Field monitoring**

The air-tightness of the balcony, the solar energy absorption and the building's heat losses, in that order, seem to be the most critical factors for the interior temperatures of the glazed space. However, the impact of these factors could not be analysed further in practice, because detailed air and surface temperature measurements with solar radiation, heat flux and air flow monitoring were not performed on any of the balconies. A follow-up research topic using the aforementioned monitoring arrangement could be, for example, the effect the amount of air leakage paths and their locations would have on the balcony's interior temperatures in different climate conditions. Another area for investigation is the heat flux through the external window, door and wall at different times of the year, as well as the behaviour of the air supply through the glazed balcony in connection with mechanical or natural ventilation. In choosing a site for the field measurements, it would be preferable to select an easily-controllable site without external trees, inhabitants or other difficult-to-control variables. Avoiding these uncertainties also helps in the creation of a simulation model, and in improving its reliability.

### **Computer simulations**

The characteristics of typical balcony typologies whose main flaws could be improved through glazing, or the features of optimized typologies for different purposes would be good topics for further simulations. In order to facilitate the design work in practice, the most typical and optimized balcony typologies would further explain the key factors affecting the space's interior temperatures and heating energy-saving effects, thus facilitating the design work in practice.

With the calibrated simulation model it is also possible to analyse the effects of different ventilation control strategies on glazed spaces, and to try to find the optimal operating modes for the ventilation systems in different seasons. Such an analysis could be conducted with the thermal insulation and g-value analysis of the added glazing, thereby optimizing the whole installation.

### **The simplified method**

The development of a simple, off-the-shelf method for energy-impact assessments that would otherwise require time-consuming and expensive measurements or complicated simulations is, in general, considered welcome among architects. Apart from its scientific value, the contribution of such an approach is the use of the research results in practice. Therefore, further development of the simplified calculation method is recommended. One option is to make a simple computer program based on the method.

The independence of the variables in the model is a major issue in relation to the model's accuracy. That is why a systematic determination of which parameters might be interdependent, and how, would be useful. Furthermore, extending the analysis to different types of base-cases in different climatic conditions and conducting a real correlation analysis of the interdependency (or not) of the variables in those situations could increase confidence in the reliability of the method in practice, and increase its scientific value.

## References

- [1] M. Seppänen, T. Koivu (ed.), BES: tutkimus avoimen elementtijärjestelmän kehittämiseksi (Development of open concrete element system), Lahti, 1969, 89 p. (in Finnish).
- [2] T. Kaasalainen, S. Huuhka, The homogenous homes of Finland: 'Standard' flats in non-standardized blocks, *Build. Res. Inf.* 44 (2015) 229-247.
- [3] S. Huuhka, T. Kaasalainen, J.H. Hakanen, J. Lahdensivu, Reusing panels from building for building: Potential in Finnish 1970s mass housing, *Resour. Conserv. Recycl.* 101 (2015) 105-121.
- [4] H. Achrén, Asunnon julkinen huone: Joustavuutta lähiöasumiseen (Public rooms of private flats: More flexibility for mass housing), Publication 2, Tampere University of Technology, Tampere, 2015, 100 p. Available from <http://urn.fi/URN:NBN:fi:tyy-201505061259>
- [5] P. Neuvonen (ed.), Kerrostalot 1880-2000 (Block of flats from 1880–2000), first ed., Rakennustieto Oy, Helsinki, 2006, 288 p. (in Finnish).
- [6] Official Statistics of Finland (OSF): Buildings and free-time residences, Statistics Finland, Helsinki. Available from [http://www.tilastokeskus.fi/til/rakke/tau\\_en.html](http://www.tilastokeskus.fi/til/rakke/tau_en.html) (Accessed 24.9.2014)
- [7] S. Boström, U. Uotila, S. Linne, K. Hilliaho, J. Lahdensivu, Erialaisten korjaustoimien vaikutuksia lähiökerrostalojen todelliseen energian kulutukseen (The Effects of Different Renovation Measures on the Energy Consumption of Suburban Block of Flats), Research report 158, Tampere University of Technology, Tampere, 2012, 77 p. (in Finnish).
- [8] J. Lahdensivu, Durability Properties and Actual Deterioration of Finnish Concrete Facades and Balconies, TUT Publ. 1028 (PhD thesis), Tampere University of Technology, Tampere, 2012, 117 p.
- [9] J. Lahdensivu, S. Varjonen, A. Köliö, Betonijulkisivujen korjausstrategiat (Repair strategies of concrete facades and balconies), Research report 148, Tampere University of Technology, Tampere, 2010, 79 p. (in Finnish) .
- [10] E. Mäkiö (ed.), Kerrostalot 1960 – 1975 (Block of flats from 1960–1975), first ed., Rakennustieto Oy, Helsinki, 1994, 271 p. (in Finnish).



- [11] I. Kummala, Parvekerakentamisen nykytila Suomessa (Present state of balcony construction in Finland), Bachelor's thesis, Tampere University of Technology, Tampere, 2014, 33 p. (in Finnish).
- [12] A. Puukko, Parvekkeiden ja terassien auringonsuojusratkaisut – tuotteet ja niiden tekniset ominaisuudet (Solutions for the sun protection of balconies and patios – products and their technical features), Bachelor's thesis, Tampere University of Technology, Tampere, 2016, 31 p. (in Finnish).
- [13] J. S. Mattila, Effect of balcony glazing on the durability of concrete structures in Nordic climate, in: Proceedings of Sustainable Construction, Materials and Practice Conference, Portugal, 2007.
- [14] Official Statistics of Finland (OSF): Buildings and free-time residences, Statistics Finland, Helsinki, 2012, Available from [http://www.stat.fi/til/rakke/2012/rakke\\_2012\\_2013-05-24\\_kat\\_002\\_en.html](http://www.stat.fi/til/rakke/2012/rakke_2012_2013-05-24_kat_002_en.html) (Accessed 9.10.2015)
- [15] Lumon 5 Balcony Glazing: Technical manual, Lumon Oy, Kouvola, 2008, 40 p. Available from <http://www.idex.is/wp-content/uploads/2013/06/lumon5-balcony.pdf>.
- [16] O.B. Jørgensen, O.J. Hendriksen, Glazed balconies and sun spaces – energy savers or energy wasters?, in: Proceedings of the third ISES Europe Solar Congress (Eurosun2000), Copenhagen, 2000.
- [17] Ympäristöopas 72: Kerrosalan laskeminen (Environment guides 72: Calculation of gross floor area), Ministry of the Environment, Helsinki, 2000, 35 p. (in Finnish).
- [18] J. Heikkilä, Parveke suomalaisen kerrostalon asuntokohtaisena ulkotilana (Balcony as an outdoor space in Finnish apartment buildings), Acta Univ. Oul. C91 (PhD thesis), University of Oulu, Oulu, 1996, 300 p. (in Finnish).
- [19] K. Hilliaho, Parvekelasituksen energiataloudelliset vaikutukset (Energy saving effects of the balcony glazing), Master of Science Thesis, Tampere University of Technology, Tampere, 2010, 147 p. (in Finnish).
- [20] M. Wall, Climate and Energy Use in Glazed Spaces, Report no TABK-96/1009 (PhD thesis), Lund University, Lund, 1996, 404 p.

- [21] A. Fallahi, F. Haghghat, H. Elsadi, Energy performance assessment of double-skin façade with thermal mass, *Energy Build.* 42 (2010) 1499-1509.
- [22] W. Oesterle, E. Lieb, R-D. Lutz, M. Heusler, *Double skin facades: Integrated planning*, Prestel, Munich, 2001, 208 p.
- [23] A.L.S. Chan, T.T. Chow, K.F. Fong, Z. Lin, Investigation on energy performance of double skin façade in Hong Kong, *Energy Build.* 41 (11) (2009) 1135-1142.
- [24] H. Poirazis, *Double skin facades for office buildings: a literature review*, A report of IEA SHC Task 34 ECBCS Annex 43, Lund University, Lund, 2006, 247 p.
- [25] W. Ding, Y. Hasemi, T. Yamada, Natural ventilation performance of a double-skin façade with a solar chimney, *Energy Build.* 37 (4) (2005) 411-418.
- [26] G. Ballestini, M. De Carli, N. Masiero, G. Tombola, Possibilities and limitations of natural ventilation in restored industrial archaeology buildings with a double-skin façade in Mediterranean climates, *Build. Environ.* 40 (2005) 983-995.
- [27] L.R. Arons, D.M.M. Glicksman, *Double skin, airflow facades: Will the popular European model work in the USA?* In: *Proceedings of the International Conference on Building Envelopes Systems and Technologies (ICBEST)*, Ottawa, 2001.
- [28] R. Hoseggen, B.J. Wachenfeldt, S.O. Hanssen, Building simulation as an assisting tool in decision making, Case study: With or without a double-skin façade?, *Energy Build.* 40 (2008) 821-827.
- [29] W.J. Stec, A.H.C. van Paassen, Symbiosis of the double-skin façade with HVAC system, *Energy Build.* 37 (2004) 461-469.
- [30] D. Saelens, J. Carmeliet, H. Hens, Energy performance assessment of multiple skin facades, *International Journal of HVAC&R Research* 9 (2) (2003) 167-186.
- [31] J.H. Yoon, E.J. Lee, J. Hensen, Integrated thermal analysis of a three story experimental building with a double-skin and a ground-coupled heat exchanger, In: *Proceedings of International Solar Energy Conference (SOLAR 97)*, Washington, 1997.
- [32] W. Lou, M. Huang, M. Zhang, N. Lin, Experimental and zonal modeling for wind pressures on double-skin facades of a tall building, *Energy Build.* 54 (2012) 179-191.

- [33] C.A. Heusler, Multiple-skin facades, *Fassade façade* 1 (1998) 15-21.
- [34] H. Poirazis, Single and double skin glazed office buildings: analyses of energy use and indoor climate, Report EBD-T--08/8 (PhD thesis), Lund University, Lund, 2008, 405 p.
- [35] S.F. Larsen, L. Rengifo, C. Filippin, Double skin glazed facades in sunny Mediterranean climates, *Energy Build.* 102 (2015) 18-31.
- [36] S.F. Corgati, M. Perino, V. Serra, Experimental assessment of the performance of an active transparent façade during actual operation conditions, *Sol. Energy* 81 (2007) 933-1013.
- [37] N. Hashemi, R. Fayaz, M. Sarshar, Thermal behavior of a ventilated double skin façade in hot arid climate, *Energy Build.* 42 (2010) 1823-1832.
- [38] T. Pasquay, Natural ventilation in high-rise buildings with double facades, saving or waste of energy, *Energy Build.* 36 (2004) 381-389.
- [39] A. Ghaffarianhoseini, U. Berardi, J. Tookey, D. H. W. Li, S. Kariminia, Exploring the advantages and challenges of double-skin façades (DSFs), *Renew. Sustain. Energy Rev.* 60 (2016) 1052-1065.
- [40] J. Hix, *The Glass House*, Phaidon Press Ltd, London, 1974, 240 p.
- [41] N. Pevsner, *A History of Building Types*, The Architectural Press Ltd, London, 1976, 352 p.
- [42] R. Saxon, *Atrium Buildings: Development and Design*, The Architectural Press Ltd, London, 1983, 182 p.
- [43] P. Aro, T. Tuononen, S. Åkerblom, *Palvelutalojen parvekkeet (The balconies of serviced flats)*, Research Institute for Health Care Facilities (Sotera) and Helsinki University of technology, Espoo, 2006, 76 p. (in Finnish)
- [44] VTT, *Putaan vuokratulojen perusparannuskokeilu (The renovation survey of Putaa rental apartments)*, VTT Technical Research Centre of Finland Ltd, Turku, 1989, 43 p. (in Finnish)
- [45] *Suunnitteluopas: Keskeisiä tavoitteita valtion tukemien asuntojen suunnittelulle (Desing guide: The key objectives of the government subsidised dwellings de-*

- sign), The Housing Finance and Development Centre of Finland (Ara), 2015, 22 p. (in Finnish)
- [46] E. Erkiö, A. Melajärvi, Parvekelasitusten energiataloudelliset ja kaupunkikuvalliset näkymät (Balcony glazing systems from the view point of energy economy and cityscape), *Lasirakentaja* 3 (1994) 23 - 27 (in Finnish).
- [47] V. Bokalders, M. Block, *Byggekologi 2: Att husshålla med resurser (Building Ecology 2: To save resources)*, AB Svensk Byggtjänst, Stockholm, 1997, 197 p. (in Swedish).
- [48] K. Voss, Solar energy in building renovation – results and experience of international demonstration buildings, *Energy Build.* 32 (3) (2000) 291 - 302.
- [49] J.-O. Dalenbäck, Solar energy in building renovation, *Energy Build.* 24 (1996), 39 - 50.
- [50] Lasitettu parveke ja lasitettu terassi asuinrakennuksessa (Glazed balcony and glazed terrace at residential building), yhtenäiset käytännöt (common practices), ARK05A, Rakennusvalvonta Helsinki-Espoo-Vantaa-Kauniainen (The building control commissions of Helsinki, Espoo, Vantaa and Kauniainen), 2015, 2 p. Available from [http://www.pksrava.fi/asp2/tulkintoja\\_print.aspx?s=32](http://www.pksrava.fi/asp2/tulkintoja_print.aspx?s=32). (in Finnish)
- [51] Asuntokohtaisen lasitetun parvekkeen osastointi, yhtenäiset käytännöt (common practices), E1-701, Rakennusvalvonta Helsinki-Espoo-Vantaa-Kauniainen (The building control commissions of Helsinki, Espoo, Vantaa and Kauniainen), 2009, 1 p. Available from [http://www.pksrava.fi/asp2/tulkintoja\\_print.aspx?s=32](http://www.pksrava.fi/asp2/tulkintoja_print.aspx?s=32). (in Finnish)
- [52] O. Kalyanova, *Double-Skin Façade: Modelling and Experimental Investigations of Thermal Performance*, PhD Thesis, Aalborg University, Aalborg, 2008, 212 p.
- [53] D. Saelens, *Energy Performance Assessments of Single Storey Multiple-Skin Facades*, PhD Thesis, Catholic University of Leuven, Leuven, 2002, 272 p.
- [54] A.H. Abdullah, Q.Meng, L. Zhao, F. Wang, Field study on indoor thermal environment in an atrium in tropical climates, *Build. Environ.* 44 (2) (2009), 431-436.
- [55] S.T. Elias-Ozkan, F. Summers, Ö. Taner, Energy efficiency of building with a solar space: two case studies from the Anatolian plateau, In: *Proceedings of the International 26<sup>th</sup> PLEA Conference*, Montreal, 2009.

- [56] J.J. Roux, C. Teodosiu, D. Covalet, R. Chareille, Validation of a glazed space simulation model using full-scale experimental data, *Energy build.* 36 (6) (2004) 557 - 565.
- [57] A. Laouadi, M. R. Atif, Comparison between computed and field measured thermal parameters in an atrium building, *Build. Environ.* 34 (2) (1998) 129 - 138.
- [58] G.J. Schoenau, A. J. Lumbis, R.W. Besant, Development and verification of a simulation model for predicting the thermal behavior of attached sunspaces, *Energy Convers. Manag.* 32 (4) (1991) 319 - 331.
- [59] A. R. Rempel, A. W. Rempel, K. V. Cashman, K. N. Gates, C. J. Page, B. Shaw, Interpretation of passive solar field data with EnergyPlus models: Unconventional wisdom from four sunspaces in Eugene Oregon, *Build. Environ.* 60 (2013) 158-172.
- [60] O.B. Jørgensen, L.T. Nielsen, Monitored results from yellow house, In: *Proceedings of the third ISES Europe Solar Congress (Eurosun2000)*, Copenhagen, 2000.
- [61] O. B. Jørgensen, L.T. Nielsen, Monitored results from an innovative solar renovation of multi-storey housing-EU SHINE-Engelsby, Flensberg, In: *Proceedings of the third ISES Europe Solar Congress (Eurosun2000)*, Copenhagen, 2000.
- [62] M. Wall, *Förvärmning av tilluft med solfångare och glasrum (Preheating of supply air through a sun collector and a glazed balcony)*, Rapport TABK-94/3017, Lund University, Lund, 1994, 27 p. (in Swedish).
- [63] J.-M. Mottard, A. Fissore, Thermal simulation of an attached sunspace and its experimental validation, *Solar Energy* 81 (3) (2007), 305-315.
- [64] C. Boonstra, *Glazed Balconies in Building Renovation*, brochure, James and James, London, 1997, 16 p.
- [65] G. Mihalakakou, On the use of sunspace for heating/cooling in Europe, *Renew. Energy* 26 (3) (2002) 415-429.
- [66] K. M. Bataineh, N. Fayez, Analysis of thermal performance of building attached sunspace, *Energy Build.* 43 (8) (2011), 1863 - 1868.

- [67] M. P. Wilson, O.B. Jørgensen, G. Johannesen, Daylighting, energy and glazed balconies: a study of a refurbishment project in Engelsby, near Flensburg, Germany, *Light. Res. Technol.* 32 (3) (2000) 127 - 132.
- [68] C. Ganem, A. Esteves, A better quality of life through the refurbishment of buildings' facades with glazed balconies, In: *Proceedings of the 20<sup>th</sup> Conference on Passive and Low Energy Architecture (PLEA2009)*, Santiago, 2003.
- [69] ASHRAE Standard 55 Project Committee, Appendix C: acceptable approximation for operative temperature, In: *ANSI/ASHRAE Standard 55-2004: thermal environmental conditions for human occupancy*, Atlanta GA: American Society for Heating, Refrigerating, and Air-Conditioning Engineers; 2004, 20 p.
- [70] D.J. Frey, Performance monitoring and results, In: J.D. Balcomb (ed.), *Passive solar buildings*, MIT Press, Cambridge, 1992, pp. 399-484.
- [71] M.S. Owen, H.E. Kennedy, *Handbook of fundamentals*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta GA, 2005.
- [72] P. G. Loutzenhiser, H. Manz, S. Moosberger, G. M. Maxwell, An empirical validation of window solar gain models and the associated interactions, *Int. J. Therm. Sci.* 48 (1) (2009) 85-95.
- [73] A. Haller, Improvement of Solar Renovation Concepts and Systems, A Technical Report of IEA SHC Task20 'Solar Energy in Building Renovation', Ernst Schweizer AG, Metallbau, Hedingen 1999, 74 p.
- [74] O. Kalyanova, F. Zanghirella, P. K. Heiselberg, M. Perino, R. L. Jensen, Measuring Air Temperature in Glazed Ventilated Facades in the Presence of Direct Solar Radiation, in: *Proceedings of Roomvent 2007*, Helsinki, 2007.
- [75] M. A. Christie, J. Glimm, J. W. Grove, D. M. Higdon, D. H. Sharp, M. M. Wood-Schultz, Error Analysis and Simulations of Complex Phenomena, *Los Alamos Sci.* 29 (2005) 6-25.
- [76] SFS-EN ISO 13789, Thermal performance of buildings - Transmission and ventilation heat transfer coefficients - Calculation method, Finnish Standards Association SFS, Helsinki, 2008, 22 p.
- [77] I. Reda, A. Andreas, Solar Position Algorithm for Solar Radiation Applications, National Renewable Energy Laboratory, Colorado, 2008, 16 p. + 17 app. p.

- [78] A. Laukkarinen, K. Hilliaho, Lasitetun parvekkeen lämpötilan ja lämpöhäviöiden laskenta (Interior temperature and heat loss calculation of glazed balcony), In: Proceeding of Building physics seminar, Tampere, 2015, pp. 181 - 186 (in Finnish).
- [79] D. van Dijk, H. Oversloot, WIS: the European Tool to Calculate Thermal and Solar Properties of Windows and Window Components, in: Proceedings of Building Simulation '03, Netherlands, 2003.
- [80] D. Coakley, P. Raftery, M. Keane, A review of methods to match building energy simulation models to measured data, *Renew. Sustain. Energy Rev.* 37 (2014) 123-141.
- [81] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, S. Tarantola, *Global Sensitivity Analysis: The Primer*, John Wiley & Sons Ltd., Chichester, 2008, 292 p.
- [82] F. Winkelmann, B. Birdsall, W. Buhl, DOE-2 supplement: version 2.1E. University of California, Berkeley, 1993, 188 p.
- [83] D. Crawley, L. Lawrie, EnergyPlus: Creating a new-generation building energy simulation program, *Energy Build.* 33 (2001) 319–331.
- [84] S. A. Klein, W. A. Beckman, J. W. Mitchell, J. A. Duffie, N. A. Duffie, T. L. Freeman et al., *TRNSYS 16: A transient system simulation program*, University of Wisconsin, Madison, 1979.
- [85] ESP-r, Energy Systems Research Unit (ESRU), University of Strathclyde, Glasgow, 1974.
- [86] User Manual: IDA Indoor Climate and Energy, version 4.5, Equa Simulation AB, Solna, 2013, 179 p. Available from <http://www.equaonline.com/iceuser/pdf/ICE45eng.pdf>
- [87] Y. Pan, Z. Huang, G. Wu, Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai, *Energy Build.* 39 (6) (2007) 651-657.
- [88] J. Vesterberg, A regression approach for assessment of building energy performance, Licentiate thesis, Umeå University, Umeå, 2014, 25 p.

- [89] T. A. Reddy, K. K. Andersen, An evaluation of classical steady-state off-line linear parameter estimation methods applied to chiller performance data, *HVAC&R Res.* 8 (1) (2002) 101-124.
- [90] D. Claridge, Building simulation for practical operational optimization, in: J. Hensen, R. Lamberts (eds.), *Building Performance Simulation for Design and Operation*, Spon Press, New York, 2011, pp. 365-380.
- [91] E. M. Ryan, T. F. Sanquist, Validation of building energy modeling tools under idealistic and realistic conditions, *Energy Build.* 47 (2012) 375-382.
- [92] G. Dall'O', L. Sarto, N. Sanna, A. Martucci, A comparison between predicted and actual energy performance for summer cooling in high-performance residential buildings in the Lombardy region (Italy), *Energy Build.* 54 (2012) 234-242.
- [93] E. Fabrizio, V. Monetti, Methodologies and Advancements in the calibration of building energy models, *Energies* 8 (4) (2015) 2548-2574.
- [94] T. A. Reddy, I. Maor, C. Panjapompon, Calibrating detailed building energy simulation programs with measured data-Part I: General methodology, *HVAC&R Res.* 13 (2007) 221-241.
- [95] D. E. Claridge, Using simulation models for building commissioning, in: *Proceedings of the Fourth International Conference for Enhanced Building Operations*, Paris, 2004.
- [96] Z. Tian, J. A. Love, Energy performance optimization of radiant slab cooling using building simulation and field measurements, *Energy Build.* 41 (2009) 320-330.
- [97] L. Morrison, R. Azebergi, A. Walker, Energy modeling for measurement and verification, in: *Proceedings of the SimBuild 2008*, Berkley, 2008.
- [98] T. A. Reddy, Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty and tools, *ASHRAE Trans.* 112 (2006) 226-240.
- [99] J. A. Clarke, Assessing building performance by simulation. *Build. Environ.* 28 (4) 1993 419-427.



- [100] R. Sonderegger, J. Avina, J. Kennedy, and P. Bailey, Deriving loadshapes from utility bills through scaled simulation, ASHRAE seminar presentation, Kansas City, 2001.
- [101] T. Mayer, F. Sebold, A. Fields, R. Famirez, B. Souza, and M. Ciminelli, DrCEUS: Energy and demand usage from commercial on-site survey data, in: Proceedings of the International Energy program Evaluation Conference, Seattle, 2003.
- [102] J. A. Clarke, P. A. Strachan, C. Pernot, An approach to the calibration of building energy simulation models, ASHRAE Trans. 99 (1993) 917-927.
- [103] A. Pedrini, F. S. Westphal, R. Lamberts, A methodology for building energy modelling and calibration, Build. Environ. 37 (2002) 903-912.
- [104] M. A. Hassan, S. S. Shebl, E. A. Ibrahim, H. A. Aglan, Modeling and validation of thermal performance of an affordable, energy efficient, healthy dwelling unit, J. Build. Simul. 4 (2011) 255-262.
- [105] Y. Heo, R. Choudhary, G. A. Augenbroe, Calibration of building energy models for retrofit analysis under uncertainty, Energy Build. 47 (2012) 550-560.
- [106] M. Manfren, N. Aste, R. Moshksar, Calibration and uncertainty analysis for computer models – A meta-model based approach for integrated building energy simulation, Appl. Energy 103 (2013) 627-641.
- [107] G. S. Pavlak, A. R. Florita, G. P. Henze, B. Rajagopalan, Comparison of Traditional and Bayesian Calibration Techniques for Gray-Box Modeling, J. Arch. Eng. 20 (2014).
- [108] S. Bertagnolio, Evidence-based model calibration for efficient building energy services, PhD Thesis, University of Liège, Liège, 2012, 88 p.
- [109] Y. Heo, Bayesian calibration of building energy models for energy retrofit decision-making under uncertainty, PhD Thesis, Georgia Institute of Technology, Atlanta, 2011, 116 p.
- [110] S. Diamond, B. Hunn, Comparison of DOE-2 computer program simulations to metered data for seven commercial buildings, ASHRAE Trans 87 (1981) 1222–1231.

- [111] M. Kaplan, J. McFerran, J. Jansen, R. Pratt, Reconciliation of a DOE2.1C model with monitored end-use data for a small office building. *ASHRAE Trans.* 96 (1990) 982–993.
- [112] D. J. Bronson, S. B. Hinchey, J. S. Haberl, D. L. O’Neal, Procedure for calibrating the DOE-simulation program to non-weather-dependent measured loads, in: *Proceedings of the ASHRAE winter meeting, Anaheim, 1992*, pp. 636–652.
- [113] T. E. Bou-Saada, J. S. Haberl, An improved procedure for developing calibrated hourly simulation models, In: *Proceedings of the 5<sup>th</sup> international IBPSA conference, Montréal, 1995*.
- [114] J. Kreider, J. Haberl, Predicting hourly building energy usage, *ASHRAE* 36 (1994) 72–81.
- [115] J. F. Kreider, J. S. Haberl, Predicting hourly building energy use: the great energy predictor shootout: overview and discussion of results, *ASHRAE Trans.* 100 (1994) 1104–1118.
- [116] ASHRAE, *Guideline 14-2002: Measurement of Energy Demand and Savings*, American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, 2002.
- [117] EVO, *International performance measurement & verification protocol*, Efficiency Valuation Organisation, 2007.
- [118] US DOE, *M&V Guidelines: Measurement and Verification for Federal Energy Projects Version 3.0*, U.S. Department of Energy, Washington, 2008.
- [119] K. Pearson, Note on regression and inheritance in the case of two parents, in: *Proceedings of the Royal Society of London* 58 (1895) 240-242.
- [120] M. Liu, K. B. Wittchen, P. K. Heiselberg, F. V. Winther, Development and sensitivity study of a simplified and dynamic method for double glazing façade and verified by a full-scale façade element, *Energy Build.* 68 (2014) 432-443.
- [121] P. Sahlin, L. Eriksson, P. Grozman, H. Johnsson, A. Shapovalov, M. Vuolle, Whole-building simulation with symbolic DAE equations and general purpose solvers, *Build. Environ.* 39 (8) (2004) 949-958.

- [122] J. Jokisalo, On design principles and calculation methods related to energy performance, Doctoral Dissertation, Helsinki University of Technology, Helsinki, 2008, 68 p.
- [123] P. Sahlin, L. Eriksson, P. Grozman, H. Johnsson, A. Shapovalov, M. Vuolle, 'Will equation-based building simulation make it? Experiences from the introduction of IDA Indoor Climate and Energy', in: Proceedings of Building Simulation 2003, Eindhoven, 2003.
- [124] M. Vuolle, An NMF based model library for building thermal simulation, in: Proceedings of building simulation, Kyoto, 1999.
- [125] P. Fritzson, Principles of Object-Oriented Modeling and Simulation with Modelica 2.1, Wiley-IEEE Press, 2004, 944 p.
- [126] A. Fouquier, S. Robert, F. Suard, L. Stéphan, A. Jay, State of the art in building modelling and energy performances prediction : A review, *Renew. Sustain. Energy Rev.* 23 (2013) 272-288.
- [127] M. Trocmé, Aide au choix de conception de bâtiments économes en énergie, Thèse doctorat, Ecole Nationale Supérieure des Mines de Paris, 2009, 148 p.
- [128] D. B. Crawley, J. W. Hand, M. Kummert, B. T. Griffith, Contrasting the capabilities of building energy performance simulation programs, *Build. Environ.* 43 (2008) 661-673.
- [129] R. C. G. M. Loonen, F. Favoino, J. L. M. Hensen, M. Overen, Review of current status, requirements and opportunities for building performance simulation of adaptive facades, *J. Build. Perform. Simu.*, 2016, 19 p.
- [130] M. Wetter, T. S. Noudui, D. Lorenzetti, E. A. Lee, A. Roth, Prototyping the new generation EnergyPlus simulation engine, in: proceedings of 14<sup>th</sup> IBPSA World Conference, Hyderabad, 2015.
- [131] J. A. Clarke, J. L. M. Hensen, Integrated building performance simulation: Progress, prospects and requirements, *Energy Build.* 91 (2015) 294-306.
- [132] M. Wetter, M. Fuchs, P. Grozman, L. Helsen, F. Jorissen, M. Lauster, D. Müller, C. Nytsch-Geusen, D. Picard, P. Sahlin, M. Thorade, IEA EBC Annex 60 Modelica Library : An International Collaboration to Develop a Free Open-Source Model Library for Buildings and Community Energy Systems, in: proceedings of 14<sup>th</sup> IBPSA World Conference, Hyderabad, 2015.

- [133] ASHRAE, Handbook of fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 1997.
- [134] K. Kondratjev, Radiation Regime of Inclined Surfaces, WMO Technical Note 152, Geneva, 1977.
- [135] R. Perez, Ineichen P., Seals R., Michalsky J., Stewart R., Modelling daylight availability and irradiance components from direct and global radiance, Sol. Energy 44 (5) (1990) 271-289.
- [136] P. Loutzenhiser, H. Manz, G. Maxwell, Empirical Validations of Shading/Daylighting/Load Interactions in Building Energy Simulation Tools, A Report of IEA SHC Task 34/ ECBCS Annex 43 Project C, 2007, 177 p.
- [137] A. M. Noorian, I. Moradi, G. A. Kamali, Evaluation of 12 models to estimate hourly diffuse irradiation on inclined surfaces, Renew. Energy 33 (2008) 1406-1412.
- [138] A. Bring, P. Sahlin, M. Vuolle, Models for building Indoor Climate and Energy Simulation, A Report of IEA SHC Task 22: Building Energy Analysis Tools, Sub-task B: Model Documentation, Royal Institute of Technology, Stockholm, 1999.
- [139] M. Wall, H. Bülow-Hübe, Solar Protection in buildings, Part 2: 2000-2002, Report EBD-R--03/1, Lund University, Lund, 2003, 157 p.
- [140] ISO/FDIS 15099: 2003(E), Thermal performances of windows, doors and shading devices—Detailed calculations, 2003.
- [141] J. Vinha, A. Laukkarinen, M. Mäkitalo, S. Nurmi, P. Huttunen, T. Pakkanen, P. Kero, E. Manelius, J. Lahdensivu, A. Köliö, K. Lähdesmäki, J. Piironen, V. Kuhnno, M. Pirinen, A. Aaltonen, J. Suonketo, J. Jokisalo, O. Teriö, A. Koskenvesa, T. Palolahti, Ilmastomuutoksen ja lämmöneristyksen lisäyksen vaikutukset vaipparakenteiden kosteusteknisessä toiminnassa ja rakennusten energiankulutuksessa (Effects of climate change and increasing of thermal insulation on moisture performance of envelope assemblies and energy consumption of building), Research report 159, Tampere University of Technology, Tampere, 2013, 354 p. (in Finnish).
- [142] Y. Li, Simulation of Flow and Heat Transfer in Ventilated Rooms, PhD thesis, KTH, Stockholm, 1992

- [143] J. Clarke, *Energy Simulation in Building Design*, Butterworth-Heinemann, 2001, 376 p.
- [144] ASHRAE, *Handbook of fundamentals*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 1993.
- [145] G. Brown, The BRIS Simulation Program for Thermal Design of Buildings and Their Services, *Energy Build.* 14 (1990) 385-400.
- [146] N. Björnsell, A. Bring, L. Eriksson, P. Grozman, M. Lindgren, P. Sahlin, A. Shapovalov, et al., IDA indoor climate and energy, in: *Proceedings of the IBPSA Building Simulation'99 Conference*, Kyoto, 1999, pp. 1–8.
- [147] G. Brown, Metod för datamaskinberäkning av värme- och ljusstrålning i rum, *VVS 10* (1963).
- [148] G. N. Walton, *Thermal Analysis Research Program Reference Manual*, NBSSIR 83-2655, National Bureau of Standards (NBS), Washington, 1983.
- [149] D. E. Fisher, C.O. Pedersen, Convective Heat Transfer in Building Energy and Thermal Load Calculations', *ASHRAE Trans.* 103 (2) (1997) 137–148.
- [150] G. Brown, E. Isfält, *Solinstrålning och solavskärmning (Solar Irradiation and Sun Shading Devices)*, Report 19:1974, Nat. Swedish Inst. for Building Res., Stockholm, 1974. (in Swedish)
- [151] I. Beausoleil-Morrison, P. Strachan, On the significance of modeling internal surface convection in dynamic whole-building simulation programs, *ASHRAE Trans.* 105 (2) (1999) 929–940.
- [152] M. W. Liddament, Power law rules – OK? *Air Infiltration Review* 8 (1987) 4–6.
- [153] I. Walker, D. Wilson, M. A. Sherman, A comparison of the power law to quadratic formulations for air infiltration calculations. *Energy Build.* 27 (1998) 293–299.
- [154] M. Sherman, A power law formulation of laminar flow in short pipes, *J. Fluids Eng.* 114 (1992) 601–605.
- [155] P. Sahlin, *Modelling and simulation methods for modular continuous system in buildings*, PhD Thesis, Royal Institute of Technology (KTH), Stockholm, 1996.

- [156] J. Jokisalo, J. Kurnitski, M. Korpi, T. Kalamees, J. Vinha, Building leakage, infiltration, and energy performance analyses for Finnish detached houses, *Build. Environ.* 44 (2009) 377-387.
- [157] SFS-EN ISO 13370, Thermal performance of buildings – Heat transfer via the ground - Calculation methods, Finnish Standards Association SFS, Helsinki, 2007, 48 p.
- [158] M. Achermann, A simplified nmf model of a Ground to Air Heat Exchanger, Lucerne School of Engineering and Architecture, Switzerland, 2000, 9 p.
- [159] EN ISO 13791:2012. Thermal performance of buildings - Calculation of internal temperatures of a room in summer without mechanical cooling - General criteria and validation procedures, 2012.
- [160] EN 15265, Energy performance of buildings - Calculation of energy needs for space heating and cooling using dynamic methods - General criteria and validation procedures, 2007.
- [161] ANSI/ASHRAE Standard 140, Standard method of test for the evaluation of building energy analysis computer programs, American Society of Heating, refrigerating, and Air-Conditioning Engineers, Atlanta, 2001.
- [162] O. Kalyanova, P. Heiselberg, Empirical Validation of Building Simulation Software: Modelling of Double Facades: Final Report, Aalborg University, 2008.
- [163] S. Moinard, G. Guyon, (eds.), Empirical validation of EDF ETNA and GENEC test-cell models, A Report of IEA Task 22, Project A.3 Empirical validation, International Energy Agency, 1999.
- [164] K. Butcher (ed.), Test for software accreditation and verification, Chartered Institution of Building Services Engineers (CIBSE), London, 2006.
- [165] A. Janssens, State of the Art of Full Scale Test Facilities for Evaluation of Building Energy Performances, IEA Annex 58 Subtask 1 Report, 2014. Available from <http://www.kuleuven.be/bwf/projects/annex58/index.htm>.
- [166] J. Travesi, G. Maxwell, C. Klaassen, M. Holtz, Empirical validation of Iowa energy resource station building energy analysis simulation models, A Report of IEA SHC Task 22: Building Energy Analysis Tools, Subtask A: Tool Evaluation, 2001, 162 p.

- [167] S. Kropf, G. Zweifel, Validation of the building simulation program IDA-ICE according to CEN 13791 'Thermal performance of buildings – Calculation of internal temperatures of a room in summer without mechanical cooling – General criteria and validation procedures', Luzern, 2001, 24 p.
- [168] M. Achermann, G. Zweifel, RADTEST – Radiant heating and cooling test cases, A report of IEA Task 22: Building Energy Analysis Tools, Subtask C: Comparative evaluation, 2003, 83 p.
- [169] S. Moosberger, IDA-ICE CIBSE-validation, Test of IDA Indoor Climate and Energy version 4.0 according to CIBSE TM33, issue 3, HTA, Luzern, 2007, 61 p.
- [170] Equa Simulation Technical Group, Validation of IDA Indoor Climate and Energy 4.0 build 4 with respect to ANSI/ASHRAE Standard 140-2004, Technical report, Solna, 2010, 44 p.
- [171] Equa Simulation AB, Validation of IDA Indoor Climate and Energy 4.0 with respect to CEN Standards EN 15255-2007 and EN 15265-2007, Technical report, Solna, 2010, 19 p.
- [172] M. Reichenbach, Apartment building in cold climate: Sunspace, In: S. R. Hastings, M. Wall, Sustainable solar housing, Volume 1 – strategies and solution, London, 2007, pp. 171-178.
- [173] G. Oliveti, N. Arcuri, M. D. Simone, R. Bruno, Solar heat gain and operative temperature in Attached sunspaces, *Renew. Energy* 39 (1) (2012) 241-249.
- [174] R. Chareille, J.J. Roux, D. Covalet, O. Hartmann, Impact of a veranda on the reduction of the energy consumption in residential buildings: an application of the CLIM2000 software, In: Proceedings of the Seventh International IBPSA Conference, Rio de Janeiro, 2001.
- [175] A. Monge-Barrio, A. Sánchez-Ostiz, Energy efficiency and thermal behaviour of attached sunspaces in the residential architecture in Spain: Summer Conditions, *Energy Build.* 108 (2015) 244-256.
- [176] Equa Simulation AB, IDA Indoor Climate and Energy, Solna, 2017. Available from <http://www.equa.se/en/ida-ice>
- [177] M. Kotttek, J. Greiser, B. Beck, et al., World Map of the Köppen - Geiger climate classification updated, *Meteorologische Zeitschrift* 15 (3) (2006) 259 - 263.

- [178] P. Pirinen, H. Simola, J. Aalto, J.P. Kaukoranta, P. Karlsson, R. Ruuhela, Climatological statistics of Finland 1981 – 2010, Reports 2012:1, Finnish Meteorological Institute, Helsinki, 2012, 96 p.
- [179] METEONORM 7, Meteorological Reference Program, Meteotest, 2015, Available from <http://www.meteonorm.com> (Accessed 9.3.2016)
- [180] G. Persson, G. Strandberg, L. Barring, E. Kjellström, Beräknade temperaturförhållanden för tre platser i Sverige – perioderna 1961-1990 and 2011-2040 (Calculated temperatures at three locations in Sweden - the periods of 1961-1990 and 2011-2040), SMHI Meteorologi Nr 124, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, 2007, 25 p. (in Swedish).
- [181] Meteorological data, Swedish Meteorological and Hydrological Institute (SMHI), 2015, Available from <http://opendata-download-metobs.smhi.se/explore/> (Accessed 19.05.2015)
- [182] C.A. Gueymard, A Simple Model for the Atmospheric Radiative Transfer of Sunshine (SMARTS2): Algorithms and performance assessment, Report FSEC-PF-270-95, Florida Solar Energy Center, Florida, 1995, 78 p.
- [183] T. Landelius, W. Josefsson, T. Persson, A system for modelling solar radiation parameters with mesoscale spatial resolution, Report RMK No. 96, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, 2001, 51 p.
- [184] STRÅNG - a mesoscale model for solar radiation, Swedish Meteorological and Hydrological Institute (SMHI), 2015, Available from <http://strang.smhi.se/> (Accessed 19.05.2015)
- [185] D. Koblick, Vectorized, Solar Azimuth and Elevation Estimation, 2009, Available from <http://www.mathworks.com/matlabcentral/fileexchange/23051-vectorized-solar-azimuth-and-elevation-estimation>
- [186] International Weather for Energy Calculations (IWEC): Users Manual and CD-ROM, ASHRAE, 2001.
- [187] International Weather for Energy Calculations 2.0 (IWEC2), ASHRAE, 2015, Available from <http://ashrae.whiteboxtechnologies.com/faq> (Accessed 18.2.2015)
- [188] K. Jylhä, T. Kalamees, H. Tietäväinen, K. Ruosteenoja, J. Jokisalo, R. Hyvönen, S. Ilomets, S. Saku, A. Hutila, Test reference year 2012 for building energy demand and impacts of climate change, Reports 2011:6, Finnish meteorological Institute, Helsinki, 2011, 112 p. (in Finnish).



- [189] J. Andersson, A. Bränd, Glasklar tilläggsisolering – möjligheter med förvärmning av tilluft (Crystal clear insulation - possibilities with preheating of ventilation supply air), Report no TVIT-5048, Lund University, Lund, 2014, 84 p. (in Swedish).
- [190] B. Nordquist, S. Elfborg, A. Vrbanjac, P. Wallènten, J. Stein, Energy saving by adding a glass-façade to a brick building, In: Proceedings of 3<sup>rd</sup> International Conference Central Europe towards Sustainable Building (CESB13), Prague, 2013.
- [191] S. Elfborg, A. Vrbanjac, Inglasad tegelfasad – en energianalys (Glazed brick facade - an energy analysis), Report no TVIT-5037, Lund University, Lund, 2012, 151 p. (in Swedish).
- [192] Official Statistics of Finland (OSF): Building and dwelling production, Statistics Finland, Helsinki, 2015, Available from [http://www.stat.fi/til/ras/2015/12/ras\\_2015\\_12\\_2016-02-26\\_tie\\_001\\_en.html](http://www.stat.fi/til/ras/2015/12/ras_2015_12_2016-02-26_tie_001_en.html) (Accessed 11.5.2016)
- [193] A. Tiihonen, Asumisväljyys lisääntyy hitaasti (Living space is increasing slowly), Statistics Finland, 2011, Available from [http://www.stat.fi/tup/vl2010/art\\_2011-10-18\\_001.html](http://www.stat.fi/tup/vl2010/art_2011-10-18_001.html) (Accessed 9.10.2015) (in Finnish).
- [194] J. Säteri, K. Kovanen, M.-L. Pallari, Kerrostalojen sisäilmaston ja energiatalouden parantaminen (Improvement of indoor air and energy efficiency in high-rise residential building), Technical Research Center of Finland, Espoo, 1999, 82 p.
- [195] J. Palonen, Asuntoilmanvaihto (Ventilation in residential buildings), in: A. Koskenvesa (ed.), Rakennustieto Oy, Helsinki, 2004, 1088 p.
- [196] D3, Rakennusten energiatehokkuus: määräykset ja ohjeet 2012 (Energy management in buildings: Regulations and guidelines 2012), The National Building Code of Finland, part D3, Ministry of the Environment, Helsinki, 2011, 27 p. (in Finnish).
- [197] Kotitalouksien sähkönkäyttö 2011 (Electricity consumption in household 2011), Research report, Ministry of employment and the economy, Helsinki, 2013, 52 p. (in Finnish).
- [198] T. Suur-Uski, Rakennusten taloteknisten järjestelmien toimivuus ja toimivuuden tunnusluvut sekä varmentaminen mittauksin ja simuloinnein (Functionality of Building Services, Functionality Indicators and Verification with Measurements

and Simulations), Master of Science Thesis, Helsinki University of Technology, Helsinki, 2007, 81 p. (in Finnish).

- [199] G. Kövári, I. Kistelegdi, Building performance simulation modeling techniques, *An International Journal for Engineering and Information Sciences* 11 (2) (2016) 135-146.
- [200] B. Nordquist, Ventilation and Window Opening in Schools - Experiments and Analysis, Report TABK 1024 (PhD Thesis), Lund University, Lund, 2002, 307 p.
- [201] P. Wallentèn, Heat Flow in Building Component, Experiment and Analysis, Report TABK 1016 (PhD Thesis), Lund University, Lund, 1998, 246 p.

# ORIGINAL PAPERS

I

## **GLAZED SPACE THERMAL SIMULATION WITH IDA-ICE 4.6.1 SOFTWARE–SUITABILITY ANALYSIS WITH CASE STUDY**

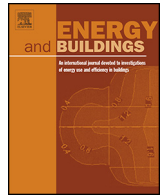
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# Glazed space thermal simulation with IDA-ICE 4.61 software—Suitability analysis with case study

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## ABSTRACT

Many previous articles point out the need of using accurate energy simulation programme for studying the indoor climate and energy use of the highly glazed spaces. This article examines the suitability of IDA Indoor Climate and Energy (IDA-ICE) software for the glazed space energy simulation in theory and practice. The analysis of how the programme meets highly glazed space simulation needs has been done and comparison to the actual field measurement case conducted by using two different window and zone models featured by the simulation tool to examine the software function in practice. The measured data is from the two flats and attached balconies situated in Tampere (61°29'53" N, 023°45'39" E), Finland.

The final outcome was that the IDA-ICE 4.61 is well suited for the glazed space studies and the most accurate results are achieved by using a detailed window and zone models. Critical input parameters were the absorption coefficient of the surfaces, the balcony's unintended ventilation, external shading and building supply air flow rate from the outside to apartment through the balcony. The results show that in design situation where attached balcony's one side is glazed and two sides opaque, the uncertainty of the input parameters can easily cause greater deviation between measured and simulated indoor temperatures than the deviation caused by the use of different zone and window models.

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## 1. Introduction

A number of studies have shown that highly glazed spaces have many good features. Temperatures within enclosed spaces are higher than outdoors [1–9] and their relative humidity is lower [4,5,10] throughout the year. As a result, there are less problems with façade degradation [6] and thermal bridges. Sunspaces also provide a buffer space against wind pressure and make it possible to take pre-heated supply air from the glazed space to reduce building energy consumption [4,5,7,10,11].

Assessing the energy saving effects of glazed space, the air temperature measurements are considered to be a useful method for the starting point of the evaluations. They reveal the dominant pathways of heat gain and loss and give an indication of thermal buffer effects and thermal comfort [12,13]. Combining air temperature measurement with internal and external surface temperature measurements by using thermocouples, it is also possible to evaluate materials' ability to store and release heat energy [14] and thus figure out the whole idea of thermal behaviour of glazed spaces. Obtaining better understanding of different factors affecting the

temperature behaviour of glazed spaces, detailed energy simulations are often needed. For that reason, simulation programmes have been widely used in sunspace studies for several decades [2,3,7–10,15–21]. The purpose of the simulations has mainly been to validate the used simulation programmes [17–19], obtain better understanding of one or more influential factors [7,10,21,23,24] and conduct a sensitivity analysis [25] as well as develop and verify a simulation model [16]. In these studies, simulation programmes have proven to be very useful tools.

Many commonly used building-energy simulation tools are not well suited for indoor climate evaluations of highly glazed spaces due to their simplified calculation method for solar radiation transmission through windows, distribution inside the sunspace and reflection inside or outside the glazed space. That is why many previous studies have expressed the need of a detailed calculation model for studying the indoor climate of highly glazed spaces [17,18,20,26–29]. Previous studies have also shown that the most accurate assessment of indoor climate may be provided by a dynamic building simulation software, which utilizes state-of-the-art calculation methods for short- and long-wave radiation and radiations distribution inside glazed space as well as between the glazed space and the adjacent room taking into account the portion of the short-wave radiation escaping from the sunspace [18,28]. The needs of detailed energy flow through the windows [22], stratified

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air temperatures in the rooms [20] and detailed analysis of the air flow within the rooms [20] are also highlighted. For that reason, the calculation software's calculation methods should be carefully found out before making a final decision on the used programme.

This article evaluates the suitability of the IDA Indoor Climate and Energy (IDA-ICE) software for the glazed space energy simulation. The paper describes the critical parameters of the highly glazed space simulations (Section 1) and analysis of how the programme meets these needs (Section 2). In addition, the analysis has involved an actual field measurement case, in which the effect of the software's different model detailing level to the calculation results has been examined. Object of the study has been (a) to analyze the suitability of the programme to highly glazed space simulation in theory and practice, and (b) bring out the key measurement and calibration parameters. The results can be used to develop the field measurement practices and simulation methods.

## 2. Simulation tool – background

IDA Indoor Climate and Energy (IDA-ICE) is one of the twenty major building energy simulation programmes [30], and according to the literature review [31], one of the four main building energy simulation tools, discussed in most articles dealing with the validation of building energy simulation models. The software as many other whole building simulation tools is based on the building geometrical description, which provides the basis for a more detailed calculation of the distribution of solar radiation in and between rooms. The software calculates energy balances dynamically taking into account climatic variations and a dynamically varying time-step. The software solves heat balance equations according to the user defined building geometry, construction, HVAC conditions and internal heat loads. Software allows use of measured climate and weather file containing the information about air temperature, relative humidity, wind direction and speed, direct normal radiation and diffuse (sky) radiation on a horizontal surface and calculates for example solar radiation based on the building location and sun position in the sky. Accuracy of the IDA-ICE simulation tool has been examined in many validation studies in recent years [32,22,33–40]. Accordingly, selection of the IDA-ICE as the simulation tool for highly glazed space simulation is well grounded [30,22,33,41].

IDA Indoor Climate and Energy software provides two different zone models. The detailed zone model with full Stefan–Boltzmann long-wave radiation has been developed for detailed calculations like indoor climate studies and the simplified zone model for energy simulation to speed up execution time in the normal design cases, where slight inaccuracy is acceptable. The difference between the models is mainly that the latter model makes a simplified calculation of the radiation exchange between all the surfaces of the room enclosure. In the energy model, the internal walls without thermal connection to surrounding zones are assumed adiabatic, whereas external walls and partitions towards other simulated zones are handled separately, because the conditions on the opposite side are different from those in the zone. The geometry of the zone is not known in detail; surface areas are known and are used for distribution of radiation. The model handles the diffuse radiation that comes into the zone from windows and from reflection of direct light (and is not reflected back out) by dividing it to the surfaces according to area ratios multiplied by their absorptance. In the climate (detailed) zone model, the view factors between the surfaces are calculated and the emitted and reflected irradiation is distributed accordingly by solving a system of radiation balance equations for all the surfaces. The distribution and absorption of diffuse light at the different surfaces is treated in a similar way. As a result, properties such as the displacement ventilation and room temperatures vertical stratification in the zone as well as operative

temperatures, comfort indices and daylight levels at arbitrary room locations can be calculated with this model. Climate zone model is only available for box-shaped zones (rectangular geometries) while energy model can handle different types of zone geometries [33,42].

In IDA-ICE direct and diffuse solar radiation is computed detailed including the exact time dependent sun position in the sky and the distribution of diffuse radiation, by default using the Perez et al.'s [43] model. As a calculation of the long wave radiation between the sky and building façade, the ground temperature is assumed to be the same as the air temperature and the sky temperature five degrees below the air temperature [33]. This assumption of the sky temperature has proved to be a rather good average value over the long term [44].

The windows can be modelled using either a simple or an ISO-15099 [32] based detailed window model (Detwind) in IDA-ICE. The difference between the detailed and the simple window model is that in the former the glazing is modelled with the optical and thermal properties of all its panes and gasses in the gaps between the panes. The angle dependent optical properties of the glazing are then calculated with consideration of multiple reflections and the solar absorption in each pane. From this both the solar light and the heat transmission are calculated. Even the heat capacity of the panes is taken into account. In the simple model the optical and thermal properties for the whole glazing (at normal incidence) are given as input data. The angle dependence of the whole glazing is then calculated by using a fixed curve for the angle dependence. Integrated window shading (internal or external shades in the plane of the window) is calculated by multiplying shading effect to the basic window parameters. After transmitted inside the zone, diffuse light is spread diffusely and the direct light beam according to exact target location. After the first reflection on a zone surface, the direct beam is spread diffusely in the room. In all reflection calculations, the whole surface that is hit is regarded to reflect with equal intensity, not just the lit portion of the surface at issue [33,42].

IDA-ICE includes multizone air flow model and can handle four different types of air flows. Typically, the air flow goes through the supply and exhaust air terminals and through envelope air leakage path, but also openings and other additional flow paths are possible to create. In the simplest case, where the two first paths of air flows are created, the size of the third flow, through the leak, is important only to fulfil mass balance equation of air flows [33,42]. Air flows in leaks are based on pressure loss equation, thus the whole air flow network calculations are always involved in ICE models.

## 3. Research materials and methods

The research material consists of acquired weather files, monitoring data from two balconies and the adjoining flats and IDA-ICE 4.61 software validation simulation results.

### 3.1. Climate and weather

Archived 2009 air temperature, relative humidity, wind speed and wind direction data were obtained from the Tampere/Pirkkala airport (20 km west of the site) weather station EFTP (WBAN 99999) and the solar radiation data from the Jokioinen Meteorological Observatory (100 km south of the site). Tampere 1981–2010 “normal” temperature data and Jokioinen 1981–2010 “normal” solar radiation data are from Finnish Meteorological Institute report no. 2012:1 [45]. Tampere “typical” temperature and solar energy data are from the ASHRAE IWEC 1.1 database [46]. The International Weather for Energy Calculation (IWEC) files are derived from up to 18 years of DATSAV3 hourly weather data originally archived at

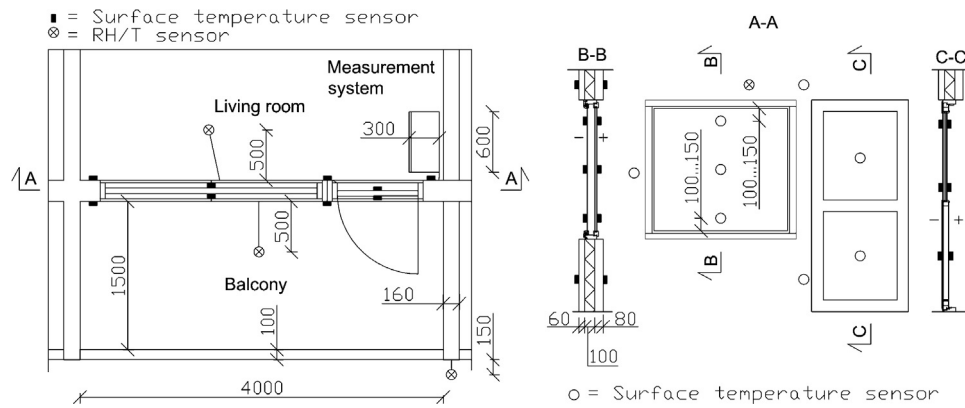


Fig. 1. Connection diagram of flat excluding balcony glazing.

the National Climatic Data Center [47]. The weather and climate condition is discussed in more detail in Section 4.1.

### 3.2. Field monitoring

The main components of the field measurement system were a portable computer, a data logger, measurement sensors, sensor transmitters, and power sources. The measurement was controlled by the Agilent Benchlink Data Logger software and an Agilent 34970A Data Logger. The surface temperature sensors were of the LM 355 type and the air temperature sensors of the HTM100 type. Small battery-powered Comark Diligence EV (N2003 and N2013) data loggers were also used. Field measurement systems were used to measure outdoor temperature, flat temperature and balcony air temperature, as well as surface temperatures on both sides of the balcony glazing and balcony wall, door, and window (inner and outer) surfaces. Temperatures were recorded at 1-h intervals for approx. 10 months (from 16th July 2009 to 24th May 2010).

Unshielded surface temperature sensors were placed in the two flats on top of each other in accordance with a connection diagram (Fig. 1). Balcony door sensors were installed in the middle of the glass pane and on the inner and outer side of the solid section. A total of four sensors were installed on the top and bottom part of the lower flat window. In the case of the upper flat window, sensors were also placed in the middle of the pane, outside and inside. The back wall sensors were placed case-specifically. Their placement was made difficult by the hot-water radiators located under the window, which affected the wall surface temperatures. A total of eight sensors were attached to the balcony glazing. The indoor air relative humidity and temperature (RH/T) sensor was in the living-room, near the balcony back wall, at a height of approx. 2.5 m. The distance of the sensor from the external wall inner surface was approx. 0.5 m. The balcony RH/T sensor was close to the ceiling at a distance of approx. 0.5 m from the balcony back wall. The sensor measuring outdoor air temperature and relative humidity was on the balcony frame wall. The outdoor air RH/T sensor was protected against solar radiation and precipitation by a special factory-made outdoor sensor guard.

To collect simulation input data, air change rate was measured by a wing wheel anemometer, airtightness by pressure test equipment, and thermal insulation by condition investigation equipment. In the same connection, the occupants were interviewed about their living habits and electricity consumption and the number of electric appliances they had – specific power consumption and daily operating time were also determined in co-operation with the occupants. The electricity consumption of 1500 kWh/year of the flat proved to be clearly below the average consumption of a similar flat in Finland. Investigation focussed on

the flat with a glazed balcony. The other flat was assumed to be in similar use to make the indoor climate conditions and use of the dwelling unit similar in both cases. This way, the balcony glazing installed in the lower flat remained the only difference between the two.

### 3.3. IDA-ICE 4.61 modelling

During the research, computational analyses were carried out using the IDA Indoor Climate and Energy (IDA-ICE) 4.61 software. Building model was created by ArchiCAD software and transferred to the simulation software in the IFC format. Building external forest was estimated using architect's city plan, on-site observation and old photos and modelled as non-transparent bars. Under the simulation were two 64 m<sup>2</sup> flats on top of each other in the middle part of the building. Lower of flats has a glazed balcony, but also unglazed balcony was modelled as a zone. Apartment's window supply air valves, balcony glazing's air gaps and open part of the unglazed balcony were modelled as a differently sized pressure driven air flow path. Depending on the pressure difference between inner and outer side, air flowed inside or outside through these openings trying to neutralize pressure difference. Mostly air was flown from the outside of the building to the inside as a reason for building's negative pressure generated by mechanical exhaust ventilation system.

Data on the building were acquired from the ArchiCAD model, one-time measurements of flat conditions, and inhabitant interviews. The location of electrical equipment and specific power were determined by site visits. Examinations were carried out in a flat with glazed balcony. Use of other flat was assumed to be similar, in order to standardize the indoor atmosphere conditions and use of premises as similar in both flats. The simulations used real temperature and humidity data measured on-site from 17th July to 31st December 2009. The temperature and relative humidity data missed due to the measurement interruption from 22nd to 30th October 2009 and from 8th November to 2nd December 2009, as well as wind speed/direction data from 17th July to 31st December 2009, were supplemented by weather observations at the Tampere/Pirkkala airport weather station. Radiation data from the simulation period 17th July to 31st December 2009 was from the Jokioinen Meteorological Observatory. For source information regarding the flat and use thereof, see Table 1 and Fig. 2.

Simulation studies were performed by comparing actual air and surface temperature values to simulated ones by using four different model detailing levels (Table 2). The most detailed one was the simulation model with a detailed window (Detwind) and a zone (Climate) model, while the most simplified one incorporated a simple window structure and a zone (Energy) model.

**Table 1**  
Apartments and balconies parameters.

Location (climate condition)	Tampere (61°29'53" N, 23°45'39" E), Finland
Orientation	South-west
Wind profile	Suburban
Balcony façade distance from the building in front	Mixed forest in front of the balcony facade
Apartment size ( $A_{APARTMENT}$ )	Two-room flat, $A_{APARTMENT} = 64 \text{ m}^2$ and $V_{APARTMENT} = 166 \text{ m}^3$
Balcony size ( $A_{BALCONY}$ )	$A_{BALCONY} = 6 \text{ m}^2$ and $V_{BALCONY} = 16 \text{ m}^3$
Apartment inside air temperature	23.3 °C
Standard of equipment, number of residents and apartment usage habits	According to the real situation inside the apartment (two residents, electricity consumption 1500 kWh/year)
Apartment type	Apartment runs from front to back of a building
Balcony type	Extended concrete balconies supported on frame walls
Building air change rate	Mostly 0.35 ACH, between 06:30–09, 11–13 and 16–18 0.7 ACH
Supply air inlet vents position	Two window vents
Glazed space unintended ventilation	1.1–2.2 ACH (monthly average)
Building air leakage coefficient (at 50 Pa pressure difference)	0.88 ACH (at 50 Pa pressure difference)
Heating capacity design of hot water radiators	According to current design in 1979
The heating system control curve position	According to current settings in the building
The heating system summer shut-off	No summer shut-off
Surfaces absorptivity (balcony and external wall)	Mostly 0.22 (balcony slab top side and external wall outer side 0.3, balustrade outer side 0.4)
Surface emissivity (balcony and external wall)	0.9
Specific heat capacity of balcony structures	900 J/(kg K)
Lambda value of balcony structures	1.35 W/(m K)
Density of balcony structures	2300 kg/m <sup>3</sup>
Window or balcony glazing blinds placement position	No blind
Wall properties (wall between apartment and balcony)	$A_{WALL} = 5.2 \text{ m}^2$ and $U_{WALL} = 0.3 \text{ W/m}^2 \text{ K}$
Window properties (wall between apartment and balcony)	$A_{WINDOW} = 3.3 \text{ m}^2$ , $U_{WINDOW} = 1.4 \text{ W/m}^2 \text{ K}$ , $g_{WINDOW} = 0.55$
Balcony door properties	$A_{DOOR} = 1.9 \text{ m}^2$ , $U_{DOOR} = 1.2 \text{ W/m}^2 \text{ K}$ , $g_{DOOR} = 0.55$
Balcony glazing properties	$A_{GLAZING} = 6.3 \text{ m}^2$ , $U_{GLAZING} = 5.8 \text{ W/m}^2 \text{ K}$ , $g_{GLAZING} = 0.82$
Glazing-to-floor area ratio ( $A_{GLAZING}/A_{BALCONY}$ )	1.05
Window and door-to-floor area ratio ( $(A_{WINDOW} + A_{DOOR})/A_{BALCONY}$ )	0.87
Glazing-to-balcony glazing eligible area ratio ( $A_{GLAZING}/(A_{BALCONY \text{ WALL}} + A_{BALCONY \text{ SIDE WALLS}} + A_{BALCONY \text{ FRONT WALL}})$ )	0.26

**Table 2**  
Four detailing levels of the model used in simulation studies and their modelling times.

Simulation cases	Zone and window model	Modelling time
Most detailed	Climate model with detailed window	35 min 23 s
Detailed	Energy model with detailed window	29 min 29 s
Simplified	Climate model with simplified window	34 min 38 s
Most simplified	Energy model with simplified window	29 min 11 s

**4. Context**

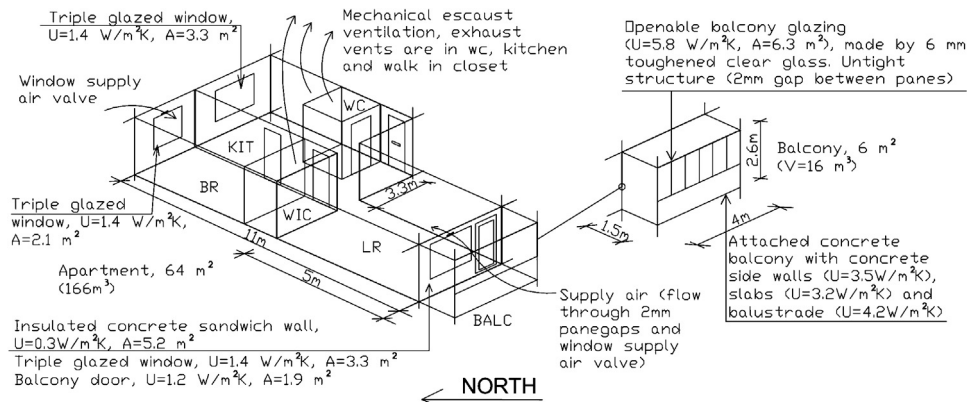
**4.1. Climate**

The city of Tampere (61°29'53" N, 23°45'39" E) lies borderline between humid continental (Köppen-Geiger Dfb) and subarctic climate (Köppen-Geiger Dfc) [48]. City's winter is cold and

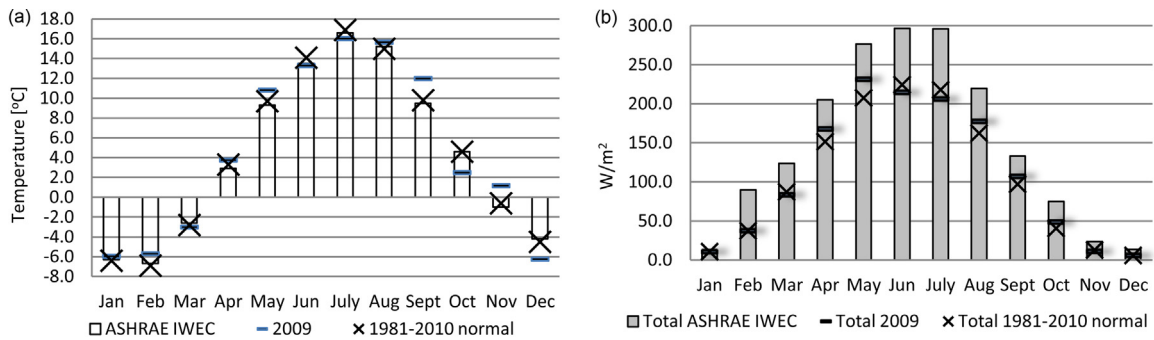
summer mild. The average temperature from November to March is below 0 °C (32 °F) and whole year below 17 °C (49 °F) (Fig. 4a). The annual average temperature is 4.4 °C (36.4 °F). Heating degree-days (HDD17) during the normal period 1981–2010 was 4424 per year and 2009 it was 4371 [45,49].

Autumn months of the field measurement period (July–December 2009) were unusual compared to “normal” and “typical” condition in Tampere (Fig. 3a). August was slightly warmer, September clearly warmer (2.5 °C) and October clearly colder (–2.1 °C) than average. November was 2.2 °C milder than average and December –2.1 °C colder. The year 2009 as a whole was slightly (0.1 °C) warmer than “normal” year. There was only slight difference between Tampere “normal” and “typical” year monthly average temperatures as shown in Fig. 3a [50].

In 2009, the sunshine duration was close to long-term 1500–2000 h average level and the total solar radiation levels a little higher than normal in August–October [50]. A comparison



**Fig. 2.** Illustration of the simulated apartment. Difference between flats on top of each other was only the balcony glazing installed in the lower flat.



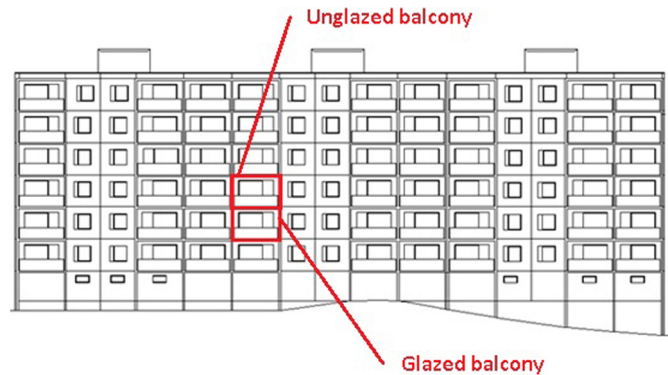
**Fig. 3.** (a, b) Climatic context. 2009 Monthly average temperatures and incident solar radiation levels compared to 1981–2010 “normal” and ASHRAE IWEC “typical” values. Autumn 2009 was exceptional in both mean temperature and incident solar radiation point of view. Figure shows that ASHRAE IWEC weather data overestimate clearly incident solar radiation levels in Tampere (compared to Jokioinen “normal” and 2009 solar radiation data).

between Tampere ASHRAE IWEC and Finnish Meteorological Institute’s nearest solar radiation observatory’s 2009 and “normal” solar radiation levels shows that the ASHRAE IWEC weather files clearly overestimates the actual solar radiation level in Tampere, Finland (Fig. 3b). It is therefore recommended to use Finnish Meteorological Institute’s solar radiation data in the energy simulations.

#### 4.2. Field site

The studied building is situated in a normal Finnish urban area in Tampere, Finland. The building is a 1+6 storey pre-cast concrete block of flats completed in 1979 with extended concrete balconies supported on frame walls (Fig. 4). The building exterior wall colour is dark red, balcony structures colour mainly white and balcony back wall and floor colours light grey. Apartment interior surfaces are all light coloured.

The building is connected to the district heating network and ventilated by a mechanical exhaust ventilation system. The heating water is delivered inside the building through hot water pipes and heat gave out with the help of free-standing radiators. The facades of the building were renovated in 2004, in which connection the windows and doors were replaced and glazing was installed in about 50% of the balconies. The condition of the HVAC systems was checked at the same time and the ventilation and radiator systems were balanced. The exhaust ventilation unit was not replaced, but was equipped with modern timer control.



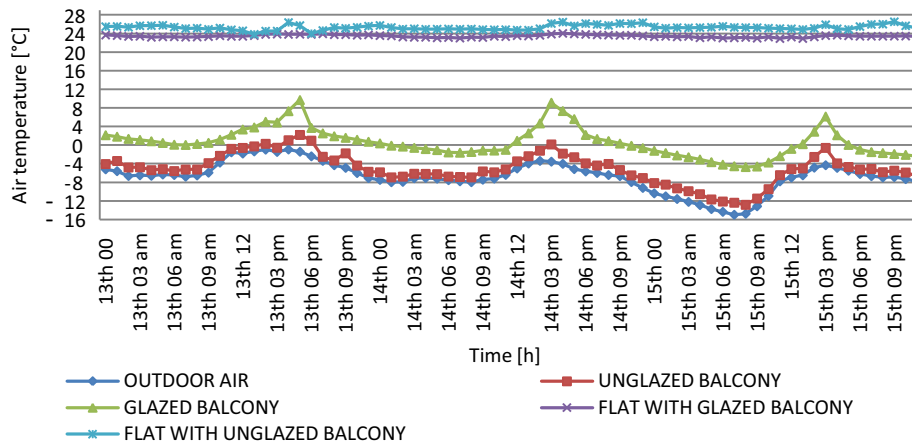
**Fig. 4.** South-western façade of the studied building.

## 5. Results and discussion

### 5.1. Field measurement

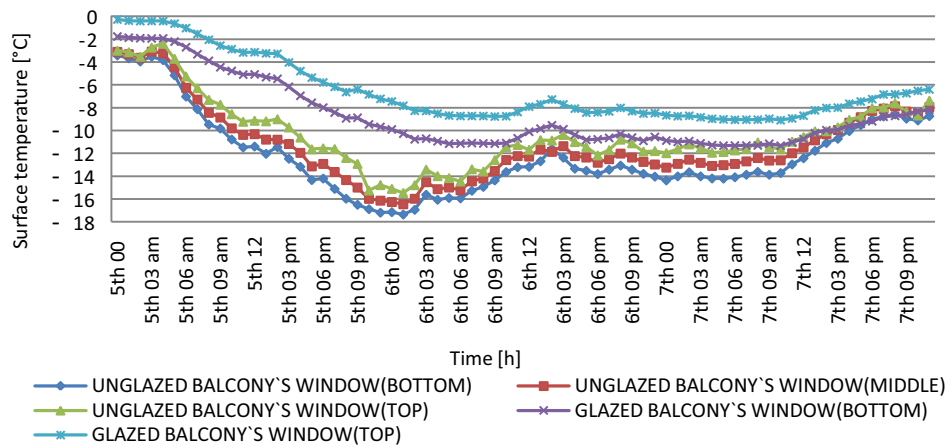
#### 5.1.1. Balcony temperatures

Temperature measurements show that temperatures inside the balconies were higher than outdoor temperatures throughout the year. On average, the unglazed balcony temperature was 0.8 °C, and the glazed balcony temperature 3.7 °C, higher than outdoor temperature. During the heating season, the temperature differences were 0.8 °C and 4.1 °C, respectively. Solar radiation has also



**Fig. 5.** Balcony, outdoor air and flat temperatures from 13th to 15th March 2010. Solar radiation had a strong effect on balcony temperatures especially in spring. Solar radiation warmed up glazed space very rapidly causing great temperature difference between space and outdoors air. This phenomenon, however, had only a slight impact on the adjacent apartment indoor air temperatures as seen in the figure.





**Fig. 6.** Measured external surface temperatures of the windows from 5th to 7th January 2010. Balcony glazing stabilized temperature variations and temperature differences between the top and bottom edges of external window surfaces. The phenomenon is strikingly evident during the periods in which the temperature difference between the apartment and outside air was very high, as during cold winter days in January, for example.

a significant effect on the temperature conditions of glazed balconies (Fig. 5). Solar radiation in spring, for example, warmed up balconies very rapidly causing momentarily increase of the temperatures inside a glazed balcony. This phenomenon had only a slight impact on the adjacent apartment indoor air temperatures as seen in Fig. 5. The highest glazed balcony and outdoor air temperature difference was 14.0 °C measured on 12th December 2009 at 9 p.m.

### 5.1.2. Flat temperatures

Average temperature inside the flats varied from 22.0 °C to 28.4 °C and from 21.7 °C to 26.4 °C depending on whether the balcony was unglazed or glazed, respectively. On average, the flat with the unglazed balcony was 1.2 °C warmer than the flat with the glazed balcony. The greatest temperature difference between the flats was 2.1 °C (in January, the coldest winter month), and the smallest 0.2 °C (in September). The temperature difference between the flats was directly proportional to the temperature difference between the glazed and non-glazed balcony. As outdoor temperatures decreased, the temperature difference between the glazed and unglazed balcony and between adjacent flats increased, and vice versa. Possible reason for this was the draught caused by the colder air through the window supply air valve as well as colder window, door and wall surface temperatures that affect the operation of the radiator thermostat inside the flat without balcony glazing. The radiator under the window inside the flat without balcony glazing was warmer than in the other flat resulting higher inside temperatures i.e. the installation of the balcony glazing reduced need to eliminate the sense of draught by overheating the flat.

### 5.1.3. Balcony window, door, and back wall surface temperatures

Balcony window, door, and back wall external surface temperatures measured inside the glazed balcony exceeded those measured inside the unglazed balcony throughout the measurement period. On average, the window, door, and wall external surface temperatures measured inside the glazed balcony exceeded the respective temperatures measured inside the unglazed balcony by 2.5 °C, 2.0 °C, and 1.4 °C, respectively. The temperature difference between the external surfaces was clearly larger during the heating season than in summertime. The temperature difference between external window surfaces was 2.8 °C in winter and 1.7 °C in summer, between external door surfaces 2.4 °C in winter and 1.3 °C in summer, and between external wall surfaces 1.6 °C in winter and 1.0 °C in summer. The measurement results indicate that balcony glazing stabilized temperature variations and temperature differences

between the top and bottom edges of external window surfaces. The phenomenon was strikingly evident during the periods in which the temperature difference between the apartment and outside air was very high, as during cold winter days in January (Fig. 6), for example.

Internal surface temperatures of the flat with an unglazed balcony were higher than those of the flat with a glazed balcony. The surface temperatures were significantly influenced by radiator temperatures, which during the heating season were clearly higher in the flat with an unglazed balcony than in the one with a glazed balcony. On average, the window, door, and internal wall surface temperatures of the flat with an unglazed balcony exceeded the respective temperatures of the flat with a glazed balcony by 1.0 °C, 0.4 °C, and 2.0 °C, respectively. In the flat with an unglazed balcony, the radiator heating effect was particularly evident in wall and window surface temperatures. For example, on 24th March 2010 at 1 p.m., with an outdoor temperature of 1.7 °C, the radiator surface temperature in the flat with an unglazed balcony was 40 °C and in the flat with a glazed balcony 31 °C. The radiators were located on the interior side of the balcony back wall right under the window.

## 5.2. IDA-ICE 4.61 simulations

Simulation results are showed in a few different ways to illustrate the real meaning of the results. At first the mean values of the simulated and measured flat and glazed balcony inside temperatures and difference between those values are described. After that mean, standard and max deviations are calculated. Mean deviation is average of all individual difference between each value in a set of, and the average of all values of that set. It tells how far, on average, all values are from the mean value. The standard deviation in turn tells how tightly all the various examples are clustered around the mean in a set of data. Max difference is maximum difference between simulated and measured values in the data.

### 5.2.1. Glazed balcony and flat indoor air temperatures

During the simulation period, the measured and simulated glazed balcony and flat mean temperatures corresponded with an accuracy of  $-0.08$ – $0.12$  °C and  $0.40$ – $0.42$  °C, respectively, due to the simulation model detailing level (Table 3). The lowest mean temperature inside the glazed balcony achieved in the climate model with detailed window and the highest in the energy model with simplified window. Temperature difference between most detailed and simplest modelling method was approximately 0.20 °C through the entire simulation period. Two-thirds (about 0.135 °C) of this

**Table 3**  
Example calculations of measured and simulated temperatures, temperature differences and standard deviation as well as mean and maximum deviations inside the glazed balcony and the flat with a glazed balcony during the whole simulation period from 17th July to 31st December 2009.

	Average temperature [°C]		Temperature difference [°C]	Standard deviation	Mean deviation	Max difference
	Measured	Simulated				
<b>Glazed balcony</b>						
Energy model with detailed window	9.96	10.01	0.05	0.93	0.63	8.49
Climate model with detailed window	9.96	9.88	-0.08	0.94	0.63	8.71
Energy model with simplified window	9.96	10.08	0.12	0.94	0.64	8.49
Climate model with simplified window	9.96	9.94	-0.02	0.94	0.64	8.71
<b>Flat</b>						
Energy model with detailed window	23.35	23.75	0.40	0.32	0.26	1.38
Climate model with detailed window	23.35	23.75	0.40	0.32	0.25	1.34
Energy model with simplified window	23.35	23.77	0.42	0.32	0.25	1.48
Climate model with simplified window	23.35	23.77	0.42	0.32	0.25	1.44

+: simulated warmer, -: measured warmer.

**Table 4**  
Apartments energy consumptions and energy saving effect of glazed balcony calculated with four different calculation accuracy.

	Flat with glazed balcony [kWh]	Flat with unglazed balcony [kWh]	Energy saving effect [kWh]	Energy saving effect [%]
Energy model with detailed window	4642.2	4842.5	200.3	4.1%
Climate model with detailed window	4631.6	4833.6	202	4.2%
Energy model with simplified window	4630.8	4866.5	235.7	4.8%
Climate model with simplified window	4619.9	4858.4	238.5	4.9%

change was due to the difference between climate and energy model and one-third (about 0.065 °C) of due to the difference between simple and detailed window model. The higher glazed balcony temperature means less heat loss from inside the building to the balcony and at the same time lower the energy consumption of the building. As a result, the energy saving effect of the balcony glazing will be over-estimated (Table 4).

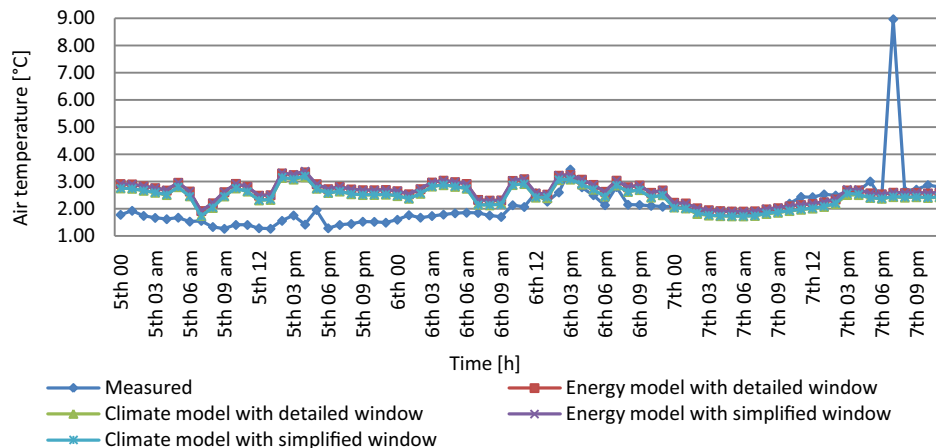
The standard and mean deviations were at the same level in all the calculations and so the difference between calculation accuracy was not seen in these results comparisons. The largest individual differences between measured and simulated glazed balcony temperatures were measured during moments when residents left the balcony door open to air the flat (Fig. 7) and do not therefore bring further clarity on the calculation accuracy. Such large difference did not occur at apartment temperatures. As a result, the smallest maximum difference between measured and simulated flat temperatures occurred in the climate model with detailed window (Table 3).

Energy saving effects differs from 4.1% to 4.9% according to calculation method (Table 4). The difference between the simplest and

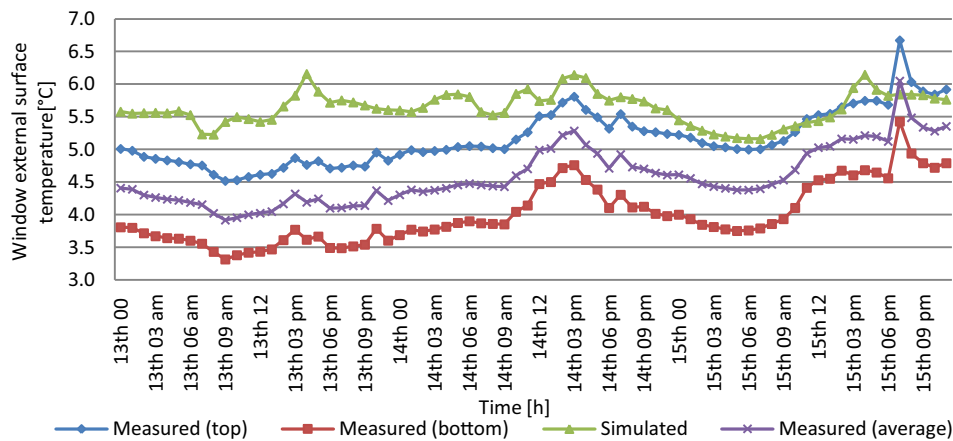
the most detailed calculation was 0.8% (15.7% change in the result). A simple window structure reduced the energy consumption of both flats, but roughly the same proportion, so that it had a very limited impact on energy saving effect of the balcony glazing. Simple and detailed window models energy saving effect differs only 0.1% (1% change in the result). Difference between energy and climate model was greater, about 36 kWh and 0.7% (14.7% change in the result). This review underlines the climate model use.

#### 5.2.2. Surface temperatures inside the glazed balcony

Surface temperature data simulation yielded promising results in the most detailed calculation. For example, the window external surface temperatures of the flat with a glazed balcony corresponded to the simulated values with an average accuracy of 0.27 °C and 0.92 °C (two measurement points), and the internal temperatures with an average accuracy of 0.42 °C and 0.65 °C. Simulated values were higher than measured values in the most detailed calculation (Fig. 8), but were even warmer in another simulation. For example, the external surfaces temperatures of the window corresponded to each other with an average accuracy of 0.69 °C and



**Fig. 7.** Measured and simulated air temperatures of the glazed balcony from 5th to 7th November 2009. The temporary divergence between the measured and simulated values was registered throughout the measurement period as a result of resident habit to left the balcony door open to air the flat. One example of this is shown on 7th November 2009 at 7 pm.



**Fig. 8.** Measured and simulated external surface temperatures of the window between the flat and the glazed balcony from 5th to 7th November 2009. The surface temperature data simulation yielded promising results.

1.34 °C, and the internal temperatures with an average accuracy of 0.44 °C and 0.67 °C in the simplest calculation. As seen from the previous results, the change in the calculation method affect only slightly to the surface temperatures of the internal surface, but significantly to the surface temperature of the external surface. For example, the change of the window external surface temperature was 0.42 °C (0.69–0.27 = 0.42 or 1.34–0.92 = 0.42) and of the internal surface temperature 0.02 °C (0.44–0.42 = 0.02 or 0.67–0.65 = 0.02). The zone model had a greater effect on the calculation results than the window model. About four-fifths of the difference cause from the differences between the climate and energy models and about one-fifth of the difference between the detailed and simplified window models. The results show clearly that the climate model with detailed window model is recommended to use in glazed space surface temperature calculations.

In the simulation, literature values for colour based absorption coefficients were used. Those coefficients cause generally a little warmer surface temperatures than measured ones and correspondence with measured and simulated values were better on the upper part of the structures (shaded by balcony slab) than on the lower part of the structures. One of the reasons was the fact that the unshielded surface temperature sensors on the lower part of the structures were exposed to the direct solar radiation and also to the sky radiation. As a result, these sensors warmed up strongly when the sun shines to the sensors and cooled more during the night as a reason for the higher exposure to the sky radiation. For eliminating these uncertainties, the real surface absorption coefficients would have been determined on site and the surface temperature sensors would have been protected against the direct solar radiation. The results, however, show that the reliable surface temperature values are possible to achieve with IDA-ICE, when using climate model with detailed window structure and reliable surface absorption coefficients.

### 5.2.3. The significance of different input parameters to the model accuracy

Parameters significance analysis shows that the importance of the detailed simulation method increases when the amount of glazing increase or external shading amount decrease (Table 5). For example, the simplest and most detailed calculation models accuracy difference changed 0.2–0.35, when amount of glazing altered from one to three sides of the glazed balcony and external tree shading was removed. On the other hand, the results also show that the difference between calculation results decreases when balcony inner surface absorption coefficients increase. This means that

dark surfaced balconies simulation accuracy difference is very small between the most detailed and simplest modelling method.

The results also show that wrong input parameters can have as significant or even greater impact on the results than different modelling method (Tables 5 and 6). For example, a change of 0.1 to the absorption coefficient causes greater effect on the calculation results (difference 0.28) than the model change from the detailed level to simplified one (0.2). In addition, the mean and standard deviation results indicate that the current calculation contains a lot of uncertainty (Table 3). Critical input parameters proved to be the amount of supply air from the glazed balcony, conduction losses from the building to the balcony and from the balcony to outdoor as well as the glazed balcony airtightness and balcony inner surface absorption coefficients.

### 5.2.4. Future perspective

In planning of similar simulation studies, special attention should be paid to the selection of the measurement site and favour rather simple measurement cases than complex ones. Another important issue is to set up a small-scale weather station for measuring wind speed, wind direction, air pressure and global horizontal radiation, direct normal radiation and diffuse radiation measurement on site. The problem in this case was that the solar radiation data was measured about 80 km, wind data 20 km and one part of the outdoor temperatures and relative humidity 20 km from site. This caused the uncertainty in the calculations. The third finding was the unshielded surface temperature sensors warming up under direct solar radiation causing error to the calculation results. This error could be avoided by using shielded surface temperature sensors. The fourth finding was the importance of using

**Table 5**

Different input parameters significance to the modelling accuracy. Result shows that the importance of the detailed simulation method increases when the amount of glazing increase or external shading amount decrease and decreases when balcony inner surface absorption coefficients increase.

Calculation case	Glazed space mean temperature difference between the most detailed and simplest calculations [°C]
Original	0.2
External tree shading excluded	0.30
Glazed side from one to three in the balcony	0.21
Glazed side from one to three in the balcony and external tree shading excluded	0.35
Absorption coefficient +0.1	0.17

**Table 6**  
Mean temperatures after model changes.

	Measured values [°C]	Originally simulated [°C]	Absorption coefficient +0.1 [°C]	30% of the external three shading excluded [°C]	Balcony glazing air leakage area halved (0.07–0.035 m <sup>2</sup> ) [°C]	Supply air vent size doubled in the wall between apartment and balcony (0.02 m <sup>2</sup> –0.04 m <sup>2</sup> ) [°C]
Climate model with detailed window	9.96	9.88	10.16	9.98	10.13	9.97
Difference between original simulation and changed simulation			0.28	0.10	0.22	0.09

measured thermal conductivity of the structures and balcony inner structures absorption coefficients. Now, the material  $U$ -values were determined by using real structure thickness and literature values for thermal conductivities. Material properties of windows and doors and  $U$ -values were from the manufacturer's product information. On this basis, the accuracy of the  $U$ -values was not absolute certainty. The fifth thing was the uncertainty of the balcony airtightness and real air flow through the balcony back wall air inlets vents. It will be possible to get a better understanding of the operation of the ventilation system in different wind conditions, and a more accurate picture of air movement from the outside to apartment through the glazed balcony by using long term measurements to track real air flow through those structures. Sixth, it is very hard to model mixed forest accurately in IDA-ICE programme. Therefore, it would have been preferable to select easier simulation site as external shading mean or set outside trees as closely as possible to the real situation after very detailed observation and measurements on site. Finally, it is very difficult to track real operation of inhabitants inside the apartment. The determination is very difficult in practice, because it is challenging to bound residents to follow instructions and if they undertake then the activity is known, but it might not be normal use of the building. Therefore, one option would be to choose a measurement site with a vacant apartment.

### 5.3. Simulation time

Calculation time varied between 29 min 11 s and 35 min 23 s depending on the calculation case (Table 2). Difference between the slowest and the fastest calculation was 6 min 36 s (difference 17.5%). Mostly slowdown was caused by the zone model change (about 16%), but also window model change caused a minor effect on the calculation time (1.5%). Energy and climate model calculation time differs very clearly, even though a total of 14 zones were in the built simulation model (7 per apartment). In the more complex simulation models, modelling time difference will be further emphasized.

## 6. Conclusion

Temperature measurements show that the temperature of the glazed and unglazed balconies is higher than outdoor temperature almost throughout the year. On average, the temperature of the unglazed balcony was 0.8 °C, and that of the glazed balcony 3.7 °C, higher than outdoor temperature. During the heating season, the temperature differences were 0.8 °C and 4.1 °C, respectively. Temperature differences between the balconies and outdoor air varied depending on time of day and season. As outdoor temperatures decreased, the temperature difference between the glazed balcony and outdoor air increased, and vice versa. The greatest temperature difference between the glazed balcony and outdoor air was 14 °C; it was measured on 12th December 2009 at 9 p.m.

The balcony window, door, and back wall external surface temperatures of the glazed balcony exceeded those of the unglazed

balcony throughout the measurement period. On average, the window, door, and wall external surface temperatures of the glazed balcony exceeded the respective temperatures of the unglazed balcony by 2.5 °C, 2.0 °C, and 1.4 °C. The temperature difference between the balconies was clearly larger during the heating season than in summertime. Internal surface temperatures of the flat with an unglazed balcony were higher than those of the flat with a glazed balcony. The surface temperatures were significantly influenced by radiator temperatures, which during the heating season were clearly higher in the flat with an unglazed balcony than in the one with a glazed balcony.

Literature review as well as comparison of the simulated and measured temperatures suggests that IDA-ICE 4.61 software is well suited for energy efficiency evaluation of balcony glazing. The highest modelling accuracy can be obtained by using a detailed window structure (Detwind) and a zone (Climate) model. Of these, the zone model had a greater effect on the calculation results than the window model. The simulation results also show that the wrong input parameters can affect as significant or even greater impact on the results than difference between model detailing levels. For example, 0.1 change to the absorption coefficient causes greater effect on the calculation results (difference 0.28) than model change from the detailed level to simplified one (0.2). The software's calculation accuracy depends on the correctness of the source data entered and the model detailing level. Both should be paid attention in the simulation studies.

## References

- [1] C. Boonstra, Glazed Balconies in Building Renovation, Brochure, James and James, London, UK, 1997, pp. 16.
- [2] A.R. Rempel, A.W. Rempel, K.V. Cashman, K.N. Gates, C.J. Page, B. Shaw, Interpretation of passive solar field data with EnergyPlus models: un-conventional wisdom from four sunspaces in Eugene, Oregon, *Build. Environ.* 60 (2013) 158–172.
- [3] G. Mihalakakou, On the use of sunspace for heating/cooling in Europe, *Renew. Energy* 26 (3) (2002) 415–429.
- [4] O.B. Joergensen, L.T. Nielsen, Monitored results from yellow house, in: Proceedings of the EuroSun2000 ISES-European Solar Conference, Copenhagen, Denmark, 19–22 June, 2000.
- [5] O.B. Joergensen, L.T. Nielsen, Monitored results from an innovative solar renovation of multi-storey housing-EU SHINE-Engelsby, Flensburg, in: Proceedings of the EuroSun2000 ISES-European Solar Conference, Copenhagen, Denmark, 19–22 June, 2000.
- [6] J.S. Mattila, Effect of balcony glazing on the durability of concrete structures in Nordic climate, in: Proceedings of Sustainable Construction, Materials and Practice Conference, Portugal, 2007.
- [7] S.T. Elias-Ozkan, F. Summers, Ö. Taner, Energy efficiency of building with a solar space: two case studies from the Anatolian plateau, in: Proceedings of the International 26th PLEA Conference, Montreal, Canada, 22–24 June, 2009.
- [8] G. Shoenau, A. Lumbis, R. Besant, An examination of operating strategies for energy efficient operation of attached sunspaces in cold climates, *Energy Convers. Manag.* 33 (1) (1992) 23–36.
- [9] G. Oliveti, N. Arcuri, M.D. Simone, R. Bruno, Solar heat gain and operative temperature in attached sunspaces, *Renew. Energy* 39 (1) (2012) 241–249.
- [10] A. Haller, Improvement of Solar Renovation Concepts and Systems, A Technical Report of IEA SHC Task20 "Solar Energy in Building Renovation", Ernst Schweizer AG, Metallbau, Hedingen, 1999, pp. 42, 49, 50, 70, 71.
- [11] O.B. Joergensen, Design of Solar Renovation Projects, A Technical Report of IEA SHC Task20 "Solar Energy in Building Renovation", Ernst Schweizer AG, Metallbau, Hedingen, 1998, pp. 47, 100.

- [12] ASHRAE Standard 55 Project Committee, Appendix C: acceptable approximation for operative temperature, in: ANSI/ASHRAE Standard 55-2004: Thermal Environmental Conditions for Human Occupancy, American Society for Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 2004, p. 20.
- [13] D.J. Frey, Performance monitoring and results, in: J.D. Balcomb (Ed.), *Passive Solar Buildings*, MIT Press, Cambridge, MA, 1992, pp. 399–484.
- [14] M.S. Owen, H.E. Kennedy, *Fundamentals*, ASHRAE Handbook, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 2005.
- [15] M.P. Wilson, O.B. Jorgensen, G. Johannesen, Daylighting, energy and glazed balconies: a study of a refurbishment project in Engelsby, near Flensburg, Germany, *Light. Res. Technol.* 32 (3) (2000) 127–132.
- [16] G.J. Schoenau, A.J. Lumbis, R.W. Besant, Development and verification of a simulation model for predicting the thermal behavior of attached sunspaces, *Energy Convers. Manag.* 32 (4) (1991) 319–331.
- [17] J.-M. Mottard, A. Fissore, Thermal simulation of an attached sunspace and its experimental validation, *Sol. Energy* 81 (3) (2007) 305–315.
- [18] J.J. Roux, C. Teodosiu, D. Covalet, R. Chareille, Validation of a glazed space simulation model using full-scale experimental data, *Energy Build.* 36 (6) (2004) 557–565.
- [19] A. Laouadi, M.R. Atif, Comparison between computed and field measured thermal parameters in an atrium building, *Build. Environ.* 34 (2) (1998) 129–138.
- [20] A. Voeltzel, F.R. Carrié, G. Guarracino, Thermal and ventilation modelling of large highly-glazed spaces, *Energy Build.* 33 (2001) 121–132.
- [21] K.M. Bataineh, N. Favez, Analysis of thermal performance of building attached sunspace, *Energy Build.* 43 (8) (2011) 1863–1868.
- [22] P.G. Loutzenhiser, H. Manz, S. Moosberger, G.M. Maxwell, An empirical validation of window solar gain models and the associated interactions, *Int. J. Therm. Sci.* 48 (1) (2009) 85–95.
- [23] M. Wall, Climate and energy use in glazed spaces, Report no TABK-96/1009 (PhD thesis), Lund University, Lund, 1996, pp. 404.
- [24] G. Mihalakakou, On the use of sunspace for space heating/cooling in Europe, *Renew. Energy* 26 (3) (2002) 415–429.
- [25] G. Mihalakakou, A. Ferrante, Energy conservation and potential of a sunspace: sensitivity analysis, *Energy Convers. Manag.* 41 (12) (2000) 1247–1264.
- [26] M. Wall, A design tool for glazed spaces, part I: description, *ASHRAE Trans.* 101 (2) (1995) 1261–1271.
- [27] P. Pfrommer, K.J. Lomas, Chr. Kupke, Solar radiation transport through slat-type blinds: a new model and its application for thermal simulation of buildings, *Sol. Energy* 57 (2) (1996) 77–91.
- [28] M. Wall, Distribution of solar radiation in glazed spaces and adjacent buildings. A comparison of simulation programs, *Energy Build.* 26 (1997) 129–135.
- [29] N. Cardinale, F. Ruggiero, Energetic aspects of bioclimatic buildings in the Mediterranean area: a comparison between two different computation methods, *Energy Build.* 31 (2000) 55–63.
- [30] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, *Build. Environ.* 43 (2008) 661–673.
- [31] E.M. Ryan, T.F. Sanquist, Validation of building energy modeling tools under idealistic and realistic conditions, *Energy Build.* 47 (2012) 375–382.
- [32] ISO/FDIS 15099:2003(E), *Thermal Performances of Windows, Doors and Shading Devices—Detailed Calculations*, 2003.
- [33] A. Bring, P. Sahlin, M. Vuolle, Models for Building Indoor Climate and Energy Simulation, A Report of Task 22, Building Energy Analysis Tools Version 1.02, Royal Institute of Technology in Stockholm, 1999.
- [34] J. Travesi, G. Maxwell, C. Klaassen, M. Holtz, Empirical Validation of Iowa Energy Resource Station Building Energy Analysis Simulation Models IEA Task 22 Sub-task A, 2001.
- [35] S. Kropf, G. Zweifel, Validation of the Building Simulation Program IDA-ICE According to CEN 13791 ‘Thermal Performance of Buildings – Calculation of Internal Temperatures of a Room in Summer Without Mechanical Cooling – General Criteria and Validation Procedures’, Luzern, 2001.
- [36] M. Achermann, G. Zweifel, RADTEST – Radiant Heating and Cooling Test Cases, Subtask C, A Report of IEA Task 22, Building Energy Analysis Tools, 2003.
- [37] F. Karlsson, P. Rohdin, M.-L. Persson, Measured and predicted energy demand of a low energy building: important aspects when using building energy simulation, *Build. Serv. Eng. Res. Technol.* 28 (3) (2007) 223–235.
- [38] S. Moosberger, IDA-ICE CIBSE-validation, Test of IDA Indoor Climate and Energy Version 4.0 According to CIBSE TM33, Issue 3, Report, HTA, Luzern, 2007.
- [39] P. Loutzenhiser, H. Manz, G. Maxwell, Empirical Validations of Shading/Daylighting/Load Interactions in Building Energy Simulation Tools, A Report for the International Energy Agency’s SHC Task 34/ECBCS Annex 43 Project C, 2007.
- [40] Equa Simulation Technical Group, Validation of IDA Indoor Climate and Energy 4.0 Build 4 with Respect to ANSI/ASHRAE Standard 140-2004, Technical Report, Solna, Sweden, 2010.
- [41] T. Kalamees, IDA ICE: the simulation tool for making whole building energy- and HAM analysis, in: Annex 41 MOIST-ENG, Working Meeting, Zurich, Switzerland, 12–14 May, 2004.
- [42] Equa Simulation AB, User Manual, IDA Indoor Climate and Energy, Version 4.5, 2014. Available from <http://www.equasonline.com/iceuser/pdf/ICE45eng.pdf> (accessed 04.07.14).
- [43] R. Perez, P. Ineichen, R. Seals, J. Michalsky, R. Stewart, Modelling daylight availability and irradiance components from direct and global radiance, *Sol. Energy* 44 (5) (1990) 271–289.
- [44] J. Vinha, A. Laukkanen, M. Mäkitalo, S. Nurmi, P. Huttunen, T. Pakkanen, P. Kero, E. Manelius, J. Lahdensivu, A. Köliö, K. Lähdesmäki, J. Piironen, V. Kuhno, M. Pirinen, A. Aaltonen, J. Suonketo, J. Jokisalo, O. Teriö, A. Koskenvesa, T. Palolahti, Ilmastonmuutoksen ja lämmöneristyksen lisäyksen vaikutukset vaipparakenteiden kosteusteknisessä toiminnassa ja rakennusten energiankulutuksessa, Tampereen teknillinen yliopisto, Rakennustekniikan laitos, Tampere, 2010, Tutkimusraportti 159, 354 s. + 43 liites.
- [45] P. Pirinen, H. Simola, J. Aalto, J.-P. Koukoranta, P. Karlsson, R. Ruuhela, Tilastoja Suomen ilmastosta, Ilmatieteen laitos, Helsinki, 2012, Raportteja 1, 96 s.
- [46] ASHRAE, International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM, ASHRAE, Atlanta, 2001.
- [47] International Weather for Energy Calculations (IWEC), EnergyPlus Energy Simulation Software Weather Data Sources, 2014, Available from [http://apps1.eere.energy.gov/buildings/energyplus/weatherdata\\_sources.cfm#IWEC](http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm#IWEC) (accessed 13.06.14).
- [48] M. Kottek, J. Greiser, Beck, et al., World map of the Köppen–Geiger climate classification updated, *Meteorol. Z.* 15 (3) (2006) 259–263.
- [49] Heating Degree Days, Finnish Meteorological Institute, 2014, Available from <http://en.ilmatieteenlaitos.fi/heating-degree-days> (accessed 12.06.14).
- [50] Weather in 2009, Finnish Meteorological Institute, 2014, Available from <http://en.ilmatieteenlaitos.fi/weather-in-2009> (accessed 12.06.14).

II

**ENERGY SAVING POTENTIAL OF GLAZED SPACE: SENSITIVITY ANALYSIS**

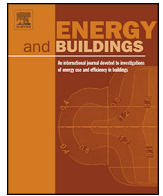
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## Energy saving potential of glazed space: Sensitivity analysis



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### ABSTRACT

This study focuses on the impact of different types of glazed balconies on the energy consumption of buildings in northern climatic conditions. The starting point was a glazed balcony in a typical Finnish block of flats of the 1970s, whose impact on the energy consumption of the building was analysed with the IDA-ICE 4.6.1 software based on 156 different calculation cases. In light of the results of the sensitivity analysis, the five key factors affecting the energy engineering design of a glazed space are the integration of the space to the building's ventilation system, heat losses from the building to the balcony and from the balcony to outdoor air, the air tightness of the balcony and the absorption coefficients of its surfaces. Research has shown that higher energy savings in kilowatt hours can be achieved in a northern than a southern climate although percentage-wise savings are higher, for example, in Central Europe than in Finland. Thus, the determination of energy savings by kilowatt hour gives a better idea of the true significance of balcony glazing in a building than a percentage-wise analysis.

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### 1. Introduction

Large glazed spaces have been architecturally and structurally interesting building details for centuries [1–3]. Their attraction has been based on the large size of the spaces, novel architectural solutions and interesting details. However, these spaces have not usually been built solely for architectural reasons but functional requirements have also been set for them as they have served as hospital waiting areas, or as reception areas of office buildings. The design of such spaces is based on the required indoor air conditions, such as minimum acceptable indoor air temperature, desired average temperature and maximum acceptable temperature. They determine the implemented solution, which takes into account issues such as heat losses of the building and the space, storage of solar radiation, solar protection and minimisation of cooling and heating needs, if the required indoor conditions cannot be achieved without an external energy source [4].

Glazed spaces in Finland are not usually big and impressive structures but quite simple and rather small spaces, such as glazed balconies. According to information received from the manufacturers, more than 500,000 of them have been installed in this country.

Comparison of this figure to the housing database of Statistics Finland reveals that about 70% of Finnish flat balconies are glazed. As a rule, glazing has not been installed to improve indoor temperature conditions, nor has the glazed space been designed for maximum thermal comfort, but the basic idea in our northern climate has been to improve the usability of the space and protect the balcony structures enclosed by the glazing [5]. Therefore, no special requirements for the indoor air conditions of glazed balconies have been presented in Finland.

The most typical Finnish balcony solution consists of stacked balconies on separate foundations protruding from the facade [6] implemented as an uninsulated precast concrete structure with untight single glazing [7]. For this reason, continuous heating of the balcony is uneconomical [8] and very rare in these latitudes. It is also typical in Finland that the energy saving and overheating impacts of balcony glazing are not known and therefore some residents keep their balcony glazing partly open through the winter, reducing the energy saving impact, and fully closed during summer, which causes overheating problems [9,10]. Thus, practical advice on the energy and indoor climate impacts and optimal use of glazing is needed. The need of such information has also been observed in previous studies [4,11].

The purpose of this study is to reveal the factors affecting the energy engineering design of glazed spaces and the magnitude of their impacts in northern climate by sensitivity analysis. In the same context, we also intend to indicate the factors with the greatest impact on the energy efficiency of buildings and produce

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information that allows improving the impact of energy efficiency measures undertaken in renovation and new construction. The basic case is a typical Finnish prefabricated concrete block of flats completed in the 1970s with protruding balconies.

## 2. Factors affecting the thermal conditions of glazed spaces—Background

One factor that affects the temperature conditions of glazed spaces is the location of a building. It has virtually no effect on the ability of the glazed space to store solar radiation [4], but a different location changes outdoor air conditions which may have a significant impact on the energy savings achieved by the glazed space. It is typical of cloudy and rainy climatic conditions that the share of diffuse radiation of short-wave solar radiation is large [12]. In windy areas glazing plays an important role as a thermal buffer zone, reducing heat losses by transmission and infiltration [13]. Rain falling on the glazing is also of significance because it cools down the exterior surface of the glazed structure and increases heat losses to outdoor air. Spray irrigation is actually used as a cooling method in warm climates [14].

The basic principle regarding location is that the more southern and milder the climate is, the bigger the energy savings percentage-wise. This is due to the increased amount of energy absorbed by the space due to the increased intensity of solar radiation [15]. However, the energy savings in kilowatt hours decrease simultaneously [16]. The highest energy savings are possible in a sunny and cold climate [13], such as that of the Southern European Alps. From the point of view of the availability of solar energy it is important that the space is appropriately orientated towards the equator ( $\pm 30^\circ$ ), although it has been observed that orientation does not play a major role as an energy saving issue [17].

To maximise the temperature difference between the glazed space and outdoor air, it is really important to optimise the balcony type and size, as well as the thermal insulation capacity and air-tightness of the structures. As a balcony type a recessed glazed balcony is superior to a protruding balcony because it has a smaller exterior glazing and profits more from the building heat losses and solar energy absorbed by the walls that connect the balcony space to the interior space [17,18]. Increasing the length of a balcony also increases heat losses from the building to the balcony. In general, a long and narrow balcony is recommended for maximising energy savings and natural light [19].

The material properties of the glazed space and the building external wall affect the energy savings gained by the glazed space. According to Ref. [20], for example, the thermal conductivity of the wall has a strong influence on the heat flux through the wall, but the density and heat capacitance (C) do not affect the values of the heat flow or the air and wall temperatures greatly [20], albeit heat capacitance affects temperature variations and thermal comfort of the space [4]. By contrast, the absorption coefficients of the surfaces and the ability of the space to store solar radiation have a strong impact on the interior temperatures of the glazed space and achieved energy savings [4].

External obstructions and solar shading affect the solar radiation stored in the glazed space. The presence of shadings during the winter months increases the thermal resistance of the sunspace external walls and blocks radiation exchange between sunspace walls and deep sky [15,21]. In summer, relatively large glazed areas of glazed balconies can lead to overheating of the balcony or the adjacent rooms [8] even in northern climates [22] in the absence of shading.

The air-tightness of the balcony has a marked impact on the temperatures of the glazed space. Ventilation with outdoor air removes a fraction of the energy absorbed and consequently lowers the

temperature of the sunspace [15]. The air exchange rate of untight glazed spaces varies daily and is highly dependent on the temperature difference between the glazed space and outdoor air as well as wind conditions [4]. The building's ventilation solution also affects the end result. From the point of view of the heating energy savings of a building it is advisable to integrate the glazed space with the mechanical exhaust ventilation and thus utilise the glazed balcony as a supply air pre-heater [13]. In this case summer time overheating of the glazed space could cause also warming of the adjacent flat, if the supply air terminals between the glazed balcony and the flat are not easily closable [23]. A recommended solution for preventing the glazed space temperature rise is the use of appropriate solar shading [22] and opening of the glazing [24].

## 3. Research materials and methods

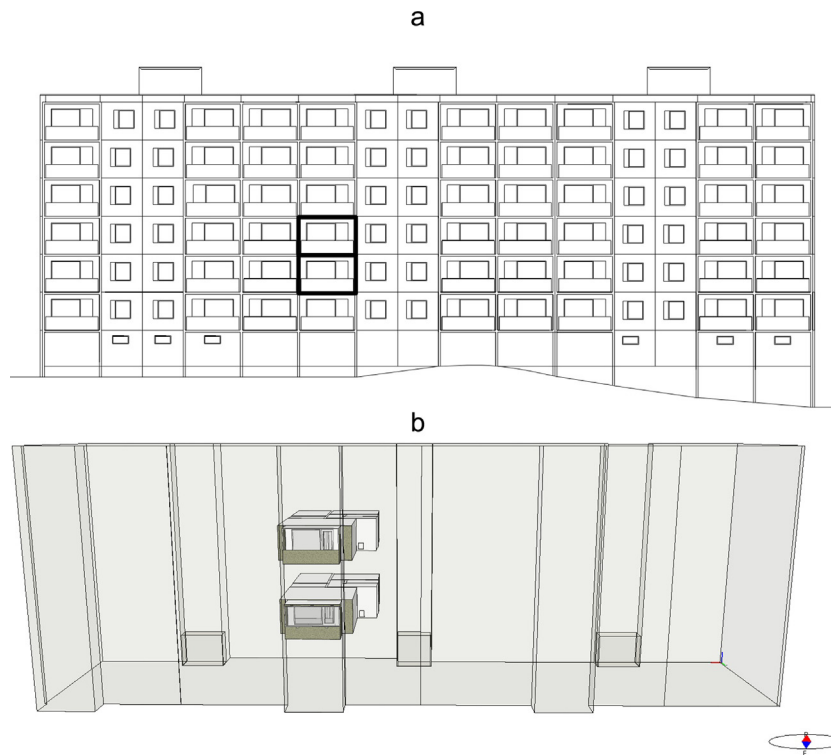
### 3.1. IDA-ICE simulation

The energy engineering analysis of glazed spaces is a special calculation case, and no commercial energy simulation software has been designed specifically for it. Thus, used simulation software is usually validated before it is used to model glazed spaces. An important aspect of the calculations is that the dynamic simulation software should take daily and yearly climatic variations into account, model the spaces geometrically, divide solar radiation into direct and diffuse radiation and correctly distribute solar radiation into the space and the adjoining building as well as through window structures. Surface resistances must also be calculated as temperature-dependent variables and more attention be paid to long-wave sky radiation calculations than in normal energy calculation [4]. The IDA-ICE 4.6.1 software used in this study incorporates the above features [25]. The software as many other whole building energy simulation tools is based on the building geometrical description, which provides the basis for a more detailed calculation of the distribution of solar radiation in and between rooms. The software calculates energy balances dynamically taking into account climatic variations and a dynamically varying time-step. The software solves heat balance equations according to the user defined building geometry, construction, HVAC conditions and internal heat loads. Software allows use of measured climate and weather file containing the information about air temperature, relative humidity, wind direction and speed, direct normal radiation and diffuse (sky) radiation on a horizontal surface and calculates for example solar radiation based on the building location and sun position in the sky. Accuracy of the IDA-ICE simulation tool has been examined in many validation studies in recent years [26–36]. Accordingly, selection of the IDA-ICE as the simulation tool for highly glazed space simulation is well grounded [26,28,37,38].

### 3.2. The modelled building and its main parameters at the beginning of the simulation

The idea of the simulation study was to create a base model which represents the typical building in Finland as well as possible. Then, a sensitivity analysis was conducted by making successive changes to the base model and performing re-simulations after each step. The variables were chosen from parameters found in a literature review to have an impact on the energy savings achieved by balcony glazing. This analysis was used to determine the relative effect of each individual parameter on building energy consumption. The final analysis included 34 calculation variables and 2 to 35 calculation cases for each. The total number of calculation cases in the sensitivity analyses was 156. The sensitivity analyses covered a wider scope than any of the studies presented in Section 2.





**Fig. 1.** (a and b) Architect's drawing (a) and simulation view (b) of the building's balcony facade. The balconies are located on top of one another (a), and the temperature conditions were as measured in a previous study [25] but simulated without heat transmission by separating them from each other. The lower balcony of the two is equipped with glazing.

The building subjected to the simulations is a typical Finnish 1 + 6 storey prefabricated concrete block of flats completed in the 1970s with 3 stairwells and 54 flats (Fig. 1). The façade of the building is of prefabricated sandwich-type panels consisting of thermal insulation between two relatively thin reinforced concrete layers connected to each other by steel trusses. The south-facing balconies are precast concrete structures with a floor slab, side panels and a parapet panel standing on their own foundations. The structures are light-coloured and have relatively high thermal masses. The structures of the subject building are based on the Concrete Element System published in 1969 [39]. Its structures and properties are highly representative of a typical 1970s block of flats in Finland [6]. The same structural system is in use in over 30,000 buildings built in 1965–1995 [40].

The simulation begins with the assumption that the building lies on open terrain in a typical Finnish suburb in Helsinki, connected to the district heating network and ventilated by a mechanical exhaust ventilation system. The building's structural characteristics, HVAC technology and standard of equipment are selected from the typical solutions used in 1970s blocks of flats [6,41]. The number of occupants and their living habits are assumed to correspond to those of a typical flat occupant in Finland [41]. The balcony glazings used consist of untight single-glazed individually opening glass panes most commonly used in Finland. Detailed information about the building, its characteristics and the simulation software's main input parameters are described in Fig. 2 and Table 1.

The simulations targeted two flats on top of one another; the balcony of the upper flat was not glazed whereas the balcony of the lower one was (Fig. 1a). Heat flow between the flats was prevented by insulating them from each other (Fig. 1b). Heat flow from the kitchen and bedroom to outdoor air was also prevented, so heat flow between the flat and outdoor air generally occurred only through the façade at the balcony. Thus, the heat losses at the

balcony via the window, door or wall represented 100% of the heat losses through the building envelope.

## 4. Results and discussion

### 4.1. Basic level

In the base model used as a starting point of the simulations, the heating energy consumption of the building was 3593.2 kW h in the case of a flat with a glazed balcony and 4135.9 kW h without glazing. Glazing saved 542.7 kW h (13.1%) of heating energy. Changes were made to this model one at a time and the simulation was run again after each change. Each calculation case with its results, except location, was recorded under a unique alphanumeric code. The first column (A) shows the initial situation or the base model whose data are also shown in Table 1. The results are presented both in kilowatt hours and percentages.

### 4.2. Availability of solar energy and ambient environmental conditions

Energy savings within Finland varied between 749 and 543 kW h (10.9–14.9%) based on location (Fig. 3). Its impact was clearly stronger than that of orientation, whose impact on energy savings varied from 499 to 543 kW h (11.0–13.1%) (Table 2). As a rule, savings measured in kilowatt hours increase as we move from south to north while percentage-wise savings decrease (Fig. 3). In percentage terms, the biggest savings could be attained in the Mediterranean countries, but considering the possible increased need of cooling and modest savings in kilowatt hours the impact of glazing is considerably greater in a northern climate than in the Mediterranean countries.

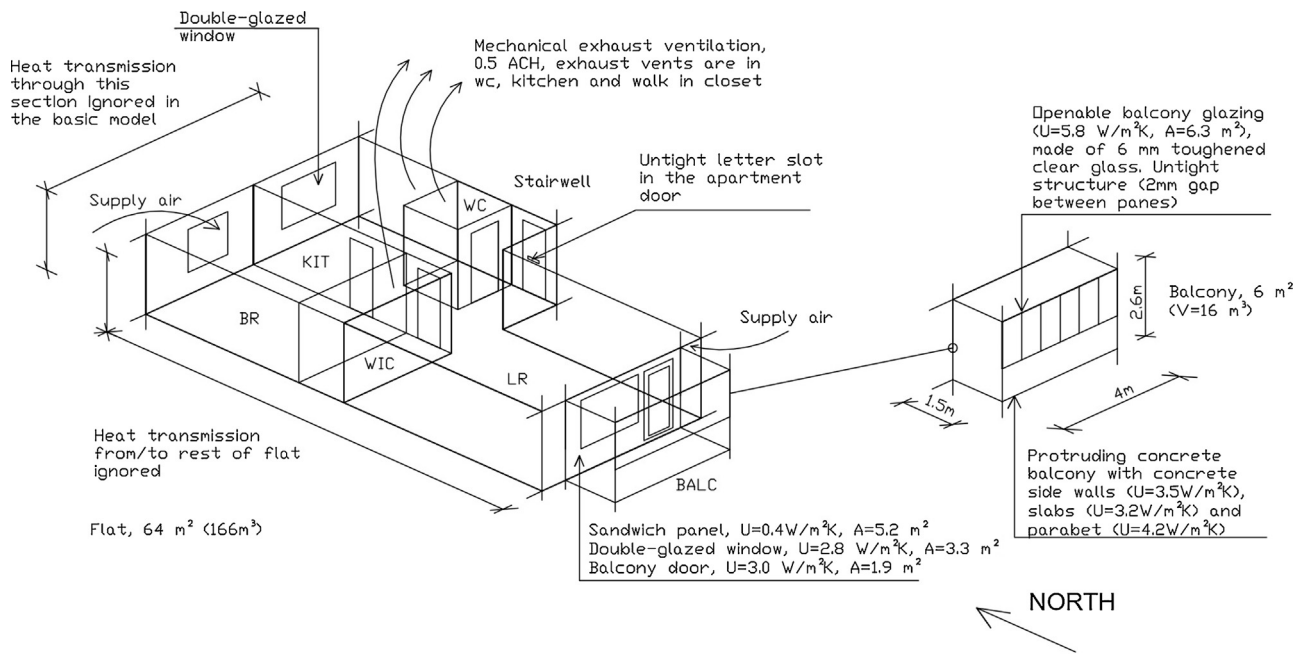


Fig. 2. Illustration of the simulated flat.

Table 1  
Base model input data table.

1	Location (climate condition)	Helsinki (60°10'15"N, 24°56'15"E), Finland
2	Orientation	South
3	Wind profile	Suburban
4	Balcony façade distance from the building in front	No building in front
5	Flat size (room number)	Two-rooms
6	Flat inside air temperature	21 °C
7	Standard of equipment and number of occupants	According to Finnish building regulations
8, 9, 10	Balcony window, door, and wall U-values	2.8, 3.0 and 0.4 W/m <sup>2</sup> K respectively
11, 12	Balcony type (depth) and balcony width	Protruding balcony measuring 1.5 m × 4.0 m
13	Number of glazed sides (parapet-type)	One side glazed (concrete parapet)
14, 15	Balcony glazing type (air-tightness) and thickness of glazing	Single clear glass (unsealed structure) and thickness 6 mm
16	Flat type	Exterior wall only on one side of the building
17, 18	Vertical and horizontal position of the balcony in building	Middle residential floor
19	Building ventilation type (air change rate)	Mechanical exhaust ventilation (0.5 ACH)
20	Supply air intake solution	Directly from the outside
21	Glazed space unintended ventilation	2–4 ACH
22	Openness of the balcony glazing (balcony glazing airing)	Completely closed
23	Building air leakage coefficient (at 50 Pa pressure difference)	1 ACH
24	Heating capacity design of hot water radiators	Heating capacity 140% of the building heat losses in Sodankylä
25	Heating system control curve position	Initial settings (Sodankylä design condition)
26	Heating system summer shut-off	Summer shut-off in June, July and August
27	Building's heat delivery system	Hot water radiator heating system (70/40 system)
28	Heat losses from the heat delivery system to the flat	No heat loss
29	Specific heat capacity of balcony structures	880 J/(kg K)
30	Lambda value of balcony structures	2.5 W/(m K)
31	Density of balcony structures	2300 kg/m <sup>3</sup>
32	Surfaces absorptivity (Balcony and external wall)	0.95
33	Surface emissivity (Balcony and external wall)	0.95
34	Window or balcony glazing blinds placement position	No blinds

A southern orientation is better than others, but the overall effect of orientation on the end result was rather modest, only 44 kW h. This is due to the closed glazed space under analysis and northern climate (weather data for Helsinki). In these conditions with only 6.3 m<sup>2</sup> of glazing on one side, hardly any solar radiation energy enters the glazed space during the winter months, so energy savings come mainly from smaller heat losses of the building. Closer to the equator and with a larger glazed area the significance of glazing would increase considerably in percentage-wise analysis, while there would be virtually no change in kilowatt hours. For example, in Barcelona conditions with a balcony glazed on three sides the energy saving impact varied between 217 and 247 kW h

(19.4–42.2%) due to orientation. The variation in percentage-wise savings was almost exclusively due to change in orientation and the variation in savings in kilowatt hours due to change in glazed area. An increase in glazed area slightly increased the energy savings in kilowatt hours provided by balcony glazing.

On the level of individual flats, the wind profile had only a minor impact on energy savings, as shown by Table 2. Likewise, external shading did not seem to have much impact on the end result although it increased the total energy consumption of flats considerably. On the basis of the results, an obstruction of building height 10 to 20 m from the glazed balcony does not reduce the availability of solar radiation significantly (Table 2).

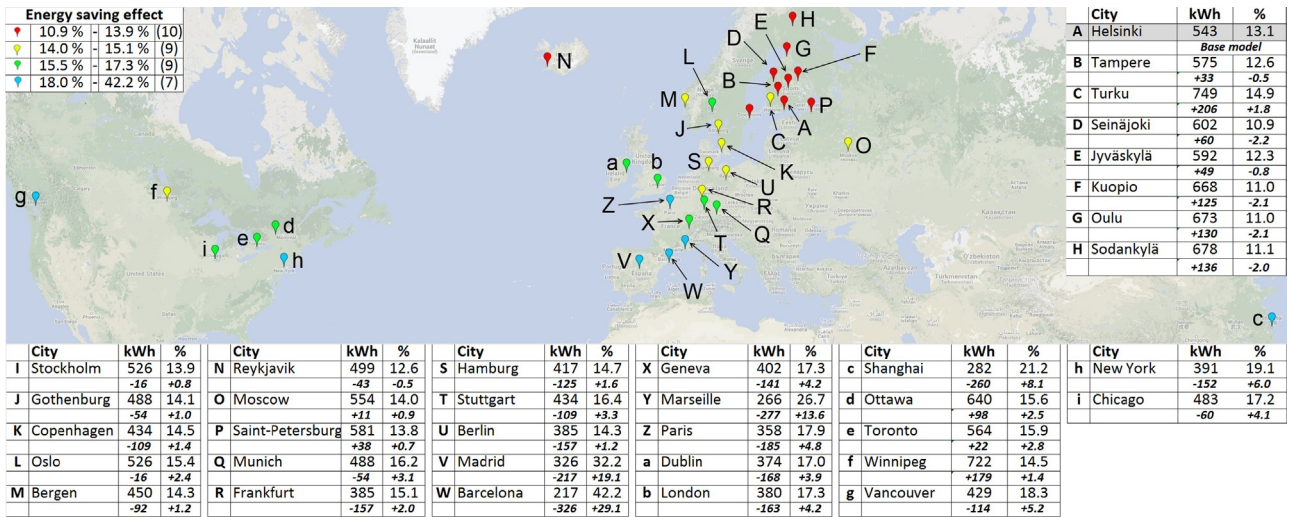


Fig. 3. Impact of building's geographical position (latitude) on the energy savings achieved by a glazed space. The results are absolute yearly values. In the initial simulation situation (base model) the building was situated in Helsinki, Finland.

Table 2

Orientation, wind profile and external obstruction calculation results. Column A shows the base model, that is, the case to which simulation results are compared after individual changes. The results are presented both as absolute savings and as differences to the base model.

	A	B	C	D	E	F	G	H
	kWh %	kWh %	kWh %	kWh %	kWh %	kWh %	kWh %	kWh %
<b>2 Orientation</b>	<b>South</b>	<b>South–West</b>	<b>West</b>	<b>North–West</b>	<b>North</b>	<b>North–East</b>	<b>East</b>	<b>South–East</b>
Absolute savings	543 13.1	516 12.4	499 11.7	505 11.1	505 11.0	510 11.3	499 11.7	510 12.3
Difference to base model		-27 -0.7	-43 -1.4	-38 -2.0	-38 -2.1	-33 -1.8	-43 -1.4	-33 -0.8
<b>3 Wind profile</b>	<b>Suburban</b>	<b>City centre</b>	<b>Open country</b>					
Absolute savings	543 13.1	548 13.2	537 13.0					
Difference to base model		+5 +0.1	-5 -0.1					
<b>4 Building distance from the building in front</b>	<b>No building in front</b>	<b>10–20 m</b>	<b>20–100 m</b>	<b>100 m</b>				
Absolute savings	543 13.1	570 12.7	548 13.0	548 13.1				
Difference to base model		+27 -0.4	+5 -0.1	+5 0.0				

4.3. Flat size and usage habits

In the analysis of the impact of flat size, the area of the envelope was kept constant and only the number of rooms inside the building was varied depending on the case. Thus the heat losses from the envelope and the benefit from the heating energy of solar radiation remained the same while the number of occupants, power consumption of lighting and electrical equipment as well as air exchange rate changed in direct proportion to flat size. From that perspective, energy savings varied from 526 to 543 kWh (10.6–15.9%) between different cases. About equal savings in kilowatt hours thus appear larger in the case of a one-room flat than a three-room flat. A comparison of energy savings in kilowatt hours is therefore more sensible.

The temperature inside a flat has a significant impact on the building's energy consumption. For example, raising the internal temperature from 19 °C to 23 °C increases the energy consumption of a flat without balcony glazing from 3479 to 4790 kWh (by 1311 kWh). Percentage-wise the total change in energy consumption is 27% (a change of 4 °C in indoor temperature), which means that raising the temperature of a flat by one degree increases its heating energy consumption by approx. 7%. The results presented in Table 3 also reveal that percentage-wise balcony glazing appears to be most useful in buildings where indoor temperatures are kept as low as possible, but based on kilowatt hours the benefit increases

with increasing indoor temperatures. On the whole, the results varied between 467 and 592 kWh (12.3–13.4%) due to changes in indoor temperature. The impact of glazing in kilowatt hours was stronger than that of orientation or external shading.

In the base model the standard of equipment and usage of the building corresponded to the national calculation guidelines of Finland and were based on floor area [42] with respect to the number of occupants (3 W/m<sup>2</sup>), lighting (11 W/m<sup>2</sup>) and electrical equipment (4 W/m<sup>2</sup>) as well as presence and usage times. These values correspond to typical usage of a flat in Finland [41]. In other calculation cases these values were changed by the percentages presented for each case. Table 3 shows that increasing the amount of electrical equipment, lighting and occupants increases internal heat loads which, consequently, reduces the need of heating energy. This is reflected in smaller savings in kilowatt hours. However, at the same time the relative significance of balcony glazing for the energy savings of the entire building grows, which means that savings increase in percentage terms.

4.4. Building and glazed space thermal losses

The insulation level of the structures between the building and the glazed space, such as windows, doors and wall, have a decisive impact on energy savings, since they largely determine how much thermal energy escapes through the structures from the flat to the



balcony, that is, how much energy the space “receives” from the flat (Table 4). The impact is even bigger if the insulation level of windows, doors and the wall is improved simultaneously. For example, changing the insulation level of windows, doors and the wall from the level of column A to the level of column E cuts energy savings from 13.3% to 3.4%.

Balcony type and size also have a decisive impact on the heat loss energy received by the balcony. From the viewpoint of energy savings, the best solution is a large recessed balcony and the poorest a small protruding balcony. A comparison of the energy savings impact of a 3 m deep recessed balcony in a building with a poor thermal insulation level (Table 4, Case 11D; 23.3%) to that of a 1.5 m deep protruding balcony (example in Section 4.4; 3.4%) demonstrates graphically the energy-saving significance of the ratio of the thermal energy lost to outdoor air through the glazed space to energy received from the building. The difference in the energy savings of the above cases was about 7-fold.

Increasing the number of glazed sides in the balcony also impacts the energy savings from balcony glazing. This impact is highly linear and similar in both kilowatt hour and percentage-wise analyses. In the base model, the protruding balcony has an airtight concrete parapet ( $U = 4.2 \text{ W/m}^2 \text{ K}$ ), solid side walls ( $U = 3.5 \text{ W/m}^2 \text{ K}$ ) and untight balcony glazing ( $U = 5.8 \text{ W/m}^2 \text{ K}$ ). Due to an increase in the number of glazed sides (Case 13), the space collects more solar radiation throughout the year while at the same time heat losses from the space to outdoor air increase because of lower  $U$ -values and higher unintended ventilation (from 2.1 to 5.3 air changes per hour). The net impact of the increased solar radiation, lower  $U$ -values and increased air exchange rate is slightly negative. If airtightness had remained on the original level, percentage-wise and kilowatt hour-based savings would have been 14.4% and 592 kWh in Case 13E, that is, the net impact of the increased glazing would have been positive. The impact of the amount of untight glazing on the inside temperatures and air exchange rates of a space is illustrated in Fig. 4.

The type of glazing has no significant impact on the energy savings achieved by a glazed space unless the air-tightness of the glazing is improved at the same time. The significance of air-tightness is even greater as thermal insulation capacity of the glazing improves because it improves the ability of the space to store heat energy, as shown in Table 4 (Case 14). In the case of single glazing, improving the air-tightness of the glazing increases energy savings by 11.5% and in the case of double glazing by 13.8%. Air-tightness and highly heat-insulating glazing have a stronger impact in the case of recessed than protruding balconies.

The material technical properties of glazing are also of importance for energy savings. This is shown, for example, by a comparison of calculation Cases 14B, 14D and 14F (Table 4). When a single-glazed pane (Case 14B) is replaced by a double-glazed one (Case 14D), solar radiation penetrating the pane drops from 0.8 to 0.75, the  $U$ -value from  $5.8 \text{ W/m}^2 \text{ K}$  to  $2.9 \text{ W/m}^2 \text{ K}$  while energy savings increase from 14.8% to 16%. Alternatively, a single-glazed pane can be replaced by a triple-glazed one (Case 14D) whereby the solar radiation penetrating the pane changes from 0.8 to 0.55, the  $U$ -value from  $5.8 \text{ W/m}^2 \text{ K}$  to  $1.1 \text{ W/m}^2 \text{ K}$ , and energy savings decrease from 14.8% to 14%. Thus, triple glazing saves slightly less energy than the single glazing of the base model. This proves that high permeability to solar radiation is more important for energy savings than a high thermal insulation level of glazing.

The energy savings achieved by a glazed space can appear small or great depending on the energy consumption level of the building. This applies especially to blocks of flats where the energy consumption of a flat may vary considerably according to its size and location in the building. For example, a flat situated in a top corner of the building consumed 1.75 times more energy due to bigger heat losses through the envelope than a centrally located flat. Consequently, about the same energy savings in kilowatt hours was proportioned to higher consumption whereby savings in percentage terms dropped from 13.1% to 6%, that is, the percentage-wise savings were only about half of the base model's. For that reason, an

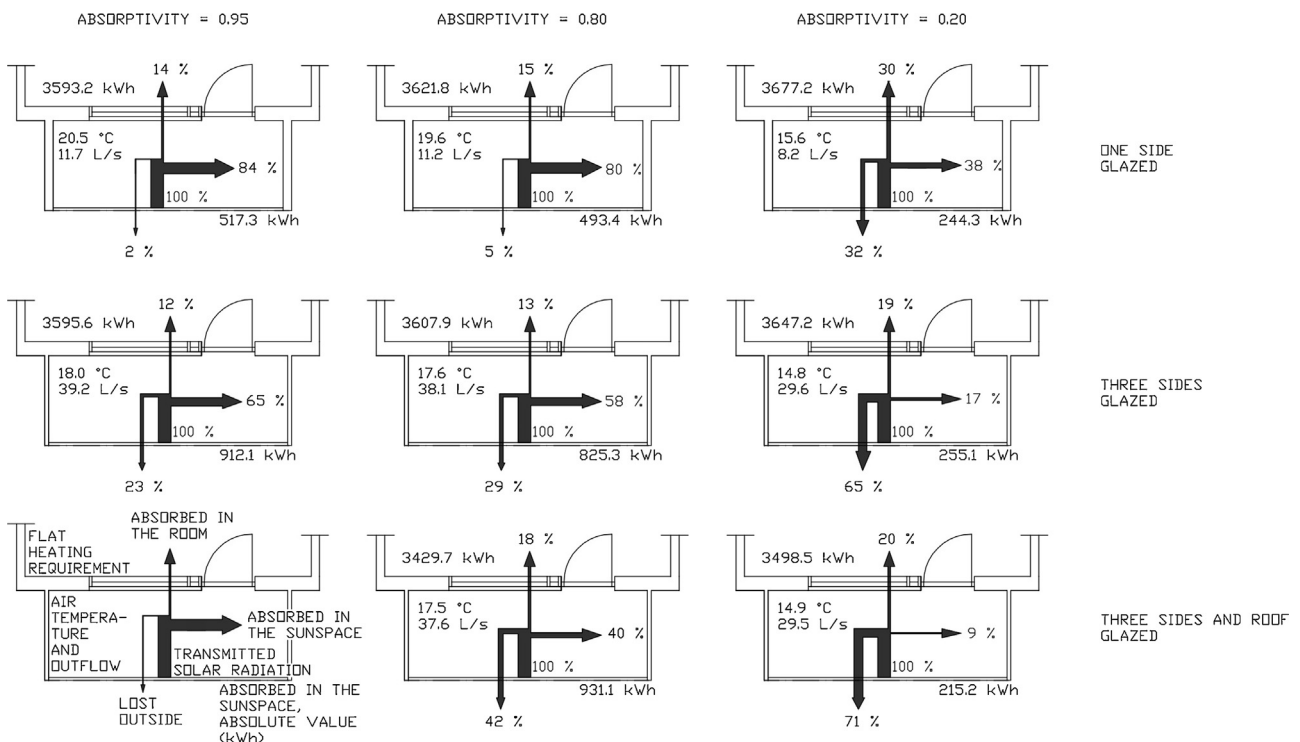


Fig. 4. Solar energy absorptivity of glazed space in relation to the amount of glazing and surface absorption coefficient.

analysis based on kilowatt hours is often more useful in assessing the real energy saving impact of glazing than a percentage-wise analysis.

#### 4.5. Intended and unintended ventilation of building and glazed space

The ventilation system and air exchange rate of a building have a significant impact on the energy savings achieved by balcony glazing. In terms of kilowatt hours, the largest savings are attained in buildings with mechanical exhaust ventilation and a high air exchange rate. In such buildings the heat from internal heat loads is transferred effectively to outdoor air by ventilation, which increases the heating need of the building and the energy savings attained by balcony glazing. At lower air exchange rates, internal heat loads contribute more to the heating the building, which reduces heating need and the energy economic benefit deriving from balcony glazing. In percentage-wise analysis, again, the lower the air exchange rate of the building the bigger the savings attained, as Table 5 shows.

The energy savings achieved by mechanical exhaust ventilation can be increased considerably by utilising the glazed balcony as a supply air pre-heater (Case 20, Table 5). Its relative significance is higher in the case of a protruding balcony than a recessed one. The amount of supply air and the air-tightness of the balcony also affect the end result. Decreasing the amount of supply air taken from the balcony by a third reduces the energy savings from balcony glazing by about 28%, doubling the untightness of a glazed balcony (Case 21B) by 11% and tripling it (Case 21C) by 19%. The air-tightness of the balcony is the more significant the less supply air is taken from the balcony. For instance, the reduction in energy savings in Case 21B grew from 11% to 22% when only a third of the building's supply air was taken through the glazed balcony.

The air-tightness of a building has an impact on the building's total energy consumption and hence also on the relative savings attained by balcony glazing, as Table 5 shows, but the impact is a minor on the whole. When the area of the building envelope increases and supply air is taken through glazed space, the significance of air-tightness grows. In the worst case scenario, the supply air does not enter the flat through the glazed space as desired but through an untight point. Then, the supply air solution does not

work as desired, which is also reflected in the results of the energy savings calculations.

#### 4.6. Building heating system and its characteristics

The dimensioning and controls of the heating system and the settings of room thermostats affect the practically achievable energy savings. This is due to the fact that in the case of a correctly dimensioned radiator system and properly adjusted heating system the entire energy saving potential achieved by balcony glazing is realised. In the case of an undersized (Case 24) or improperly adjusted heating system (Case 25), the occupant may have set the room thermostat to a temperature that could not be attained in the flat. Then, part of the savings attained by the installation of balcony glazing goes to increasing the indoor temperature if the thermostat is not reset after the installation, as shown in Fig. 5.

The heat distribution method and heat losses of heat distribution seem to have little significance for energy savings. On the other hand, there is a slight difference between the heat distribution systems due to their assumed system heat losses. The best energy economy is attained with an ideal heater since the production of heat is lossless. Table 6 also shows that shutting off the heating system for June, July and August (the summer season) has a minor impact on energy savings. However, in terms of overall economy, it is sensible to shut off the heating system for the summer if heating is not otherwise necessary in the building.

#### 4.7. Glazed space construction materials and material properties

The density and specific heat capacity of balcony structures have no impact on the energy savings achieved by glazing, albeit specific heat capacity has a clear effect on the daily temperature variation inside the glazed space (Fig. 6). By contrast, the thermal conductivity of the structures has an impact on energy savings because it improves the thermal insulation capacity of the structure, as shown by the calculation results for Case 30 (Table 7). However, the effect is rather modest. A five-fold change in the lambda values between Cases 30A and 30B improved energy savings in kilowatt hours by 14.5% and 11.5% in percentage-wise analysis.

The absorption coefficient of surfaces has a significant impact on energy savings, as shown in Table 7. It determines how much

**Table 5**  
Building ventilation type and supply air intake solution as well as building and glazed space air-tightness calculation results. Column A shows the base model, that is, the case to which simulation results are compared after individual changes. The results are presented both as absolute savings and as differences to the base model.

	A		B		C		D		E	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
<b>19 Building ventilation type (air exchange rate)</b>	<b>Mechanical exhaust (0.5 ACH)</b>		<b>Mechanical exhaust (0.4 ACH)</b>		<b>Mechanical exhaust (0.2 ACH)</b>		<b>50% heat recovery ventilation</b>		<b>75% heat recovery ventilation</b>	
Absolute savings	543	13.1	532	15.5	429	23.2	456	17.6	418	18.1
Difference to base model			-10.9	+2.4	-114	+10.1	-87	+4.5	-125	+5.0
<b>20 Supply air intake solution</b>	<b>Directly from the outside</b>		<b>Through the glazed balcony</b>							
Absolute savings	543	13.1	1015	25.9						
Difference to base model			+472	+12.8						
<b>21 Glazed space unintended ventilation</b>	<b>1.5–2.6 ACH</b>		<b>2.8–4.9 ACH</b>		<b>3.7–6.5 ACH</b>					
Absolute savings	543	13.1	483	11.7	440	10.6				
Difference to base model			-60	-1.4	-103	-2.5				
<b>22 Openness of the balcony glazing</b>	<b>Completely closed</b>		<b>1% (airing position)</b>		<b>2% open</b>		<b>8% open</b>		<b>15% (one pane open)</b>	
Absolute savings	543	13.1	488	11.8	440	10.6	364	8.8	226	6.4
Difference to base model			-54	-1.3	-103	-2.5	-179	-4.3	-277	-6.7
<b>23 Building air leakage coefficient</b>	<b>1 ACH</b>		<b>0.5 ACH</b>		<b>2 ACH</b>		<b>4 ACH</b>			
Absolute savings	543	13.1	543	13.6	537	12.2	543	10.9		
Difference to base model			0	+0.5	-5	-0.9	0	-2.2		

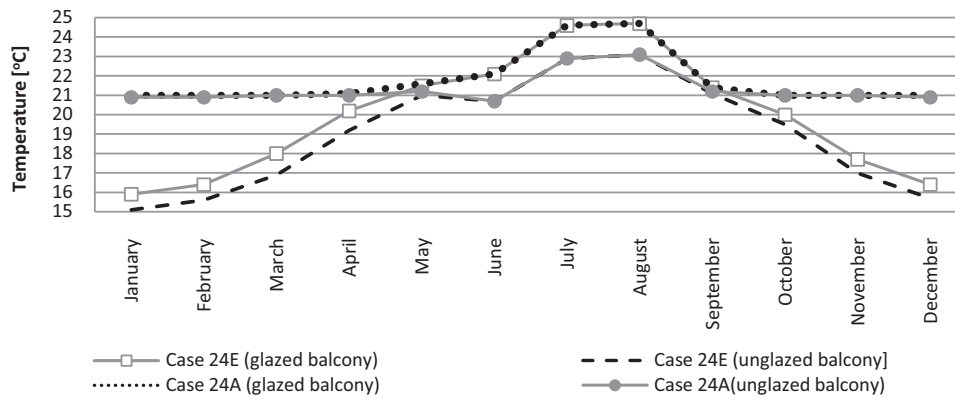


Fig. 5. Mean living room air temperatures at two different heating system capacities.

Table 6

Heating-system-capacity design, control and heat delivery calculation results. Column A shows the base model, that is, the case to which simulation results are compared after individual changes. The results are presented both as absolute savings and as differences to the base model.

	A		B		C		D		E	
	kW h	%	kW h	%	kW h	%	kW h	%	kW h	%
<b>24 Heating capacity design</b>	<b>Oversized 40%</b>		<b>Oversized 20%</b>		<b>Properly sized</b>		<b>Undersized 20%</b>		<b>Undersized 40%</b>	
Absolute savings	543	13.1	532	12.8	440	11.0	385	10.5	336	10.1
Difference to base model			-11	-0.3	-103	-2.1	-157	-2.6	-206	-3.0
<b>25 Heating system adjustment curve position</b>	<b>Initial settings (Sodankylä design condition)</b>		<b>Lowest value increased by +4 °C</b>		<b>Lowest value increased by +8 °C</b>		<b>Lowest value decreased by -4 °C</b>		<b>Lowest value decreased by -8 °C</b>	
Absolute savings	543	13.1	559	13.4	564	13.5	478	11.8	423	10.9
Difference to base model			+16	+0.3	+22	+0.4	-65	-1.3	-119	-2.2
<b>26 Heating system summer shut-off</b>	<b>June–August</b>		<b>No shut-off</b>							
Absolute savings	543	13.1	575	13.8						
Difference to base model			+33	+0.7						
<b>27 Building heat delivery system (70/40 system)</b>	<b>Hot water radiator heating system</b>		<b>Ideal heater</b>		<b>Underfloor water heating system</b>		<b>Electric underfloor heating system</b>			
Absolute savings	543	13.1	608	14.0	564	13.0	630	14.1		
Difference to base model			+65	+0.9	+22	-0.1	+87	+1.1		
<b>28 Heat losses from the heat delivery system to the flat</b>	<b>No heat loss</b>		<b>10% heat loss</b>		<b>20% heat loss</b>		<b>30% heat loss</b>		<b>40% heat loss</b>	
Absolute savings	543	13.1	543	13.4	548	13.5	548	13.8	548	13.9
Difference to base model			0	+0.3	+5	+0.4	+5	+0.7	+5	+0.8

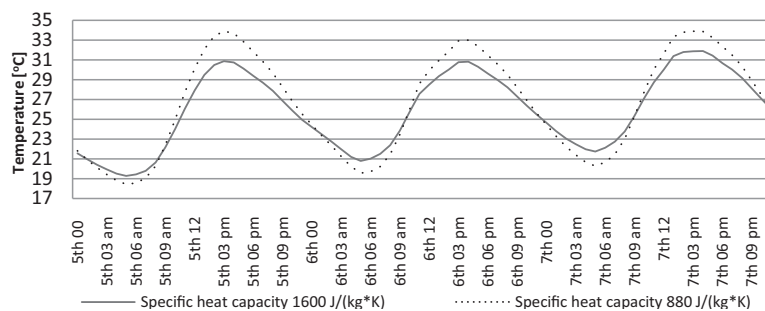


Fig. 6. Inside temperature of a glazed balcony from 5 to 7 May based on the specific heat capacity of balcony structures.

solar radiation energy is stored in the balcony and how much is reflected back to outdoor air (Fig. 4). The impact is clearly visible even with glazing on just one side (Case 32), but it is even clearer in the case of glazing on several sides (Fig. 4). The impact of emissivity is not as high, since the emissivity of the coatings of balcony structures generally used in Finland does not vary as much as absorption coefficients. As a rule, however, surfaces of high absorption capacity, but low emissivity, should be preferred.

#### 4.8. Solar shading

In the window blind simulations blinds were installed on windows of both flats and the glass panes of the glazed balconies. The blinds were assumed to be used throughout the year and remain always closed to facilitate calculations. Cases 34B, 34C and 34D of Table 8 show that window blinds have virtually no impact on energy savings if they are used the same way in both flats, albeit

**Table 7**  
Calculation results on balcony structures' material and surface parameters. Column A shows the base model, that is, the case to which simulation results are compared after individual changes. The results are presented both as absolute savings and as differences from the base model.

		A		B		C		D		E		F	
		kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
<b>29</b>	<b>Specific heat capacity</b>	<b>880J/(kg K)</b>		<b>800J/(kg K)</b>		<b>1000J/(kg K)</b>		<b>1200J/(kg K)</b>		<b>1400J/(kg K)</b>		<b>1600J/(kg K)</b>	
	Absolute savings	543	13.1	543	13.1	543	13.1	543	13.1	548	13.2	548	13.2
	Difference to base model			0	0.0	0	0.0	0	0.0	+5	+0.1	+5	+0.1
<b>30</b>	<b>Lambda value</b>	<b>2.5W/(m K)</b>		<b>0.5W/(m K)</b>		<b>0.9W/(m K)</b>		<b>1.3W/(m K)</b>		<b>1.7W/(m K)</b>		<b>2.1W/(m K)</b>	
	Absolute savings	543	13.1	635	14.8	592	14.1	575	13.8	559	13.4	548	13.2
	Difference to base model			+92	+1.7	+49	+1.0	+33	+0.7	+16	+0.3	+5	+0.1
<b>31</b>	<b>Density</b>	<b>2300 kg/m<sup>3</sup></b>		<b>500 kg/m<sup>3</sup></b>		<b>1000 kg/m<sup>3</sup></b>		<b>1500 kg/m<sup>3</sup></b>		<b>2000 kg/m<sup>3</sup></b>		<b>2500 kg/m<sup>3</sup></b>	
	Absolute savings	543	13.1	537	12.8	537	13.0	543	13.0	543	13.1	543	13.1
	Difference to base model			-5	-0.3	-5	-0.1	1	-0.1	0	0.0	0	0.0
<b>32</b>	<b>Surface absorptivity</b>	<b>0.95</b>		<b>0.9</b>		<b>0.8</b>		<b>0.6</b>		<b>0.4</b>		<b>0.2</b>	
	Absolute savings	543	13.1	532	12.8	516	12.4	467	11.4	412	10.2	336	8.5
	Difference to base model			-10.9	-0.3	-27	-0.7	-76	-1.7	-130	-2.9	-206	-4.6
<b>33</b>	<b>Surface emissivity</b>	<b>0.95</b>		<b>0.9</b>		<b>0.8</b>		<b>0.6</b>		<b>0.4</b>		<b>0.2</b>	
	Absolute savings	543	13.1	548	13.2	564	13.6	597	14.4	630	15.2	662	16.1
	Difference to base model			+5	+0.1	+22	+0.5	+54	+1.3	+87	+2.1	+119	+3.0

**Table 8**  
Solar shading calculation results. Column A shows the base model, that is, the case to which simulation results are compared after individual changes. The results are presented both as absolute savings and as differences from the base model.

		A		B		C		D		E		F	
		kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
<b>34</b>	<b>Window or balcony glazing blind positions</b>	<b>No blind</b>		<b>Window external blinds</b>		<b>Window blinds between panes</b>		<b>Window internal blinds</b>		<b>Balcony glazing internal blinds</b>		<b>Balcony glazing external blinds</b>	
	Absolute savings	543	13.1	516	12.6	526	12.8	548	13.0	201	4.9	114	2.8
	Difference to base model			-27	-0.5	-16	-0.3	+5	-0.1	-342	-8.3	-429	-10.3

they increase the total energy consumption of the building as external shading does (Case 4, Table 2). By contrast, balcony glazing blinds have a really big impact on energy savings if they are kept closed for the entire heating season, because they only shield the flat with balcony glazing from solar radiation which can penetrate the flat without balcony glazing unobstructed. Then, the thermal insulation effect of the blinds does not come even close to compensating the loss of solar radiation energy (Table 8, Cases 34E and 34F). On the other hand, this analysis also proves the ability of blinds to prevent solar radiation from penetrating the balcony which together with airing through the balcony glazing ensures efficient ventilation in summer. For example, opening of one balcony glass pane as in calculation Case 34F reduces the energy savings effect to roughly 0.8%. This leads to the conclusion that the glazing has virtually no impact on the heating up of balcony air during summertime.

## 5. Conclusions

The sensitivity analysis involving 34 calculation variables and 156 cases was conducted taking extensively into account the affecting factors by comparing them to a predefined basic case in Finland. The objective was to reveal the most critical factors affecting the energy saving benefits of glazed space in building and the magnitude of their impacts in northern climate. The properties examined in the calculations were primarily the features of the glazed space, but also building properties affecting the building's ability to take advantage of glazing as an energy saving mean. The basic case of the dynamic simulations was a typical Finnish prefabricated concrete block of flats completed in the 1970s with protruding balconies.

The energy saving potential of the Finnish building stock from 1960s to 1970s varies between 80 kWh (1%) and 1600 kWh (30%), having typically about 400 kWh (9%). The key variables in the

energy engineering design of a glazed space proved to be the integration of the space in the building's ventilation, heat losses from the building to the glazed space and from the space outdoors (balcony type and  $U$ -values of structures), air-tightness of the balcony, and absorption coefficients of surfaces. The key properties of the building with regard to the energy saving potential of the glazed space, again, are the sizing and adjustment of the heating system, selection of a ventilation system and the indoor temperature level of the flat, as well as the building's energy consumption level, which depends largely on the size and heat losses of the flat (location of the flat in the building).

The results showed that the energy savings impact of a glazed space vary a lot between cases and depend, not only on the properties of the glazed space, but also on the building and its properties. The basic case proved to be a very potential glazing installation target with an energy saving potential of 543 kWh (13.1%) in consequence of reasonable low unintended ventilation level of the balcony structures and weak thermal insulation, especially if directed to the south and balconies surface painted with dark colors, such as in the calculation, even if the supply air should be drawn in the building from outside the glazed space and not through it unlike the general practice in 1970s buildings. The study also showed that single glazed balcony glazing with air gaps and openable panes are a good option for balconies, especially for situations such as Finland, where the construction regulations require untight solutions. Tightly and with double glazing implemented solutions are counted in the building gross-floor area and ventilation demanded to arrange separately. These will significantly increase the costs of the glazing installation. Therefore, the current solution is recommended.

The study showed that energy savings in kilowatt hours are larger in a Northern climatic condition than in Central Europe. The most suitable targets for glazing are old buildings with recessed



balconies that get their supply air through a glazed space. The calculations also proved that percentage-wise analysis of energy savings was not sensible in all cases because it yielded partly misleading results. Therefore, a percentage-wise analysis of energy savings should be complemented by an analysis based on kilowatt hours.

## References

- [1] J. Hix, *The Glass House*, Phaidon Press Ltd, London, Great Britain, 1974.
- [2] N. Pevsner, *A History of Building Types*, The Architectural Press Ltd, London, Great Britain, 1976.
- [3] R. Saxon, *Atrium Buildings, Development and Design*, The Architectural Press Ltd, London, Great Britain, 1983.
- [4] M. Wall, Climate and energy use in glazed spaces, in: Report No TABK-96/1009, Lund University, Lund, 1996, pp. 404 (PhD Thesis).
- [5] J.S. Mattila, Effect of balcony glazing on the durability of concrete structures in Nordic climate, in: Proceedings of Sustainable Construction, Materials and Practice Conference, Portugal, 2007.
- [6] P. Neuvonen (toim.), *Kerrostalot 1880–2000*, Arkkitehtuuri, rakennustekniikka, korjaaminen, Rakennustieto Oy, Helsinki, 2006, pp. 288s.
- [7] Lumon Oy, *Lumon 5 Balcony Glazing*, Kouvola, 40 p. <http://www.idx.is/wp-content/uploads/2013/06/lumon5-balcony.pdf>.
- [8] O.B. Jørgensen, O.J. Hendriksen, Glazed balconies and sun spaces—energy savers or energy wasters? in: Proceedings of the 3rd Int. ISES Europe Solar Congress, Eurosun 2000, 19–22 Jun 2000, Copenhagen, Denmark, 2000.
- [9] J. Heikkilä, Parveke suomalaisen kerrostalon asuntokohtaisena ulkotilana, Oulun yliopisto, Väitöskirja, Oulu, 1996, pp. 300s.
- [10] K. Hilliaho, Parvekelasien energiataloudelliset vaikutukset, Tampereen teknillinen yliopisto, Diplomityö, Tampere, 2010, pp. 164s.
- [11] K. Voss, Solar energy in building renovation—results and experience of international demonstration buildings *Energy Build.* 32 (3) (2000) 291–302.
- [12] A.R. Rempel, A.W. Rempel, K.V. Cashman, K.N. Gates, C.J. Page, B. Shaw, Interpretation of passive solar field data with EnergyPlus models: un-conventional wisdom from four sunspaces in Eugene, Oregon, *Build. Environ.* 60 (2013) 158–172.
- [13] C. Boonstra, *Glazed Balconies in Building Renovation*, Brochure, James and James, London, UK, 1997, pp. 16.
- [14] A.H. Abdullah, Q. Meng, L. Zhao, F. Wang, Field study on indoor thermal environment in an atrium in tropical climates, *Build. Environ.* 44 (2) (2009) 431–436.
- [15] G. Olivetti, N. Arcuri, M.D. Simone, R. Bruno, Solar heat gain and operative temperature in attached sunspaces, *Renewable Energy* 39 (1) (2012) 241–249.
- [16] R. Chareille, J.J. Roux, D. Covalet, O. Hartmann, Impact of a veranda on the reduction of the energy consumption in residential buildings: an application of the CLIM2000 software, in: Proceedings of the Seventh International IBPSA Conference, 13–15 August 2001, Rio de Janeiro, Brazil, 2001, pp. 1359–1366.
- [17] C. Ganem, A. Esteves, A better quality of life through the refurbishment of building's facades with glazed balconies, in: Proceedings of the 20th Conference on Passive and Low Energy Architecture, 9–12 November 2003, Santiago, Chile, 2003.
- [18] E. Erkiö, A. Melajärvi, Parvekelasitusten energiataloudelliset ja kaupunkikuvalliset näkymät, *Lasirakentaja* 3 (1994) 23–27 (Tampere 1994).
- [19] M. Reichenbach, Apartment building in cold climate: sunspace, in: S.R. Hastings, M. Wall (Eds.), *Sustainable Solar Housing, Volume 1—Strategies and Solution*, Earthscan from Routledge Publisher, London, 2007, pp. 171–178.
- [20] K.M. Bataineh, N. Favez, Analysis of thermal performance of building attached sunspace, *Energy Build.* 43 (8) (2011) 1863–1868.
- [21] J.-M. Mottard, A. Fissore, Thermal simulation of an attached sunspace and its experimental validation, *Sol. Energy* 81 (3) (2007) 305–315.
- [22] G. Mihalakakou, On the use of sunspace for heating/cooling in Europe, *Renewable Energy* 26 (3) (2002) 415–429.
- [23] W. Maria, Fövärmning av tilluft med solfångare och glasrum, in: Rapport TABK-94/3017, Lund University, Lund, 1994, pp. 27.
- [24] A. Haller, Improvement of solar renovation concepts and systems, in: A Technical Report of IEA SHC Task20 “Solar Energy in Building Renovation”, Ernst Schweizer AG, Metallbau, Hedingen, 1999, pp. 74.
- [25] K. Hilliaho, J. Lahdensivu, J. Vinha, Glazed space thermal simulation with IDA-ICE 4.6.1 software—suitability analysis with case study, *Energy Build.* 89 (2015) 132–141.
- [26] P.G. Loutzenhiser, H. Manz, S. Moosberger, G.M. Maxwell, An empirical validation of window solar gain models and the associated interactions, *Int. J. Therm. Sci.* 48 (1) (2009) 85–95.
- [27] ISO, FDIS, Thermal performances of windows, doors and shading devices—detailed calculations, in: ISO/FDIS 15099: 2003(E), 2003.
- [28] A. Bring, P. Sahlin, M. Vuolle, Models for Building Indoor Climate and Energy Simulation. A Report of IEA SHC Task 22: Building Energy Analysis Tools, Royal Institute of Technology in Stockholm, Stockholm, 1999, pp. 110.
- [29] J. Travesi, G. Maxwell, C. Klaassen, M. Holtz, Empirical validation of Iowa energy resource station building energy analysis simulation models, in: IEA Task 22, Subtask A, 2001.
- [30] S. Kropf, G. Zweifel, Validation of the Building Simulation Program IDA-ICE According to CEN 13791 “Thermal Performance of Buildings—Calculation of Internal Temperatures of a Room in Summer without Mechanical Cooling—General Criteria and Validation Procedures”, Hochschule Technik+Architektur Luzern, HLK Engineering, Luzern, 2001.
- [31] M. Achermann, G. Zweifel, RADTEST—radiant heating and cooling test cases, subtask C, in: A Report of IEA Task 22, Building Energy Analysis Tools, 2003.
- [32] F. Karlsson, P. Rohdin, M.-L. Persson, Measured and predicted energy demand of a low energy building: important aspects when using building energy simulation, *Build. Serv. Eng. Res. Technol.* 28 (3) (2007) 223–235.
- [33] S. Moosberger, IDA-ICE CIBSE-validation, test of IDA indoor climate and energy version 4.0 according to CIBSE TM33, issue 3, in: Report 2007, HTA, Luzern, 2007.
- [34] P. Loutzenhiser, H. Manz, G. Maxwell, Empirical validations of shading/daylighting/load interactions in building energy simulation tools, in: A Report for the International Energy Agency's SHC Task 34/ECBCS Annex 43 Project C, 2007.
- [35] Equa Simulation Technical Group, Validation of IDA Indoor Climate and Energy 4.0 Build 4 with Respect to ANSI/ASHRAE Standard 140-2004, Technical Report, Equa Simulation Technical Group, Solna, Sweden, 2010.
- [36] M. Achermann, Validation of IDA ICE Version 2.11.06, HTA (Hochschule Technik+Architektur), Luzern, Switzerland, 2000.
- [37] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, *Build. Environ.* 43 (2008) 661–673.
- [38] T. Kalamees, IDA ICE: the simulation tool for making whole building energy- and HAM analysis, in: Annex 41 MOIST-ENG, Working Meeting, 12–14 May, 2004, Zurich, Switzerland, 2004.
- [39] M. Seppänen, T. Koivu (toim.), BES: tutkimus avoimen elementtjärjestelmän kehittämiseksi, Suomen betoniteollisuuden järjestö, Helsinki, 1969, pp. 89 s.
- [40] Official Statistics of Finland (OSF), Buildings and Free-time Residences, Official Statistics of Finland (OSF), Helsinki, Statistics Finland, 2014, ([http://www.tilastokeskus.fi/til/rakke/tau\\_en.html](http://www.tilastokeskus.fi/til/rakke/tau_en.html)).
- [41] Työ- ja elinkeinoministeriö, Kotitalouksien sähkönkäyttö 2011, in: Tutkimusraportti 26.2.2013, Työ- ja elinkeinoministeriö, Helsinki, 2013, pp. 52 s.
- [42] Ympäristöministeriö, Rakennetun ympäristön osasto, RakMk D3, Suomen rakentamismääräyskokoelma, osa D3: Rakennusten energiatehokkuus, määräykset ja ohjeet 2012, Ympäristöministeriö, Rakennetun ympäristön osasto, Helsinki, 2011, 27 s.+liitt. 8 s.

### III

## **EFFECTS OF ADDED GLAZING ON BALCONY INDOOR TEMPERATURES: FIELD MEASUREMENTS**

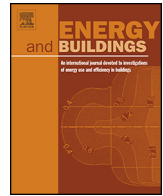
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# Effects of added glazing on Balcony indoor temperatures: Field measurements



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## ABSTRACT

In this study the temperatures on 22 balconies (17 glazed) and adjacent flats were monitored with an aim to determine the key factors affecting the ability of a glazed balcony to warm up and remain warm without a heater. Considered were glazed balconies in different locations, the amount of glazing and building heat loss, the tightness of balcony vertical structures, and balcony ability to capture solar radiation.

Temperature monitoring showed that over a year the air temperature of both glazed and unglazed balconies remained almost without an exception above the outdoor air temperature. On average, the temperatures of unglazed balconies were 2.0 °C and those of glazed balconies 5.0 °C higher than the outdoor air temperature. The three key factors affecting the glazed balcony temperatures seemed to be the level of air leakage in the balcony vertical structures, the balcony's ability to capture solar radiation, and the heat gain from an adjacent flat, in that order. The air tightness of the glazing was the most crucial factor, since it affected the results all the year round. Solar radiation was important from spring to autumn and heat gain in midwinter.

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## 1. Introduction

For centuries, large glazed spaces have been architecturally and structurally interesting building details [1–3]. Their attraction lies in large spaces, novel architectural solutions, and interesting details. However, these spaces have not usually been built solely for architectural reasons, but functional requirements have also been set for them as they have served as hospital waiting areas, reception areas in office buildings, etc. The design of such spaces is based on required indoor air conditions, such as minimum acceptable indoor air temperature, desired average temperature, and maximum acceptable temperature. They determine the design solution, which takes into account issues such as heat losses in the building and the space, storage of solar radiation, solar protection, and minimisation of cooling and heating needs, if the required indoor conditions cannot be realized without an external energy source [4].

In Finland, glazed spaces are not usually big and impressive structures but quite simple and rather small spaces, such as glazed balconies. The glazing system consists of 5–6 opening balcony glass panes, characterized by transparent 6-mm float glass panes

( $U=5.8\text{ W/m}^2\text{ K}$ ,  $g=0.82$ ) and non-insulated aluminum profiles. Between the panes have usually 2–3-mm air gaps [5], allowing sufficient natural ventilation in the balcony and making continuous heating of the balcony uneconomical [6]. Because many Finns are not aware of the energy saving and overheating impacts of balcony glazing, some residents keep their balcony glazing partly open throughout the winter, reducing thus energy savings, and fully closed during summer, causing thereby overheating problems [7,8]. This is partly due to a lack of broader study of glazed balcony temperature behavior in northern climate conditions and lacking information about the key factors affecting the energy and indoor climate design of a glazed space. The need for such information has also been emphasized in other studies [4,9].

This paper presents the results of a study conducted by measuring temperatures on 22 balconies (17 glazed) and adjacent flats in Tampere, Finland, to determine the effect of building conduction losses, tightness of balcony vertical structures, ability to capture solar radiation, and the amount of glazing and locations on the balcony indoor climate. The study sought to find the key factors affecting the ability of glazed balconies to warm up in northern climate conditions and thereby to improve glazed balcony temperature behavior for future design.

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## 2. Background

According to the literature, glazed space air temperatures have been measured to evaluate, e.g., thermal comfort and operative temperatures on many occasions and almost all over the world. Studies have usually focused on either a clearly different climate [10–12], another continent [13–15], or central Europe [16,17], where the climate conditions differ from those in Finland. Thus their perspective has been different (e.g., emphasis on overheating rather than on energy saving). Their measurements have focused on atrium [10,13], sunspace [12,15,18] or some solar space [11], though some balcony glazing studies have also been made [16,17,19]. Older measurements have focused on indoor climate behavior [12,16] and later ones, either partially [15] or wholly [12,18], on the validation of simulation programs. The only extensive field monitoring of glazed balconies is over ten years old, conducted under the International Energy Agency (IEA) Solar Heating and Cooling (SHC) program Task 20 “Solar energy in building renovation”. Its results are available, e.g., in Refs. [9,20,21]. Rather than by extensive field measurements, the sensitivity of glazed space characteristics to space temperatures has been mainly analyzed by computer simulation [22,23]. Glazing has generally been single glazing [17,24] and/or double glazing [6,23,25] with sliding [19,26] or non-sliding panes [12], and as a rule with vertical frames [6,19,23,25]. Previous studies have rarely focused on the most commonly used frameless single glazing in Finland with a sliding and pane-by-pane opening glazing system, such as that in Ref. [24]. A special feature of this glazing are its 2–3-mm air gaps between the panes, which makes it a significantly un-tighter solution than that in previous studies.

Some studies in Finland and the neighboring countries have monitored balcony temperatures [4,8,19,24,27]. In most of them, either the number of measured balconies has been small [4,19,24] and/or their research perspective has been other than to improve the thermal behavior of a glazed balcony [19,24]. Some aforementioned studies have also focused on the potential of balcony glazing for energy savings [4,8,19,27], a topic also discussed in Refs. [7,28], though without temperature measurements.

In terms of measurement technicalities, the previous studies differ very little. Usually monitored have been the temperatures of the sunspace, the adjacent living space, and the outside air (dry bulb and relative humidity) while at the same time using factory-calibrated data loggers [11,13,15–17], some temperature sensors [15], and/or thermocouples (shielded or unshielded) [10,12,13,18]. Temperatures have usually been recorded at 10-min [15], 15-min [11,14,16,17], 20-min [10], or 1-h intervals, and measurements have lasted from a few days to several years [24]. The most common temperature recording interval has been 10 or 15 min, but one monitoring study has established that a logging interval of one hour would be sufficient [16]. Of particular importance has also been to use the same measuring intervals with individual loggers [16] and to start temperature recording simultaneously for easier later comparison of the results.

The results of the previous studies clearly show that the temperatures of a glazed space, such as sunspaces [11,15,29] and glazed balconies [8,24,27] are higher than the outdoor air temperature. They also show that to maximize the temperature difference between a glazed space and the outdoor air, space type and size must be optimized along with the thermal insulation capacity and air-tightness of the structures. As to the balcony type, a recessed glazed balcony is superior to a protruding balcony, because it has a small exterior glazed area and a large exterior wall area, through this balcony receives transferred heat from the adjacent flat [16,27]. Increasing the length of a balcony also increases transmission losses from the adjacent flat. In general, a long and narrow balcony is recommended for maximizing energy savings and natural light [30].

The location affects the energy saving effect and the indoor climate of a glazed space. The basic principle is that the more southern and milder the climate, the higher the yearly mean temperature and the bigger the percentage of energy savings. This is because of the increased amount of energy absorbed by the space due to the increased intensity of solar radiation [31]. The highest energy savings are possible in a sunny and cold climate [20], such as that of the southern European Alps. Orientation, external obstructions, and solar shading also affect the solar radiation stored, because they limit the amount of radiation entering the space. It is important that the space be oriented towards the equator ( $\pm 30^\circ$ ), though it has been observed that orientation is not the major contributor to the energy savings of a glazed balcony [26]. It is also proved that added glazing area can increase the amount of solar energy absorbed and lead to the overheating of the balcony or the adjacent rooms [6], even in northern climates [22] in the absence of shading.

The material properties of the glazed space and the building external wall affect the indoor temperature and energy savings of the glazed space. According to Ref. [23], e.g., the thermal conductivity of the wall strongly affects the heat flux through the wall, but its density and heat capacitance (C) have only a small effect [23], albeit heat capacitance affects temperature variations and the thermal comfort of the space [4]. By contrast, the absorption coefficients of the surfaces and the ability of the space to store solar radiation have a strong impact on the interior temperatures of the glazed space and the energy savings [4].

The air-tightness of the envelope structures of glazed spaces has a further marked impact on their temperatures. Ventilation with outdoor air removes a fraction of the energy absorbed and consequently lowers the temperature of the sunspace [31]. The air exchange rate of un-tight glazed spaces varies daily and greatly depends on the temperature difference between the glazed space and the outdoor air and the wind conditions [4]. The building's ventilation solution also affects the end result. In terms of the heating energy savings of the building, it is advisable to integrate the glazed space with mechanical exhaust ventilation and thus use the glazed balcony as a supply air pre-heater [20]. The overheat of the glazed space could thus warm up the adjacent flat in summer time, if the supply air terminals between the glazed balcony and the flat are not easily closable [19]. Excessive indoor temperatures could be prevented by using an appropriate solar shading solution with the glazing [22] and by increasing airing by opening the balcony glazing [32].

As mentioned above, most glazed space studies have focused on glazed spaces other than glazed balconies and with glazing solutions different from the typical Finnish one. In addition, the climate conditions in those studies have differed from the northern European climate, and their sensitivity analysis has been founded on computer models instead of field monitoring.

## 3. Research materials and methods

The research material consists of climate and weather information on Tampere, a description of the studied buildings and balconies, and a monitoring set up for 22 balconies and their adjoining flats.

### 3.1. Climate and weather

The city of Tampere ( $61^\circ 29' 53'' \text{N}$ ,  $23^\circ 45' 39'' \text{E}$ ) is located about 200 km north of the Finland's southern coastal line. Its winter is cold and summer mild (Köppen-Geiger Dfc) [33]. The annual average temperature of the city is  $4.4^\circ \text{C}$  ( $36.4^\circ \text{F}$ ), and in a normal year, it has 4424 heating degree-days (HDD17) [34].

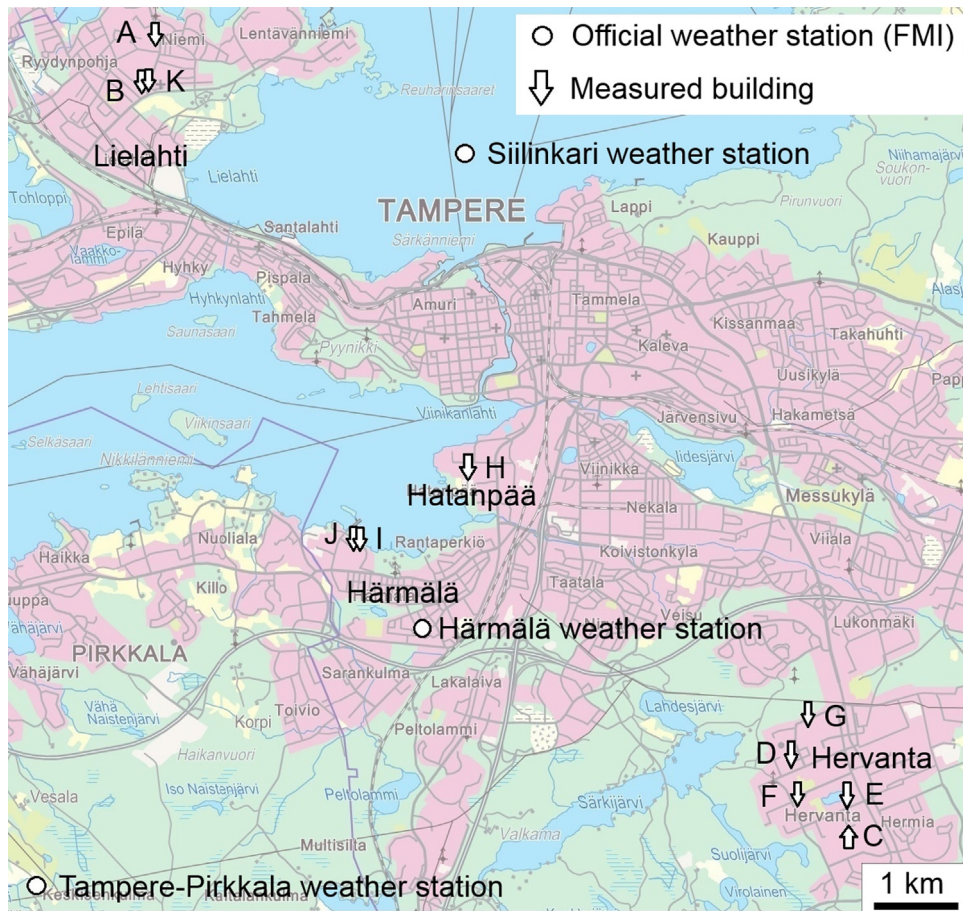


Fig. 1. Measured buildings are located in three suburban areas in Tampere. The weather stations (three) of the Finnish Meteorological Institute (FMI) are shown in dots. The Tampere-Pirkkala airport weather station is located in the bottom left corner.

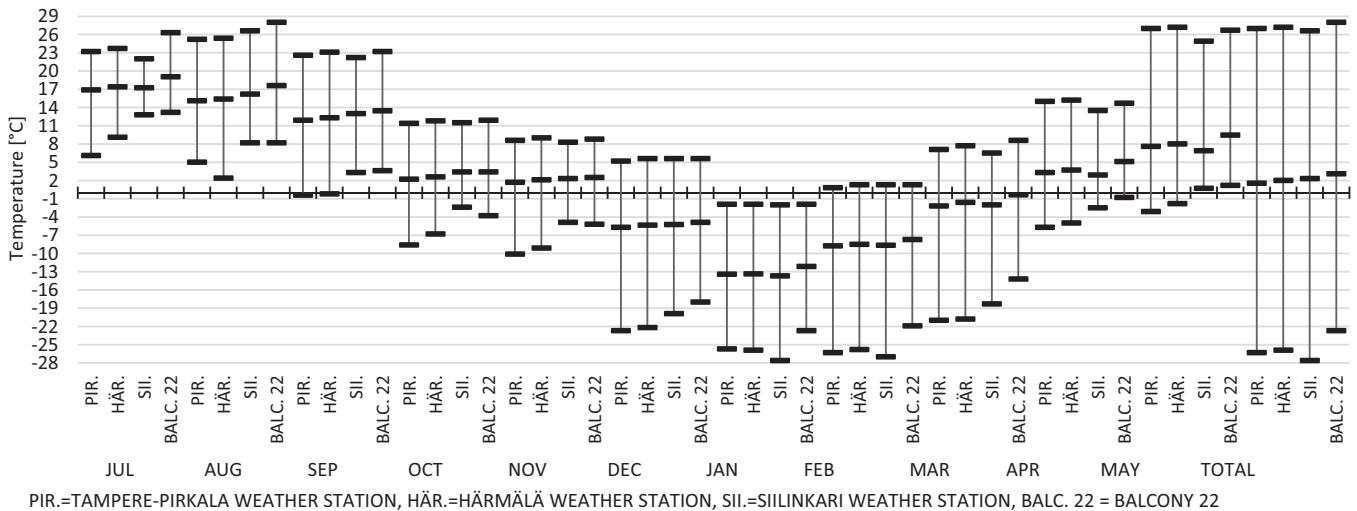


Fig. 2. Monthly mean temperatures at Siilinkari, Härmälä, and Tampere-Pirkkala weather stations (station locations shown in Fig. 1).

The Finnish Meteorological Institute measured the outside temperature at the measurement time in three different locations of Tampere region (Fig. 1). The stablest temperature among the stations was monitored at Tampere–Pirkkala airport (Fig. 2) and chosen for the reference outdoor temperature in this study. The station’s average temperature was 1.5 °C with a range of –26.3 °C (on 20th February 2010 at 8 AM) to 27.0 °C (on 16th May 2010 at 3

PM). In the measurement period, the warmest month was July and the coldest January.

Comparison of the measurement period and normal year outdoor temperatures [34] at Tampere-Pirkkala as well as the measurement period and normal year global solar radiation level at Jokioinen (nearest, about 100 km from Tampere) reveals that the only significant deviation from the long-term average is the unusually cold winter in the middle of measurement period (Fig. 3). The

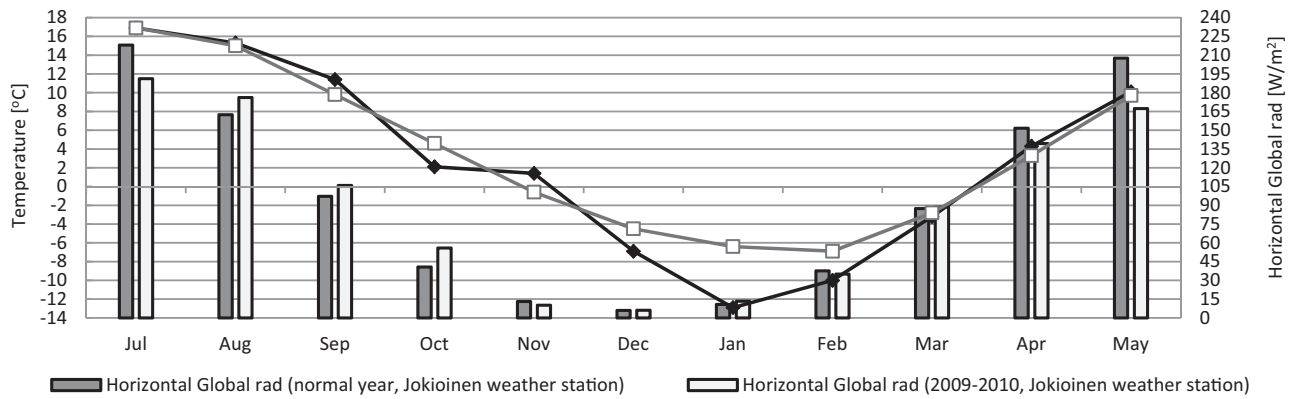


Fig. 3. Monthly average temperatures and horizontal global radiation during the field measurement period compared to a normal year.

deviations between the July and May radiation values were caused by different measurement times: the normal yearly values covered whole months and the measurement period values half the respective months (the measurement period was from 17th July 2009 to 17th May 2010). Thus the values are not directly comparable.

### 3.2. Studied buildings and balconies

Eleven blocks of flats in four different urban areas in the city of Tampere were chosen for the study and specified from oldest to newest by individual letter codes (Fig. 4). The oldest building was from 1966 (Building A) and the most recent from 2006 (Building K). Most buildings are of typical 1970s prefabricated element-based construction. Four pre-1978 buildings did not originally include balconies for all flats, but balconies were later added to two of them (buildings C and D). In their external wall, window, door, and balcony structures, the 1970s buildings B–F were similar at the time of their completion. However, with the exception of building E, their windows doors, and balcony railings in buildings B, C and D have since been renovated.

### 3.3. Test site acquisition

The site was acquired in co-operation with the staff of Lumon Oy, a balcony glazing company, and VVO-Yhtymät Oyj, a real estate company. Test sites for the study were selected from among the real estate company's rental flats, because they were near enough for regular follow-up. Almost all the balconies in the chosen blocks of flats were also partly glazed, allowing thus temperature measurement of glazed and unglazed balconies in the same building. From among the tenants who consented, flats suited for the study were chosen based on the building's age, structural solutions, and facade orientation. Additionally, some balconies were acquired through other networks (researcher's own flat etc.). Five of the blocks of flats are located in Hervanta, two in Härmälä, three in Lielähti, and one in Hatanpää (Fig. 1).

### 3.4. Representation methods of balconies

The balconies studied are described in numerical code from coldest to warmest and specified by rectangles and circles for unglazed and glazed balconies, respectively (Fig. 5). Numbers 1–17 are glazed and 18–22 unglazed balconies, which means, that all the glazed balconies were warmer than the unglazed ones. Also shown are building ages and facade orientations, balcony glazing use characteristics (openness grade of glazing), and measured period mean temperatures. The openness grades were as follows: balcony glazing fully closed (closed), one glass pane 2.5 cm open (ventilation

position), and one glass pane fully open (one pane open). Balconies without information on the openness grade are unglazed.

### 3.5. Evaluation of balcony properties

Solar energy absorption on balconies, heat transfer by conduction from an adjacent flat to the balcony, and unintended ventilation from balcony to outside were estimated for each building on a scale of very low to very high (Table 1). Heat losses were estimated by inspecting structural and architectural drawings and solar energy absorption with the help of architectural drawings and by visual observation of the building sites. Solar absorption considered external obstructions and balcony orientation. The air leakage of the balcony vertical structures, designated as “tightness level” in this paper, was estimated by measuring the air gaps on site and by inspecting the structural drawings. Tightness was chosen instead of leakage because “very high” would then in all instances represent the best condition and “very low” the poorest. The leakage level of a glazed space could perhaps be better indicated by using fan pressurization equipment [4], but those measurements are hampered by intensive labor demands and difficulty to produce enough pressure difference between leaky glazing structures. Hence these tests were excluded in this study.

### 3.6. Field measurements

In these blocks of flats, data loggers were installed on ceilings in 17 glazed and 5 non-glazed balconies and in the adjoining flats for about 10 months from 17th July 2009 to 17th May 2010. Monitored were air temperature and relative humidity on the balconies and in the adjoining flats. Data were recorded at 1-h intervals with factory-calibrated Comark Diligence EV (N2003 and N2013) data loggers, whose accuracy (Table 2) was confirmed before measurements with TUT calibration equipment. The precision of the devices was  $T = \pm 0.5\text{ }^{\circ}\text{C}$  and  $\text{RH} = \pm 3\% \text{ RH}$ .

Data loggers were installed at circa 2 m from the floor and at least 4 m from the external walls. External loggers were installed on balcony ceilings, away from sunshine, and at least 0.5 m from external walls (the most common installation arrangement is shown in Fig. 6). In logger installation, mechanical attachment was avoided.

Measurements of indoor, outdoor, and balcony temperatures enabled determination of the actual temperatures and heat loss reduction (Eq. (1)) in the building section adjacent to the balcony as a whole (including balcony back wall, windows, and door) after glazing installation. The results are reliable, if the measuring



Fig. 4. Balconies in the studied blocks of flats, showing well the decade of their construction. The buildings are identified by a letter code A–K (see also Table 1).

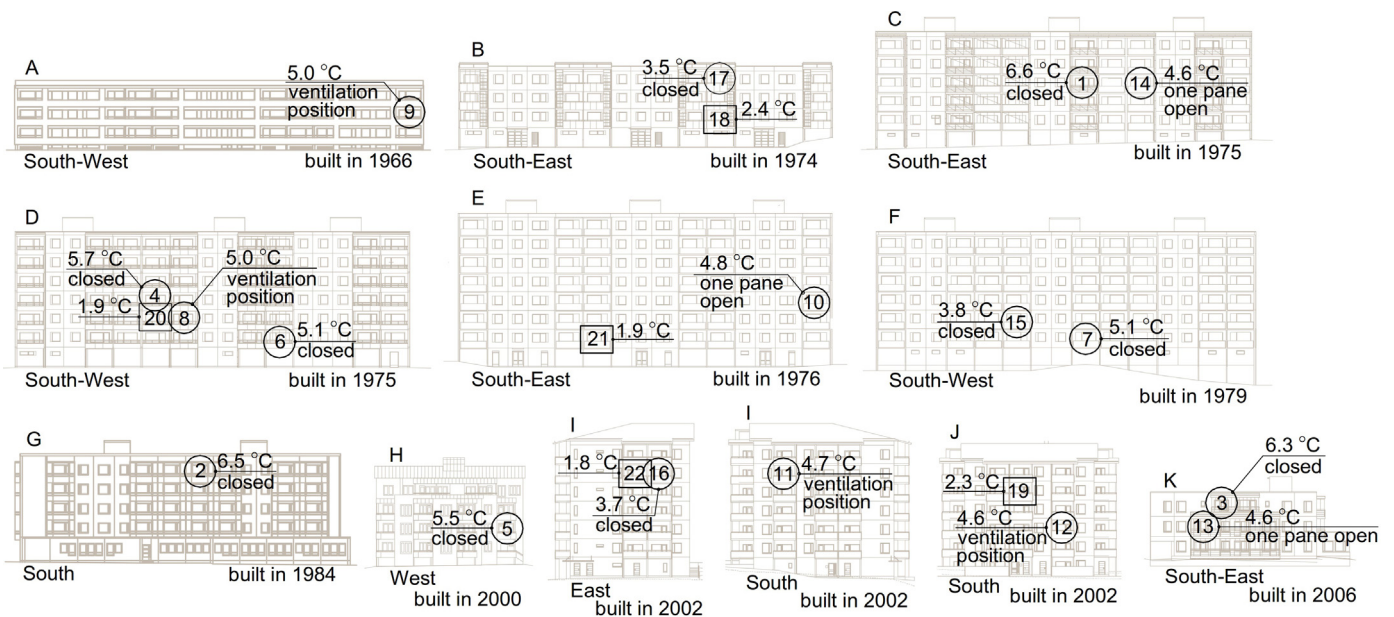


Fig. 5. Studied block of flats from oldest to newest, identified by a letter code A–K. Balconies are numbered from warmest to coldest. Numbers 1–17 are glazed balconies and 18–22 unglazed ones.

**Table 1**  
The building-specific information on the studied buildings.

Building code	Balcony codes	Location	Building type, construction year, external wall structure and U-value	Balcony type, dimensions (Number of glazed sides informed in parentheses)	U-values of windows and doors	Balcony material (parapet material informed in parentheses)	Heat transfer by conduction ( $\sum U \cdot A$ ) from adjacent flat to balcony [W/K]	Solar absorption level of balconies (External obstruction informed in parentheses)	Overall tightness of the balcony <sup>a</sup> (after user effect)
A	9	Lielahiti	in-situ frame, band façade, 1966, brick U=0.47	Recessed, w=3.8m, d=1.5m, h=2.6m, (1)	U=1.8 (windows), U=1.4 (doors)	Concrete balcony, (hardboard parapet)	Very high, 15.9	Typical (adjacent building)	High (typical)
B	17, 18	Lielahiti	precast concrete, 1974, concrete sandwich panel, U=0.4	Protruding, w=4.0m, d=1.9m, h=3.1 or 2.6 m (1)	U=1.2 (windows), U=1.2 (doors)	concrete balcony (extended 0.5m), (hardboard parapet)	Typical, 9.5	Very high (no external obstruction)	Very low
C	1, 14	Hervanta	precast concrete, 1975, concrete sandwich panel, U=0.4	Protruding, w=4.0m, d=1.5m, h=2.6 m (both 1 and 2)	U=1.2 (windows), U=1.2 (doors)	concrete balcony, (30% glass, 70% concrete parapet)	Low, 7.4	Very high (no external obstruction)	Very high (low)
D	4, 6, 8, 20	Hervanta	precast concrete, 1975, concrete sandwich panel, U=0.4	Protruding, w=4.0m, d=1.5m, h=2.6 m (both 1 and 2)	U=1.4 (windows), U=1.2 (doors)	concrete balcony, (hardboard parapet)	Typical, 9.5	High (building ≈50 m in front)	High (typical)
E	10, 21	Hervanta	precast concrete, 1976, concrete sandwich panel, U=0.4	Protruding, w=4.0m, d=1.5m, h=2.6 m (1)	U=2.1 (windows), U=2.0 (doors)	concrete balcony, (concrete parapet)	High, 12.7	Low (medium dense forest in front)	Very high (low)
F	7, 15	Hervanta	precast concrete, 1979, concrete sandwich panel, U=0.29	Protruding, w=4.0m, d=1.5m, h=2.6 m (1)	U=1.2 (windows), U=1.2 (doors)	concrete balcony, (concrete parapet)	Low, 7.7	Very low (dense forest in front)	Very high
G	2	Hervanta	precast concrete, 1984, concrete sandwich panel, U=0.29	Protruding, w=3.9m, d=2.2m, h=2.6 m (1)	U=1.8 (windows), U=2.0 (doors)	concrete balcony, (concrete parapet)	Typical, 10.3	Very high (no external obstruction)	Very high
H	5	Hatanpää	precast concrete, 2002, concrete sandwich panel, U=0.27	Protruding, w=2.8m, d=2.4m, h=3.0 m (2)	U=1.4 (windows), U=1.4 (doors)	concrete balcony, (concrete parapet)	Low, 8.0	Very high (no external obstruction)	Very high
I	11, 16, 22	Härmälä	precast concrete, 2002, concrete sandwich panel, U=0.27	Protruding, w=3.6m, d=2.4m, h=2.8 m (2 and 3)	U=1.4 (Windows), U=1.4 (doors)	concrete balcony, (sheet metal parapet)	Low, 7.8	Typical (buildings adjacent and ahead)	Typical (low)
J	12, 19	Härmälä	precast concrete, 2002, concrete sandwich panel, U=0.27	Protruding, w=3.6m, d=2.4m, h=2.8 m (3)	U=1.4 (windows), U=1.4 (doors)	concrete balcony, (sheet metal parapet)	Low, 7.8	High (adjacent buildings)	Typical (low)
K	3, 13	Lielahiti	precast concrete, 2006, concrete sandwich panel, U=0.24	Protruding, w=4.3m, d=2.0m, h=2.7 m (2)	U=1.2 (windows), U=1.2 (doors)	concrete balcony, (glass parapet)	Very low, 6.3	Very high (no external obstruction)	Very high (low)

<sup>a</sup> In Finland, all balcony glazing structures are leaky structures because of 2–3-mm air gaps between the glass panes, yet the air outflow can range, according to our estimation, from 1l/s to 40l/s because of different overall glazed balcony solutions (the main things are the tightness of the balcony vertical structures and balcony heat gains from solar radiation and transfer from the adjacent flat). This effect was assessed at this point. In some flats, residents left their balcony glazing periodically partly open or even for the entire measurement period. This effect on overall balcony tightness is given in parentheses.



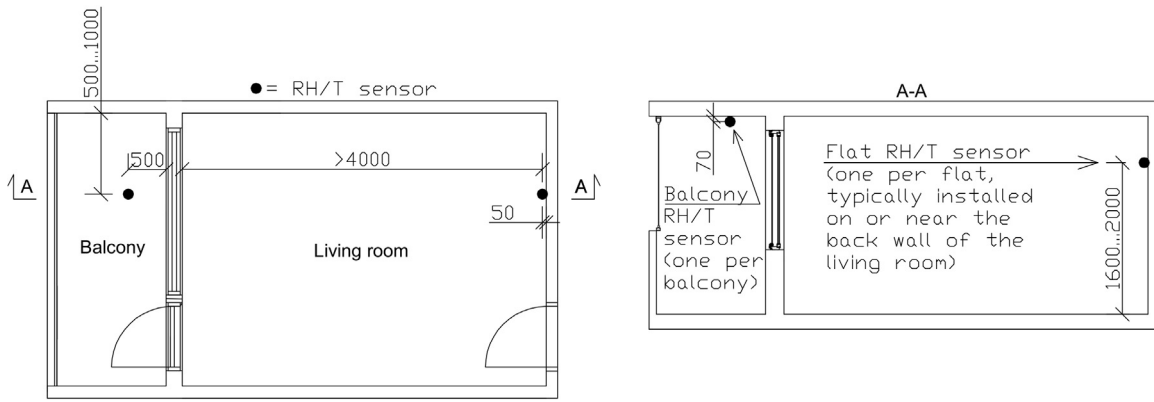


Fig. 6. Arrangement of monitoring in a balcony and flat.

devices are accurate enough and calibrated, and if measurements are properly taken.

$$\text{Heat loss reduction} = 1 - \frac{T_{\text{FLAT}} - T_{\text{BALCONY}}}{T_{\text{FLAT}} - T_{\text{OUTDOOR}}} \quad (1)$$

## 4. Results and discussion

### 4.1. Balcony temperatures

#### 4.1.1. Temperatures of unglazed balconies

In general, the surrounding buildings, trees and the balcony vertical structures form a micro-climate inside the balconies, a phenomenon that can be observed from the slightly higher measured temperature values in the balconies than those in the open terrain. The phenomenon is the most obvious in the minimum temperatures, but also the mean and maximum temperatures differ somewhat from the outdoor air temperatures (Fig. 7a). On average, the temperatures of the five unglazed balconies differed 2 °C from the outdoor air temperature measured at the Tampere-Pirkkala airport and ranged from 1.8 °C to 2.4 °C, depending on the balcony (Table 3).

Analysis of the monthly level (Fig. 8) shows that there is considerable deviation between the warmest and the coldest unglazed balconies and between unglazed balconies and the outdoor air. Differences between the median and maximum temperatures on unglazed balconies and the outside temperature stand out in autumn and spring, but minimum temperature differences are more consistent. The temperature difference between unglazed balconies (balconies 22 and 18) shows deviations that are smoother than those between unglazed balconies and the outside and mostly follow the same trend throughout the year. The only significant deviation between the balconies can be seen in the maximum temperatures in spring and autumn.

A daily temperature review of the balconies confirms the same trend as the monthly level study (Fig. 9). Day temperatures, divided into a six-hour average, show clearly that unglazed balconies do not cool as much as the outside air during a cold winter night. Similarly, solar radiation in spring warms up balconies with the intensity of warming depending significantly on balcony orientation and external obstructions. Balconies facing south (balcony 19) warm up most, and those facing east (balcony 22) the least.

#### 4.1.2. Temperatures of glazed balconies

On average, the temperatures of 17 glazed balconies differed 5.0 °C from the outdoor temperature and ranged from 3.5 °C to 6.6 °C, depending on the balcony. The importance of glazing (all 17 pc) for balcony indoor temperatures varied seasonally. Glazing had the highest effect in March, when the average temperature differ-

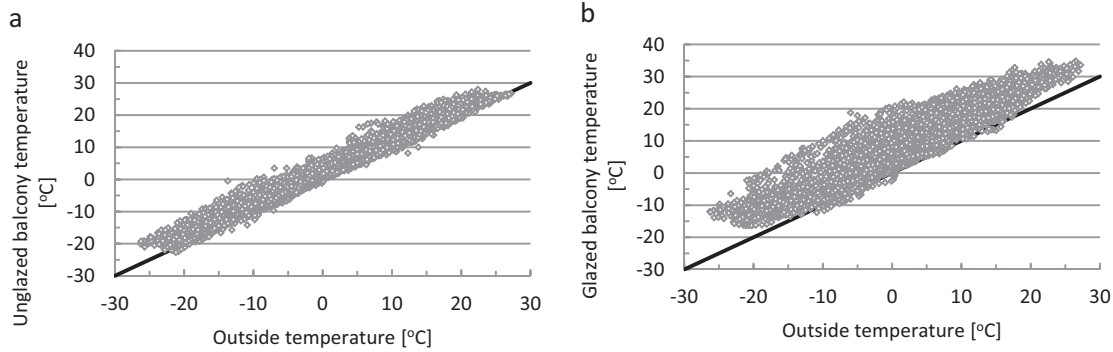
ence of the 17 glazed balconies was 6.6 °C compared to the outdoor air and the lowest in November with a 2.8 °C temperature difference. Calculated seasonally, the average temperature differences between the glazed balconies and the outdoor air were 4.2 °C in autumn (Sep–Dec) and 5.8 °C in spring (Mar–May). A difference of more than one and a half degrees between the autumn and spring values was caused by solar radiation, since it affected temperatures more in spring than in autumn. Annually, the warmest was an extended balcony (balcony 1) glazed on two sides in a block of flats built in 1975 (Building C), whose solar absorption was very high, air tightness very high, and heat loss low (Table 3). In contrast, the coldest was an extended balcony (balcony 17) glazed on one side in a building one year older (Building B), whose heat loss was low, solar energy absorption very high, and air tightness very low. This shows that balcony air tightness seems to be the most critical factor for balcony indoor temperatures.

Monthly analysis showed marked differences in the individual behavior of glazed balconies. Balcony 1 warmed up significantly from solar radiation and showed good ability to store solar energy in its structures. Consequently, the results differed clearly from the coldest glazed balcony (balcony 17). However, also the coldest glazed balcony performed better than unglazed balconies, and occasionally their temperatures clearly differed from those of unglazed ones, as can be inferred from the high maximum temperatures of balcony 17 in October and March. Those monthly deviations are interesting because balconies 17 and 18 were located in the same building and on top of each other. Thus both balconies received the same amount of solar radiation, yet they differed greatly in their temperature behavior.

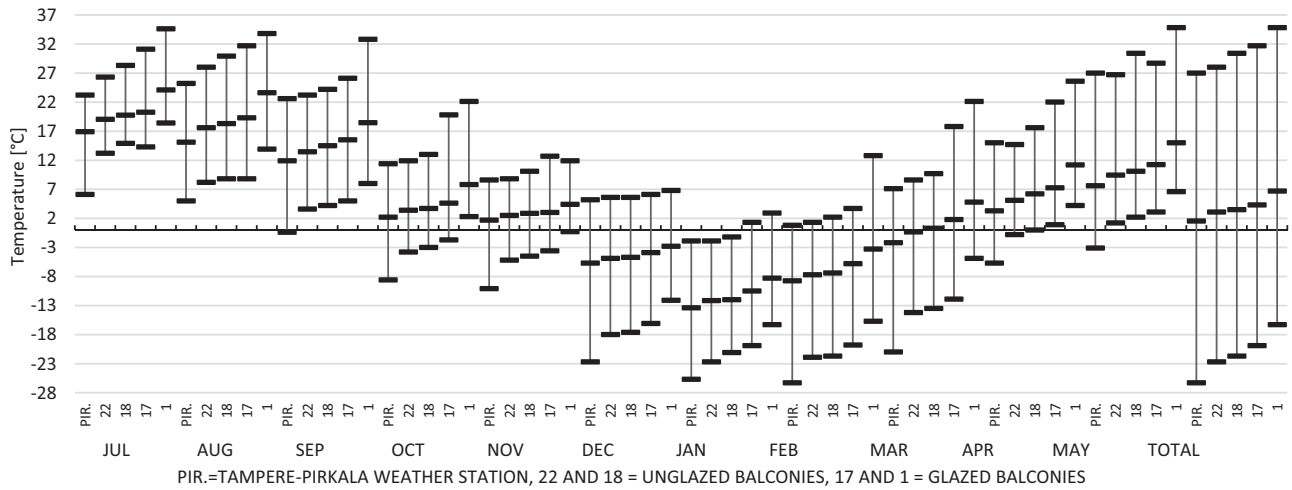
Characteristically, glazed balconies seemed to undergo strong fluctuation in their temperature and the outdoor air. Typically, temperature differences were greatest in spring and autumn and lowest in mid-winter. The largest differences between the balconies and the outdoor air were caused by solar radiation. Another factor was airing flats through the balcony door, though only one tenant did it systematically and for long periods during the year (Balcony 7). Overall, these temperature differences ranged from –5.8 °C to 29.6 °C during the measurement period. The highest below air temperature value was measured on balcony 7, a brief –5.8 °C below the outdoor temperature due to a rapid increase in the outdoor temperature, to which the concrete glazed balcony reacted with a short delay. The greatest difference was measured during solar radiation, which rapidly warmed up balcony 3 and caused a 29.6 °C temperature difference between the space and the outdoors air. However, this phenomenon had only a slight impact on the indoor air temperatures of the adjacent flat, because it was momentary and abated quickly as the sun went down.

**Table 2**  
Measurement range, display resolution, and accuracy of the used Comark Diligence EV (N2003 and N2013) data loggers.

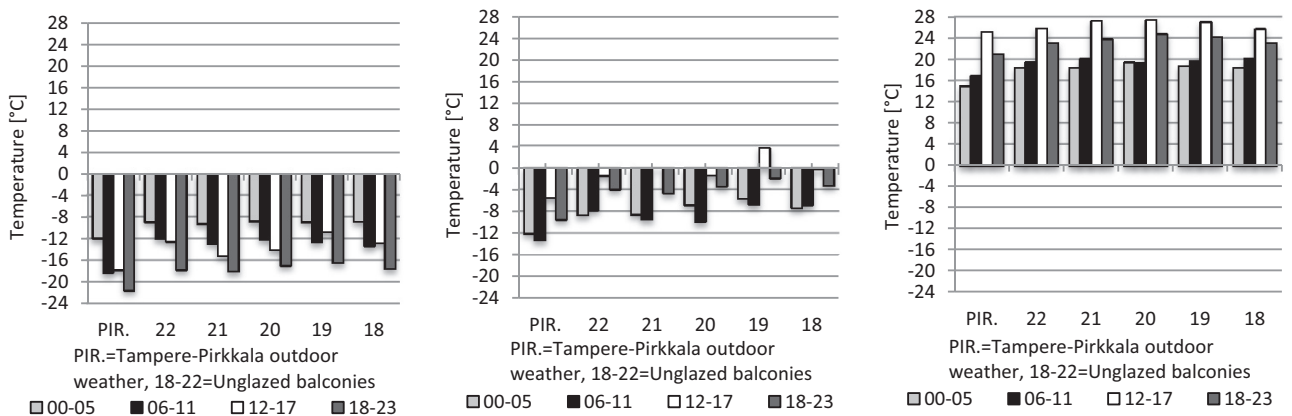
	Measurement range	Display resolution	Accuracy $-25^{\circ}\text{C}$ to $+50^{\circ}\text{C}$
Temperature	$-20^{\circ}\text{C}$ to $+60^{\circ}\text{C}$	$0.1^{\circ}$	$\pm 0.5^{\circ}$
	Measurement range	Display resolution	Accuracy $-20^{\circ}\text{C}$ to $+80^{\circ}\text{C}$
Humidity	0–97%	0.1% RH	$\pm 3$ RH



**Fig. 7.** (a,b) Temperatures of the coldest unglazed balcony (code 22, left) and of the warmest glazed balcony (code 1, right) in relation to the outdoor temperature measured at the Tampere-Pirkkala weather station.



**Fig. 8.** Monthly and total temperature behavior of the coldest and the warmest unglazed and glazed balconies and that at the Tampere-Pirkkala weather station.



**Fig. 9.** One cold winter day (26th January), an early spring day (15th Mars), and a late spring day (16th May) and Tampere-Pirkkala outdoor weather divided into six-hour periods.

#### 4.1.3. Comparison of glazed and unglazed balconies

In comparison of the balconies, glazed balconies were almost without exception warmer than unglazed balconies (Fig. 10). On average, their temperature difference was 3.0 °C, which was slightly more than the average difference between glazed and unglazed balconies in the same buildings. Only in July, August, and September was the unglazed balcony 18 with very high solar absorption (Table 1) warmer than the glazed balcony 15 with a dense forest in front of it. In addition, in October, the unglazed balcony 19 was warmer than the glazed balcony 16 on the east side of the adjacent building. However, the difference between the two was slight: 0.2 °C in July and 0.3 °C in the other months.

Comparison of glazed and unglazed balcony scatter diagram (Fig. 7) reveals three important observations. First, the set of points is clearly widely spread out, which shows that occasional deviations relative to the ambient air are clearly higher in glazed balcony than unglazed balcony temperatures. Second, the set of points in the glazed balcony scatter diagram are more apparent in the black line (denoting outdoor temperature); i.e., balcony temperatures are clearly separate from the outdoor temperature and yet, almost without exception, higher. Momentarily, balcony temperatures are also below the outside temperature, but such moments are limited to a range of –13 °C and 18 °C. Third, the set of plots is most clearly detached from the outdoor temperature at its lowest and highest end of the temperature range, which indicates that glazing has the most significant effect during cold (outside temperature <13 °C) and warm days (ambient temperature >18 °C).

## 4.2. Factors affecting balcony inside temperatures

### 4.2.1. Heat loss reduction

Results show that the glazed balcony temperatures cannot be evaluated based on the buildings' age, as is evident from the mean ages of the different heat loss reduction groups (Table 4). Because the average age of all the groups ranges from 1985 to 1987, each group includes both new and old buildings. Furthermore, comparison of the results in terms of heat transfer by conduction ( $\sum U \cdot A$ ) from the adjacent flat (column 9 in Table 4) shows that conduction loss is not a good indication of glazed balcony performance, because it contains only one balcony heat balance component. This can be seen, e.g., by comparing conduction loss reductions with total heat loss reductions. Conduction loss was the lowest in the group whose total change in heat loss (>25%) was the highest. In contrast, the total heat loss reduction calculated with equation 1 gives a good picture of the actual temperature behavior of the balconies.

Heat transfer by conduction from building to balcony has a significant impact on the temperatures of glazed balconies during the coldest months of the year (Dec, Jan, and Feb). Because solar radiation is hardly available in the Tampere region in this period, glazed balconies are heated mostly via heat losses from the building. The balconies with most their wall within the building's "warm" enclosure structures (e.g., integrated balconies) seem to perform better than the protruding ones. The reason is higher heat transfer from the adjacent flat (on three sides of the balcony) and higher overall balcony tightness (one glazed side) than in protruding balconies with two or three glazed sides. However, if the solution is not tight enough, a good overall solution cannot be reached. For example, the integrated balcony (Balcony 9) shows the highest heat losses in January, but it is not the best balcony in this period because of poor tightness. A better solution, for example, is balcony 2 with typical heat loss but very high tightness.

### 4.2.2. Location (microclimate)

Measurements made by the Finnish Meteorological Institute (Section 3.1) showed that small local differences occurred in the outside temperatures during the measurement period, even though

the measuring stations sought to eliminate the effect of microclimatic factors. A strengthening of these effects can easily be inferred from comparing the results on the balconies with the Tampere–Pirkkala temperature information (Table 5).

The coldest unglazed balcony was located in Härmälä (Balcony 22), the two next coldest in Hervanta (Balcony 20 and 21), the fourth coldest in Härmälä (Balcony 19), and the warmest in Lielähti. Interestingly, the temperature differed by 0.5 °C between the two unglazed balconies in Härmälä 15–20 meters apart from each other. The warmer balcony (Balcony 19) was 2.3 °C warmer than the outside and the colder one (balcony 22) 1.8 °C. Both balconies were open on two sides but oriented differently, which may explain the difference. The colder balcony was at a windy spot facing east and the warmer one in a sheltered area facing south. In addition, their solar absorption levels differed greatly. Balcony 22 showed typical solar energy absorption and balcony 19 a high level. Interestingly, the temperature difference between the two balconies was greater than that between the coldest (Hervanta) and the warmest (Lielähti) area (0.4 °C) (Table 5). It seems that the temperature differences between these unglazed balconies stemmed mostly from their different capabilities to absorb and store outside heat and from air circulation around them (cooling effect of wind). In some locations, more attention seems to have been paid to microclimate design, which resulted in a slight difference in unglazed balcony temperatures, though geographically the areas are less than 20 km apart with little effect on results in that respect.

### 4.2.3. Solar absorption (orientation and external obstacles)

On average, the impact on balcony temperatures of the difference between the best (very high) and the weakest (very low) solar absorption level was about 1.0 °C (Table 6). All the balconies with high or very high solar absorption warmed up strongly or very strongly in spring with the sun shining on them. The solar absorption levels of the three warmest balconies were also very high (Table 3). The warmest glazed balcony (Balcony 1) was in a block of flats in Hervanta with its indoor temperatures 6.6 °C higher than the outside because of very high solar absorption and structural tightness (Table 1). The second best balcony (Balcony 2) was also in Hervanta and the third best (Balcony 3) in Härmälä. Their temperature differences were 6.5 °C and 6.3 °C, respectively, above the outside air. However, balconies 11 and 7 deviated from the general pattern. Balcony 11 with three glazed sides received solar radiation clearly more than its classification indicates (typical solar absorption) (Fig. 11). In contrast, the warming effect on balcony 7 was unlikely due to solar radiation but to extended flat ventilation through the open balcony door (Fig. 12).

In addition to external obstruction, the balconies' orientation seemed to affect their ability to capture solar radiation. However, the orientation effect could not be analyzed in detail because the sample size was not sufficient for all orientations. In addition, the reliability of the analysis would have undermined external obstruction, which is also affected by the availability of solar energy. However, based on the research, southward orientation seems recommended. Furthermore, a deviation of  $\pm 45^\circ$  from the South seems not to result in significantly reduced solar radiation. Of the five most energy-saving, glazed balconies, two were south-east oriented and the remaining three west, south-west, and south oriented (Table 3). Because there was almost no shading in front of those balconies, they received solar radiation also in winter. As mentioned above, the west-facing balcony had two open sides with one on the south side; consequently, it received more solar radiation than the south-facing balconies with one open side.

As a whole, solar absorption seems a more critical factor than heat loss from building to balcony or the building's location. The three annually warmest balconies (Balcony 1, 2 and 3) were far from the warmest in November and December, but without exception

**Table 3**  
Balconies ranked from warmest to coldest based on their mean air temperatures over the whole measurement period.

Balcony number	Building code	Construction year	Mean temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]	Temperature difference to outside air <sup>a</sup> [°C]	Adjacent flat temperature [°C]	Heat loss reduction [%], calculated according to equation 1.	Heat transfer by conduction ( $\sum U \cdot A$ ) from adjacent flat to balcony [W/K]	Solar absorption level of balconies (reason)	Overall tightness of the balcony vertical structures	The number of the glazed sides of the balconies
Unglazed balconies												
1.	C	1975	8.1	34.8	-16.3	6.6	23.7	29.8	Low, 7.4	Very high (no external obstruction)	Very high	2
2.	G	1984	8.0	36.9	-13.3	6.5	23.1	30.1	Typical, 10.3	Very high (no external obstruction)	Very high	1
3.	K	2006	7.9	39.0	-16.7	6.3	23.1	29.4	Very low, 6.3	Very high (no external obstruction)	Very high	2
4.	D	1975	7.3	33.6	-14.6	5.7	22.7	27.1	Typical, 9.5	High (building ≈50 m in front)	High	1
5.	H	2000	7.0	33.4	-16.1	5.5	23.5	25.1	Low, 8.0	Very high (no external obstruction)	Very high	2
6.	D	1975	6.7	35.6	-15.7	5.1	23.6	23.2	Typical, 9.5	High (building ≈50 m in front)	High	1
7.	F	1979	6.6	29.6	-15.8	5.1	21.5	25.4	Low, 7.7	Very low (dense forest in front)	Very high	1
8.	D	1975	6.5	36.1	-17.3	5.0	23.5	22.8	Typical, 9.5	High (building ≈50 m in front)	Typical	2
9.	A	1966	6.5	34.6	-14.9	5.0	23.0	23.3	Very high, 15.9	Typical (adjacent building)	Typical	1
10.	E	1976	6.3	29.1	-15.4	4.8	21.7	23.6	High, 12.7	Low (medium dense forest in front)	Low	1
11.	I	2002	6.2	35.6	-17.2	4.7	24.9	20.1	Low, 7.8	Typical (buildings adjacent and ahead)	Low	3
12.	J	2002	6.2	37.0	-18.1	4.6	24.2	20.4	Low, 7.8	High (adjacent buildings)	Low	3
13.	K	2006	6.1	31.3	-16.3	4.6	23.9	20.5	Very low, 6.3	Very high (no external obstruction)	Low	2
14.	C	1975	6.1	33.4	-16.7	4.6	23.3	21.0	Low, 7.4	Very high (no external obstruction)	Low	1
15.	F	1979	5.3	30.9	-16.5	3.8	23.6	17.1	Low, 7.7	obstruction)	Very high	1
16.	I	2002	5.2	32.4	-18.1	3.7	23.6	16.6	Low, 7.8	Very low (dense forest in front)	Typical	2
17.	B	1974	5.1	31.7	-19.9	3.5	22.6	16.8	Typical, 9.5	Typical (buildings adjacent and ahead)	Very low	1
Unglazed balconies												
18.	B	1974	3.9	30.4	-21.7	2.4	23.4	11.0	Typical, 9.5	Very high (no external obstruction)	Very high	2
19.	J	2002	3.8	29.4	-21.7	2.3	23.9	10.1	Low, 7.8	High (adjacent buildings)	Very high	1
20.	D	1975	3.4	30.8	-21.7	1.9	23.2	8.7	Typical, 9.5	High (building ≈50 m in front)	Typical	2
21.	E	1976	3.4	29.5	-22.2	1.9	23.3	8.7	High, 12.7	Low (medium dense forest in front)	Very low	1
22.	I	2002	3.3	28.0	-22.7	1.8	25.1	7.5	Low, 7.8	Typical (buildings adjacent and ahead)	Very low	1
Outdoor air (Tampere–Pirkkala airport weather station)												
			1.5	27.0	-26.3							

<sup>a</sup> Temperature difference has been calculated by deducting Tampere–Pirkkala average outdoor air temperature (1.5 °C) from average balcony temperature over the whole period. For example, balcony 1 temperature difference is 8.1–1.5=6.6 °C.

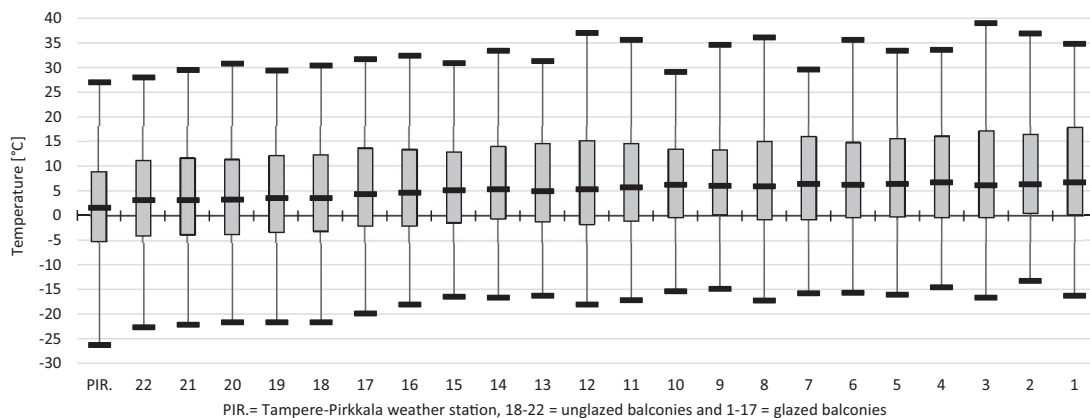


Fig. 10. Overall behavior of outdoor air temperatures in unglazed and glazed balconies during the measurement period.

Table 4

Balcony mean air temperatures and the temperature difference between balconies and outdoor air in terms of balcony conduction loss reduction.

Balcony number	Construction year	Mean temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]	Temperature difference to outside air* [°C]	Adjacent flat temperature [°C]	Heat loss reduction [%], calculated according to equation 1.	Heat transfer by conduction ( $\sum U^*A$ ) from adjacent flat to balcony [W/K]	Number of measured balconies
Outdoor air (Tampere–Pirkkala airport weather station)		1.5	27.0	–26.3					
Heat loss reduction <15% (Unglazed balconies)									
20	1986	3.6 ± 0.3	29.6 ± 1.1	–22.0 ± 0.4	2.1 ± 0.3	23.8 ± 0.8	9.2 ± 1.4	9.5 ± 2.0	5
Heat loss reduction 15–20% (glazed balconies)									
16	1985	5.2 ± 0.1	31.7 ± 0.8	–18.2 ± 1.7	3.7 ± 0.1	23.3 ± 0.6	16.8 ± 0.2	8.3 ± 1.0	3
Heat loss reduction 20–25% (glazed balconies)									
10	1985	6.3 ± 0.2	34.1 ± 2.7	–16.5 ± 1.1	4.8 ± 0.2	23.5 ± 0.9	21.9 ± 1.5	9.6 ± 3.2	8
Heat loss reduction >25% (glazed balconies)									
4	1987	7.5 ± 0.6	34.6 ± 3.2	–15.5 ± 1.3	6.0 ± 0.6	22.9 ± 0.8	27.8 ± 2.3	8.2 ± 1.5	6

Table 5

Balcony mean air temperatures and the temperature difference between the balconies and outdoor air in terms of building locations in Tampere suburban areas.

Balcony number	Construction year	Mean temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]	Temperature difference to outside air* [°C]	Adjacent flat temperature [°C]	Heat loss reduction [%], calculated according to equation 1.	Heat transfer by conduction ( $\sum U^*A$ ) from adjacent flat to balcony [W/K]	Number of measured balconies	
Outdoor air (Tampere–Pirkkala airport weather station)		1.5	27.0	–26.3						
Hervanta										
Unglazed	21	1976	3.4 ± 0.0	30.2 ± 0.9	–22.0 ± 0.4	1.9 ± 0.0	23.3 ± 0.1	8.7 ± 0.0	11.1 ± 2.3	2
Glazed	7	1977	6.8 ± 0.9	33.3 ± 2.9	–15.7 ± 1.2	5.3 ± 0.9	23.0 ± 0.8	24.4 ± 4.2	9.1 ± 1.8	9
Härmälä										
Unglazed	21	2002	3.5 ± 0.4	28.7 ± 1.0	–22.2 ± 0.7	2.0 ± 0.4	24.5 ± 0.8	8.8 ± 1.9	7.8 ± 0.0	2
Glazed	13	2002	5.9 ± 0.6	35.0 ± 2.4	–17.8 ± 0.5	4.3 ± 0.6	24.2 ± 0.7	19.0 ± 2.1	7.8 ± 0.0	3
Lielähti										
Unglazed	18	1974	3.9	30.4	–21.7	2.4	23.4	11.0	9.5	1
Glazed	11	1988	6.4 ± 1.2	34.2 ± 3.6	–17.0 ± 2.1	4.9 ± 1.2	23.2 ± 0.5	22.5 ± 5.3	9.5 ± 4.5	4
Hatanpää										
Glazed	5	2000	7.0	33.4	–16.1	5.5	23.5	25.1	8.0	1

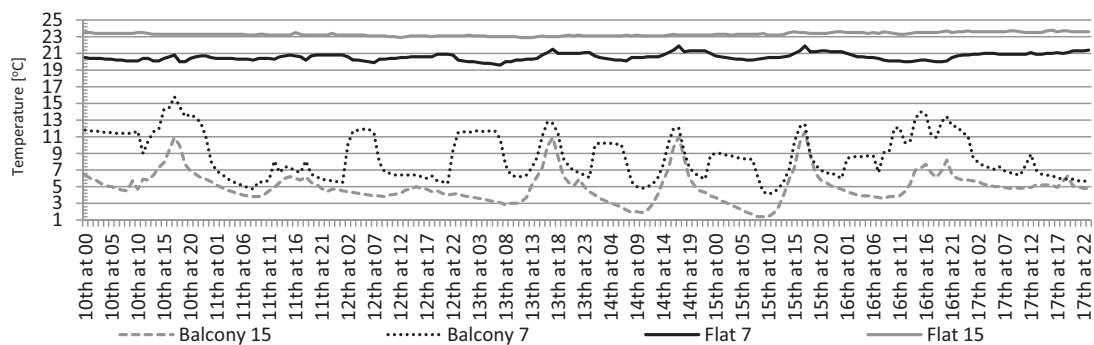
they were the warmest in spring and autumn. Solar radiation seems to start affecting monthly temperatures as early as in January. In February, the second coldest month of the year, heat losses from buildings to balconies affect the results greatly, but low heat loss can be compensated for by the spring sun, whose effect is also significant.

#### 4.2.4. Amount of glazing

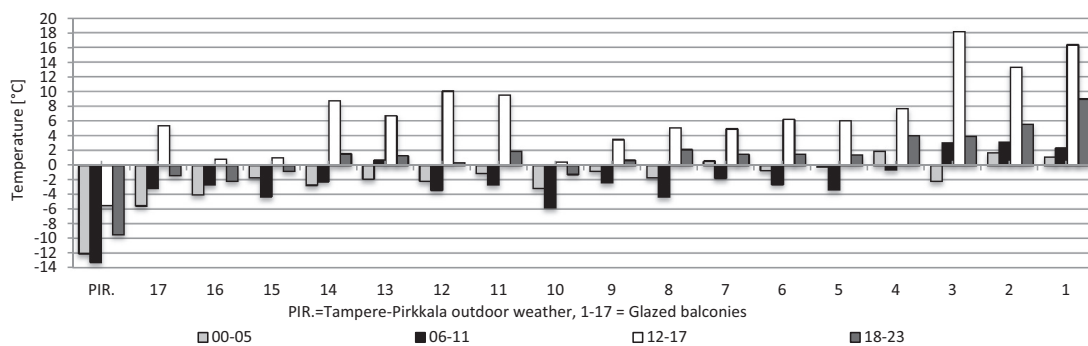
Increasing the amount of glazing by replacing a 180-mm thick balcony side wall element ( $U = 3.5 \text{ W/m}^2\text{K}$ ) with balcony glazing ( $U = 5.7 \text{ W/m}^2\text{K}$ ) increased slightly conduction heat losses from balcony to outside air. Increased glazing affected also the air tightness of the balcony, because a part of a tight wall structure was replaced with a leaky glazing structure, which increased unintended ventilation on the glazed balcony. On the other hand, increased glazing

**Table 6**  
Balcony mean air temperatures and the temperature difference between the balconies and outdoor air in terms of the number of external obstacles.

Balcony number	Construction year	Mean temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]	Temperature difference to outside air* [°C]	Adjacent flat temperature [°C]	Heat loss reduction [%], calculated according to equation 1.	Heat transfer by conduction ( $\sum U^*A$ ) from adjacent flat to balcony [W/K]	Number of measured balconies
Outdoor air (Tampere–Pirkkala airport weather station)		1.5	27.0	−26.3					
Unglazed balconies									
20	1986	3.6 ± 0.3	29.6 ± 1.1	−22.0 ± 0.4	2.0 ± 0.3	23.8 ± 0.8	9.2 ± 1.4	9.5 ± 2.0	5
Very low solar absorption level of balconies									
11	1979	5.9 ± 0.9	30.3 ± 0.9	−16.2 ± 0.5	4.4 ± 0.9	22.6 ± 1.5	21.2 ± 5.9	7.7 ± 0.0	2
Low solar absorption level of balconies									
10	1976	6.3	29.1	−15.4	4.8	21.7	23.6	12.7	1
Typical solar absorption level of balconies									
12	1990	6.0 ± 0.7	34.2 ± 1.6	16.7 ± 1.7	4.5 ± 0.7	23.8 ± 1.0	20.0 ± 3.4	10.5 ± 4.7	3
High solar absorption level of balconies									
8	1982	6.7 ± 0.4	35.6 ± 1.4	−16.4 ± 1.6	5.1 ± 0.5	23.5 ± 0.6	23.4 ± 2.8	9.1 ± 0.9	4
Very high solar absorption level of balconies									
8	1989	6.9 ± 1.2	34.4 ± 2.8	−16.5 ± 1.9	5.4 ± 1.2	23.3 ± 0.4	24.6 ± 5.3	7.9 ± 1.5	7



**Fig. 11.** One early spring day (15th March) and outdoor weather at Tampere-Pirkkala divided into six-hour periods.



**Fig. 12.** Temperatures of balcony 15 and 7 and of adjacent apartments from 10 to 17 October 2009. The figure shows how the resident of flat 7 ventilated the flat by keeping the balcony door open, especially at night.

increased the balcony’s solar absorption, thus compensating for conduction heat losses and increasing unintended ventilation. The effect of these factors is discussed in this section.

Table 7 shows that balconies with two or more open side capture a lot of solar radiation (from two or three directions), though they are also untighter than the balconies with one open side (untightness is directly proportional to the amount of glazing). In general, this means that temperature fluctuations become greater with an increased amount of glazing. On average, the solar energy absorption of balconies with one glazed side was typical, those with two

glazed sides very high, and those with three glazed sides high (Table 3). Similarly, the air tightness of the balconies was high, high, and low, respectively. The optimal solution for the indoor air temperature mean seems to be balconies glazed on two sides because of their high solar absorption and tightness (Table 7). In contrast, the coldest temperatures were recorded for balconies with three glazed sides, low tightness, and high solar energy absorption, which means that increased unintended ventilation lowered the results more than increased solar energy absorption could compensate for.

**Table 7**  
Balcony mean air temperatures and the temperature difference between the balconies and outdoor air in terms of the number of balcony glazed sides.

Balcony number	Construction year	Mean temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]	Temperature difference to outside air* [°C]	Adjacent flat temperature [°C]	Heat loss reduction [%], calculated according to equation 1.	Heat transfer by conduction ( $\sum U^*A$ ) from adjacent flat to balcony [W/K]	Number of measured balconies
Outdoor air (Tampere–Pirkkala airport weather station)		1.5	27.0	−26.3					
Unglazed balconies									
20	1986	3.6 ± 0.3	29.6 ± 1.1	−22.0 ± 0.4	2.0 ± 0.3	23.8 ± 0.8	9.2 ± 1.4	9.5 ± 2.0	5
Glazed balconies, one glazed side									
9	1976	6.4 ± 0.9	32.8 ± 2.7	−15.9 ± 1.8	4.9 ± 0.9	22.8 ± 0.8	23.1 ± 4.3	10.0 ± 2.7	9
Glazed balconies, two glazed side									
8	1994	6.8 ± 1.1	34.5 ± 2.8	−16.8 ± 0.8	5.3 ± 1.1	23.6 ± 0.3	24.0 ± 5.1	7.6 ± 1.2	6
Glazed balconies, three glazed side									
12	2002	6.2 ± 0.1	36.3 ± 1.0	−17.7 ± 0.6	4.7 ± 0.1	24.6 ± 0.5	20.3 ± 0.2	7.8 ± 0.0	2

On average, the temperature difference between the balconies with two and three open sides was 0.6 °C.

#### 4.2.5. Tightness of balcony vertical structures

The average temperature difference between the balconies with very high tightness and those with very low tightness is 2.1 °C (Table 8), i.e., clearly more than in any other review in Section 4.2. Furthermore, the difference between balconies with very high and low tightness was significant (1.0 °C). This clearly shows the importance of tightness for the final result. Table 8 also reveals that the maximum temperature of the balconies with very high tightness is lower than that of balconies with typical or high tightness. At the same time, heat transfer by conduction from flat to balconies is the lowest for balconies with very high tightness (7.9 W/K), but the change in their total heat losses (26.1%) is the highest. These findings indicate that tightness is the most important factor in terms of balcony indoor temperatures. The effect of tightness bears also on balcony minimum temperatures, which have increased with improved tightness. The balconies with high tightness show an average minimum temperature of −15.2 °C and those with very high tightness an average minimum temperature of −15.8 °C. This result has been seen even if the balconies with high tightness receive more heat from the adjacent apartment (heat transfer through enclosed structures) during the winter season than those with very high tightness.

The importance of tight structures is also confirmed in Table 3. The air leakage of glazed balcony 17 (the coldest) was the highest in the group, and the five coldest balconies included three leakiest glazed balconies. However, the air tightness of two of those balconies was very high (Balcony 14 and 13), but for some reason the tenant had left the glazing open for the entire measurement period, thus contributing to a low total tightness. The effect of increased air circulation to the balcony temperatures was particularly evident in buildings C and D. For example, in building C, the glazing on balcony 1 was kept closed whereas that on balcony 14 was partly open for the whole measurement period, resulting in a 2.0 °C temperature difference (6.6 °C and 4.6 °C, respectively) between the balconies, though they were almost adjacent to each other. Similarly, in building K, the average temperatures were 6.3 °C with the balcony closed and 4.6 °C with the balcony partly open (one pane open). Resident activity was also instrumental in another context. For example, balcony 7 warmed effectively when its door was left open for long periods during the measurement period (Fig. 12), yielding a significant difference in the average temperature of the balconies in the same building (1.3 °C between balconies 7 and 15).

#### 4.3. Possible uncertainties

The measurement data used, like large field data in general, included several possible sources of error, which may have affected the results and led to misinterpretations of the results. Such sources of error comprise the following:

- Different placements of the measurement devices (The devices were not all identically positioned, because the new mechanical attachment was avoided).
- Wrong information about buildings, balconies, and balcony glazing structural properties (buildings are not necessarily built according to blueprints).
- A lack of knowledge of tenant activities in flats and balconies (most important).
- Inaccuracy of the building's external shading and balcony tightness (evaluated by measuring air gaps on site, inspecting structural drawings, and visually observing on-site).
- Uncertainty caused by the cooling effect of air entering a flat through a glazed balcony (if the inlet was inside a glazed balcony). The effect of an air inlet on temperature drop is typically in the range of 1–3 °C, depending on the volume of the balcony in relation to that of the flat [9].
- Temperature stratification on the balcony and its variation depending on the case.

It is impossible to assess afterwards the impact of the above errors. The only option then is to make the sample size as large as possible to minimize the effect of various errors. In some cases, though the sample size was not sufficient enough to generalize about the results, it yet produced valuable, practical information about glazed balcony temperature behavior and provided valuable comparison material for computational analysis.

## 5. Conclusion

Measurements showed that the temperature of both glazed and unglazed balconies is above the outdoor temperature almost throughout the year. On average, the temperature of the unglazed balcony was 2.0 °C and that of the glazed balcony 5.0 °C higher than outdoors. The differences in temperature between the balconies and the outdoor air varied depending on the time of day and the season. As outdoor temperatures decreased, the difference in temperature between the glazed balcony and the outdoor air increased, and vice versa. The greatest temperature difference between the glazed balcony and the outside air was measured dur-

**Table 8**

Balcony mean air temperatures and the temperature difference between the balconies and the outdoor in terms of structural air tightness.

Balcony number	Construction year	Mean temperature [°C]	Maximum temperature [°C]	Minimum temperature [°C]	Temperature difference to outside air* [°C]	Adjacent flat temperature [°C]	Heat loss reduction [%], calculated according to equation 1.	Heat transfer by conduction ( $\sum U^*A$ ) from adjacent flat to balcony [W/K]	Number of measured balconies
Outdoor air (Tampere–Pirkkala airport weather station)		1.5	27.0	−26.3					
Unglazed balconies									
20	1986	3.6 ± 0.3	29.6 ± 1.1	−22.0 ± 0.4	2.0 ± 0.3	23.8 ± 0.8	9.2 ± 1.4	9.5 ± 2.0	5
Very low overall tightness of the balcony vertical structures									
17	1974	5.1	31.7	−19.9	3.5	22.6	16.8	9.5	1
Low overall tightness of the balcony vertical structures									
12	1992	6.2 ± 0.1	33.3 ± 3.2	−16.7 ± 1.0	4.7 ± 0.1	23.6 ± 1.2	21.1 ± 1.4	8.4 ± 2.5	5
Typical overall tightness of the balcony vertical structures									
11	1981	6.1 ± 0.8	34.4 ± 1.9	−16.8 ± 1.7	4.6 ± 0.8	23.4 ± 0.3	20.9 ± 3.8	11.1 ± 4.3	3
High overall tightness of the balcony vertical structures									
5	1975	7.0 ± 0.4	34.6 ± 1.4	−15.2 ± 0.8	5.4 ± 0.4	23.2 ± 0.6	25.1 ± 2.8	9.5 ± 0.0	2
Very high overall tightness of the balcony vertical structures									
6	1987	7.2 ± 1.1	34.1 ± 3.6	−15.8 ± 1.3	5.6 ± 1.1	23.1 ± 0.8	26.1 ± 5.0	7.9 ± 1.3	6

ing solar radiation, which warmed up the glazed space very rapidly and caused the greatest temperature difference between the space and the outdoor air (29.6 °C). The three key factors affecting the indoor temperatures of the glazed balconies seemed to be structural air tightness, absorption of solar radiation, and heat losses from building to balcony, in that order. Air tightness was the most crucial factor since it affected the results all year round. Solar radiation was significant only in spring, summer, and autumn because of Finland's high latitudinal location. Heat loss from building to balcony, in turn, was relevant in mid-winter when the difference in temperature between the building and the outdoors could be as high as 60 °C. In mid-winter, glazing a balcony as opposed to an unglazed balcony brings the benefit of being able to store the heat loss from the building inside the balcony.

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### References

- [1] J. Hix, *The Glass House*, Phaidon Press Ltd., London Great Britain, 1974.
- [2] N. Pevsner, *A History of Building Types*, The Architectural Press Ltd., London Great Britain, 1976.
- [3] R. Saxon, *Atrium Buildings, Development and Design*, The Architectural Press Ltd., London, Great Britain, 1983.
- [4] M. Wall, *Climate and energy use in glazed spaces*, in: Report no TABK-96/1009, Lund University, Lund, 1996pp. 404 (PhD thesis).
- [5] Lumon Oy, *Lumon 5 Balcony Glazing*, Kouvola, 40p. <http://www.idex.is/wp-content/uploads/2013/06/lumon5-balcony.pdf>.
- [6] O.B. Jorgensen, O.J. Hendriksen, *Glazed balconies and sun spaces ?energy savers or energy wasters?* in: Proceedings of the 3rd Int. ISES Europe Solar Congress, Eurosun 2000, 19–22 Jun 2000, Copenhagen, Denmark, 2000.
- [7] J. Heikkilä, *Parveke suomalaisen kerrostalon asunkohtaisena ulkotilana (Balcony as an outdoor space in Finnish apartment buildings)*, Acta Univ. Oul. C91, University of Oulu, Oulu, 1996, pp. 300 (PhD thesis). (In Finnish).
- [8] K. Hilliaho, *Parvekelasituksen energiatiloudelliset vaikutukset (Energy saving effects of the balcony glazing)*, in: Master of Science Thesis, Tampere University of Technology, Tampere, 2010, pp. pp. 147 (In Finnish).
- [9] K. Voss, *Solar energy in building renovation—results and experience of international demonstration buildings* *Energy Build.* 32 (3) (2000) 291–302.
- [10] A.H. Abdullah, Q. Meng, L. Zhao, F. Wang, *Field study on indoor thermal environment in an atrium in tropical climates*, *Build. Environ.* 44 (2) (2009) 431–436.
- [11] S.T. Elias-Ozkan, F. Summers, Ö. Taner, *Energy efficiency of building with a solar space: two case studies from the Anatolian plateau*, in: Proceedings of the International 26th PLEA Conference, 22–24 June 2009, Montreal, Canada, 2009.
- [12] J.J. Roux, C. Teodosiu, D. Covallet, R. Chareille, *Validation of a glazed space simulation model using full-scale experimental data*, *Energy Build.* 36 (6) (2004) 557–565.
- [13] A. Laouadi, M.R. Atif, *Comparison between computed and field measured thermal parameters in an atrium building*, *Build. Environ.* 34 (2) (1998) 129–138.
- [14] G.J. Schoenau, A.J. Lumbis, R.W. Besant, *Development and verification of a simulation model for predicting the thermal behavior of attached sunspaces*, *Energy Convers. Manage.* 32 (4) (1991) 319–331.
- [15] A.R. Rempel, A.W. Rempel, K.V. Cashman, K.N. Gates, C.J. Page, B. Shaw, *Interpretation of passive solar field data with EnergyPlus models: un-conventional wisdom from four sunspaces in Eugene, Oregon*, *Build. Environ.* 60 (2013) 158–172.
- [16] L.T. Joergensen, *Monitored results from yellow house*, in: Proceedings of the EuroSun2000 ISES-European Solar Conference, 19–22 June 2000, Copenhagen, Denmark, 2000.
- [17] O.B. Joergensen, L.T. Nielsen, *Monitored results from an innovative solar renovation of multi-storey housing-EU SHINE-Engelsby, Flensburg*, in: Proceedings of the EuroSun2000 ISES-European Solar Conference, 19–22 June 2000, Copenhagen, Denmark, 2000.
- [18] J.-M. Mottard, A. Fissore, *Thermal simulation of an attached sunspace and its experimental validation*, *Sol. Energy* 81 (3) (2007) 305–315.
- [19] M. Wall, *Förförvarmning av tilluft med solfångare och glasrum*, in: Rapport TABK-94/3017, Lund University, Lund, 1994, pp. 27.
- [20] C. Boonstra, *Glazed Balconies in Building Renovation*, Brochure, James and James, London, UK, 1997, pp.16.
- [21] J.-O. Dalenbäck, *Solar energy in building renovation*, *Energy Build.* 24 (1996) 39–50.
- [22] G. Mihalakakou, *On the use of sunspace for heating/cooling in Europe*, *Renew. Energy* 26 (3) (2002) 415–429.
- [23] K.M. Bataineh, N. Fayed, *Analysis of thermal performance of building attached sunspace*, *Energy Build.* 43 (8) (2011) 1863–1868.
- [24] J.S. Mattila, *Effect of balcony glazing on the durability of concrete structures in Nordic climate*, in: Proceedings of Sustainable Construction, Materials and Practice Conference, Portugal, 2007.
- [25] M.P. Wilson, O.B. Jorgensen, G. Johannesen, *Daylighting, energy and glazed balconies: a study of a refurbishment project in Engelsby, near Flensburg, Germany*, *Light. Res. Technol.* 32 (3) (2000) 127–132.
- [26] C. Ganem, A. Esteves, *A better quality of life through the refurbishment of building's facades with glazed balconies*, in: Proceedings of the 20th Conference on Passive and Low Energy Architecture, 9–12 November 2003, Santiago, Chile, 2003.
- [27] E. Erkiö, A. Melajärvi, *Parvekelasitusten energiatiloudelliset ja kaupunkikuvalliset näkymät (Balcony glazing systems from the view point of energy economy and cityscape)*, *Lasirakentaja* 3 (1994) 23–27.
- [28] S. Boström, U. Uotila, S. Linne, K. Hilliaho, J. Lahdensivu, *Erialaisten korjaustoimien vaikutuksia lähiökerrostalojen todelliseen energian kulutukseen (The Effects of Different Renovation Measures on the Energy*



- Consumption of Suburban Block of Flats), Tampere University of Technology, Department of Civil Engineering, Research report 158, Tampere, 2012, pp. 77. (In Finnish).
- [29] G. Shoenau, A. Lumbis, R. Besant, An examination of operating strategies for energy efficient operation of attached sunspaces in cold climates, *Energy Convers. Manage.* 33 (1) (1992) 23–36.
- [30] M. Reichenbach, Apartment building in cold climate: sunspace, in: S.R. Hastings, M. Wall (Eds.), *Strategies and Solution*, vol. 1, Sustainable solar housing, London, 2007, pp. 171–178.
- [31] G. Oliveti, N. Arcuri, M.D. Simone, R. Bruno, Solar heat gain and operative temperature in Attached sunspaces, *Renew. Energy* 39 (1) (2012) 241–249.
- [32] A. Haller, Improvement of Solar Renovation Concepts and Systems, A Technical Report of IEA SHC Task20 Solar Energy in Building Renovation, Ernst Schweizer AG, Metallbau, Hedingen, 1999, pp. 74.
- [33] M. Kottek, J. Greiser, B. Beck, et al., World Map of the Köppen–Geiger climate classification updated, *Meteorol. Z.* 15 (3) (2006) 259–263.
- [34] H. Pirinen, J. Simola, J.P. Aalto, P. Kaukoranta, Climatological statistics of Finland 1981–2010, in: *Reports 2012:1*, Finnish Meteorological Institute, Helsinki, 2012, pp. 96.

## IV

### **GLAZED SPACES: A SIMPLIFIED CALCULATION METHOD FOR THE EVALUATION OF ENERGY SAVINGS AND INTERIOR TEM- PERATURES**

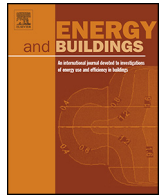
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# Glazed spaces: A simplified calculation method for the evaluation of energy savings and interior temperatures



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## ABSTRACT

Previous studies have shown that temperatures inside glazed balconies are almost without exception higher than those of outside air. This is due to the space's ability to capture and store the building's heat losses and solar radiation. The interior temperatures and energy saving effects of glazed balconies are, however, not particularly good in Finland, because the implemented solutions are not optimized for these issues. The purpose of this study is to introduce simplified evaluation methods for the energy saving and interior air temperature evaluation of glazed spaces and to verify the method reliably with the help of measured and simulated values of typical Finnish 1970s apartment blocks. The presented method can be used for optimizing and showing the energy saving impact as well as the mean, maximum and minimum temperatures of different type of glazed spaces in the preliminary design stage. The results show that the accuracy of the method is sufficient for designing if nine parameters are changed at most. The accuracy is affected by the number of changes made in relation to the typical 1970s apartment blocks in Finland, which was chosen as a starting point for the method's development.

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## 1. Introduction

In the end of 2012, the Finnish housing stock consisted of 57,849 blocks of flats, 77,931 row houses and 1,122,315 detached houses. In total, there were 1,258,095 residential buildings, which accounted for 85.3% of the Finnish building stock. [1]. The blocks of flats alone contain 1.29 million dwellings, that is, 44% of all homes [2]. About 0.8 million (63%) of the flats have a balcony [3]. According to information received from Finnish balcony glazing manufactures, more than 500,000 of those are glazed (Fig. 1), which corresponds to approximately 70% of Finland's apartment balconies [4,5]. The balcony glazing systems used in Finland are almost solely openable frameless systems (Fig. 1) with 5–6 transparent 6 mm float glass panes (Fig. 2). There are 2–3 mm air gaps between the glass panes, guaranteeing a sufficient level of ventilation in the balcony and yet providing protection against wind, rain and snow.

The thermal behavior of glazed spaces has been studied extensively with the help of measurements [6–15] and computations [4,9,16–20]. The studies have shown that the temperatures inside the enclosed spaces are higher [7–10,19,21–24] and the relative humidities are lower [8,10,16] than outside throughout the year. However, the results have rarely had any effect in practical design work, at least in Finland. This has been due to (a) the general belief that glass-enclosed spaces do not have energy economic importance in the Nordic climate; (b) the lack of easily accessible information about key factors affecting the energy savings and indoor climate of glazed spaces; and (c) the complexity and labor intensity of the current dynamic calculation programs.

The purpose of this study was to develop a table method that would be usable in practical design work for the evaluation of the energy saving potential and interior temperatures of glazed spaces, and to analyze the accuracy of the method with the help of a corresponding energy simulation study and results from field measurements. As a result of the study, a simplified method for the evaluation of the energy saving potential and interior temperatures of glazed balconies is launched, and its reliability demonstrated with the help of Finnish 1970s large-panel apartment blocks. The results provide a good basis for initiating the use of the method as well as developing the calculation principles further.

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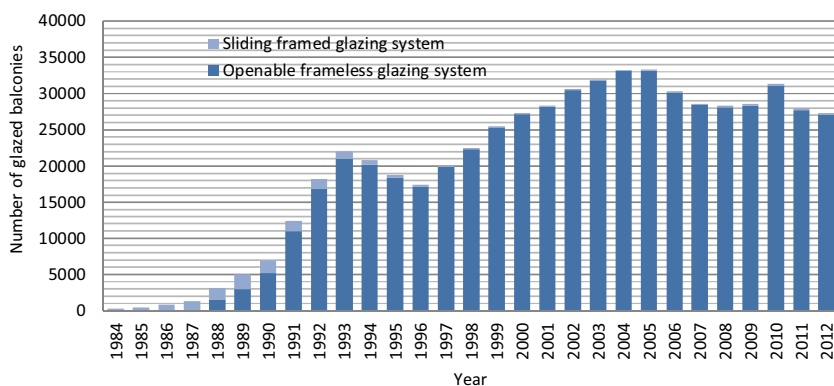


Fig. 1. Balcony glazing installations in Finland in 1984–2012 [5].



Fig. 2. Balconies with openable balcony glazing in a 1970s apartment building.

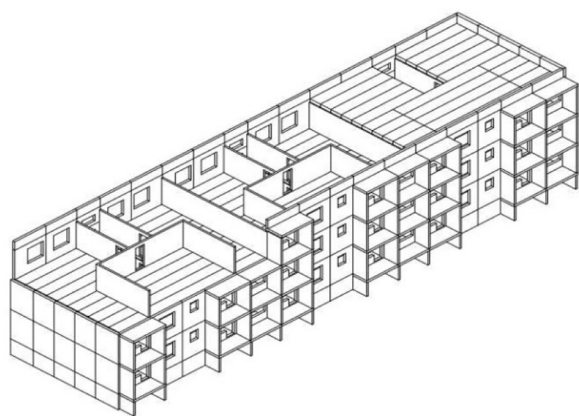


Fig. 3. Panel structures of a typical Finnish block of flats. Adapted from [25].

## 2. Background

### 2.1. Finnish building stock

Most Finnish blocks of flats and balconies have been built after the 1960s with precast concrete panel systems. The majority of them were built with an open-source panel system called BES, developed in the late 1960s and shared by all producers. The prior factory-specific panel systems were highly similar to BES in terms of layout design and overall appearance but slightly different with regard to the floor slab type and structural detailing. In all, the structures, panels and plans of blocks of flats built in Finland from the 1960s on are highly standardized [25–28].

The majority of the buildings are slab blocks [26], which typically have 3–4 stories [29] and 2–3 staircases (Fig. 3). The residential floors are usually located above the ground floor and are usually

identical with each other. The buildings contain ten different basic flat types that range from studio flats to four-room homes [26]. The most common apartment type is the two-room flat that extends from one side of the building to the other [26,29]. The smallest flats (studios and small two-room flats) are located on only one side of the building [26,28]. The buildings have mechanical exhaust ventilation systems that produce suction. Exhaust vents are located in kitchens, bathrooms and (possible) walk-in closets. The replacement air is taken in through trickle vents that are typically placed in bedrooms and living rooms. This implies that the replacement air often enters the flat through the balcony. The buildings usually heat with district heating and the heat is distributed with the help of hot-water radiators located below windows.

In slab blocks, balconies are usually located only on one of the building's longitudinal facades (Fig. 3) [25,28]. Balconies can be either protruding or recessed, and they can be self-supporting (with sidewalls or columns), cantilevered or suspended from the load-bearing frame of the building. [25,30]. Since 1960, by far the most common balcony type has been the protruding self-supporting balcony with load-bearing sidewalls [25,31]. The parapets are typically also made of concrete (Fig. 2). Prior to 1968, the regulation banned balconies from studios of publicly subsidized buildings [30]. Between 1968 and 1976, one balcony per flat was allowed regardless of the size of the flat [25,30]. From 1977 on, one balcony per flat became a requirement in public housing [30]. Since balcony glazing was fairly rare before the 1990s (Fig. 1), it is always a retrofit solution in older buildings and usually part of a balcony renovation strategy. If the glazing resembles an external wall structurally (e.g. has poor ventilation and fair heat insulation), the balcony will be included in the building's gross floor area and its ventilation is to be arranged separately, increasing the cost of glazing significantly. Therefore, Finnish glazing systems have nowadays almost exclusively single glazing, air gaps and openable panes.

### 2.2. Previous studies

#### 2.2.1. Field measurements

In a prior study [6,32], field measurements were performed in 11 apartment blocks of different ages in the city of Tampere. Five of them were typical BES blocks from the 1970s, built between 1974 and 1979 (Fig. 4). The four buildings built before 1978 did not originally have balconies in the smallest flats, but they have been retrofitted in two of them (Buildings 2 and 3 in Fig. 4). When it comes to the structures of external walls, windows, doors and balconies, the buildings were highly similar at the time of their completion. However, as a result of renovations, the windows, doors and balcony railings have been replaced in most cases (Building 4 excluded).



Fig. 4. The balcony facades of Buildings 1–5 [6].

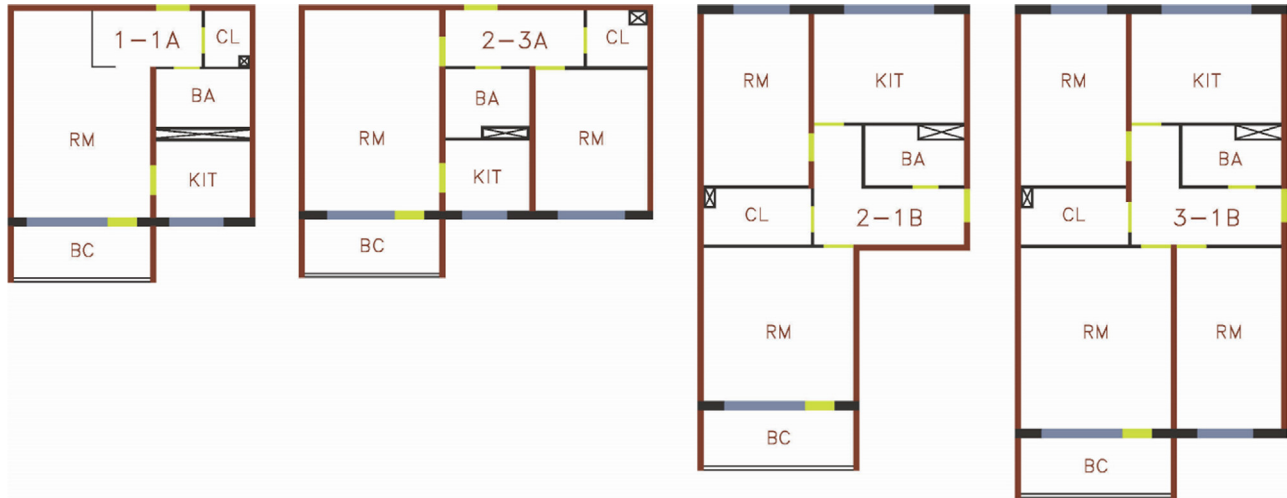


Fig. 5. The measured flat types (adapted from [26]). They are representative of the 1970s age cohort according to Ref. [26]. The flat type codes (e.g. 1–1A) follow the coding defined in Ref. [26].

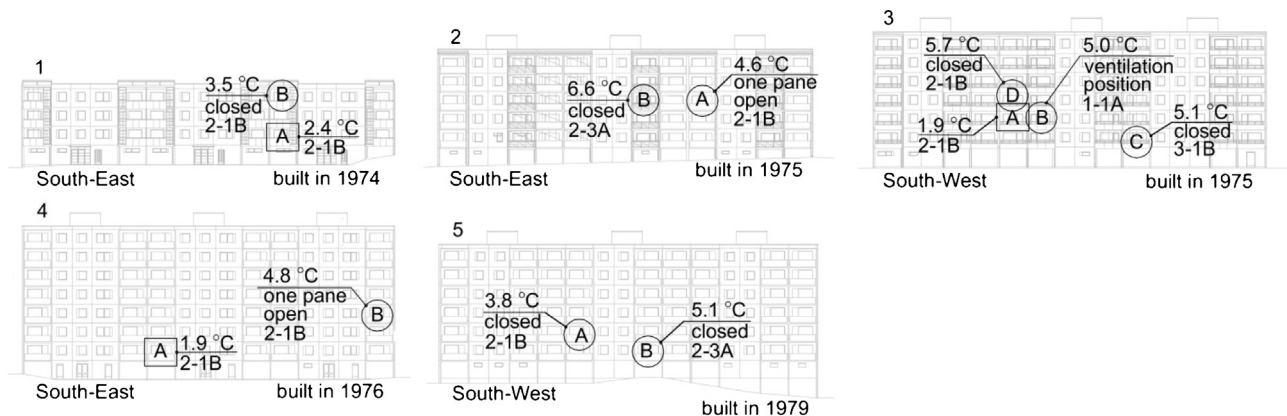


Fig. 6. The five studied apartment buildings. Flat type codes, indicating the size and shape of the flat, are given in Fig. 5. Measured flats and balconies are specified with individual number and letter codes [6].

The monitored apartments are representative flat types in this age cohort [26] and they included one studio; two small two-room flats; eight large two-room flats; and one three-room flat (Fig. 5). In total, 12 balconies and adjacent flats were monitored for 10 months (8/2009–5/2010). Data loggers were installed in the apartment and onto balcony ceilings, on locations not exposed to sunshine. Monitored balconies are sorted by the number of the building (1–5) and a letter given for the apartment (A–D). They are shown in Fig. 6, where unglazed balconies are marked with rectangles and glazed balconies are circled. The yearly mean temperatures of measured balconies increase in an alphabetical order (A being the coldest). The figure includes also building years, facade orientations, measured mean temperatures and use habits of glazing.

The field measurements suggested that the balconies were almost without exceptions warmer than the outside air. On average, the temperature differences between the outside and the balcony were 3.5–6.6 °C for glazed and 1.9–2.4 °C for unglazed balconies. The temperature difference varied greatly, depending on the time of the day and the season. Significant temperature differences were also detected between balconies of the same building, although their structural solutions were mostly very similar. This was due to the differences in the amount of inlet air through the balcony; the tightness of the retrofitted glazing structures; the existence of external shading; location; glazing's surface area; building's heat losses; and residents' use habits (ventilation through balcony glazing and/or balcony door). The three key factors affect-

**Table 1**  
Input data used in simulation for the base case [4], Building 3 and Building 5.

Location (climate condition)	Base case: Helsinki (60° 10' 15" N, 24° 56' 15" E); Buildings 3 & 5: Tampere (61° 29' 53" N, 23° 45' 39" E)
Orientation	Base case: south; Buildings 3 & 5: south-west
Wind profile	Suburban
Balcony façade distance from the building in front	Base case: No building in front; Building 3: Building ≈50 m in front of B3 (high solar absorption); Building 5: Dense forest in front of B5 (very low solar absorption)
Flat size (room number)	Two rooms
Room temperature	Base case: 21 °C Building 3, flat D: 22.7 °C Building 5, flat A: 23.6 °C
Standard of equipment and number of occupants	According to Finnish building regulation
Window U-value (A=3.3 m <sup>2</sup> )	Base case: U=2.8 W/m <sup>2</sup> K, g=0.75; Building 3: U=1.4 W/m <sup>2</sup> K, g=0.55; Building 5: U=1.2 W/m <sup>2</sup> K, g=0.55
Door U-value (A=1.9 m <sup>2</sup> )	Base case: U=3.0 W/m <sup>2</sup> K, g=0.75; Buildings 3 & 5: U=1.2 W/m <sup>2</sup> K, g=0.55
Exterior wall U-values (A=5.2 m <sup>2</sup> )	Base case: U=0.4 W/m <sup>2</sup> K; Building 3: U=0.4 W/m <sup>2</sup> K; Building 5: U=0.29 W/m <sup>2</sup> K
Balcony type (depth) and balcony width	Protruding balcony measuring 1.5 m × 4.0 m
Number of glazed sides (parapet type)	One side glazed (concrete parapet)
Type and thickness of balcony glazing	Single clear glass (U = 5.8 W/m <sup>2</sup> K, g = 0.82), thickness 6 mm
Balcony's relation to exterior wall	Base case: Balcony covers the flat's exterior wall completely; Buildings 3 & 5: Balcony covers one-third of the flat's exterior walls
Vertical & horizontal position of the balcony	The middlemost balcony in the building
Building ventilation type (air change rate)	Mechanical exhaust ventilation (0.5 ACH)
Supply air intake solution	Base case: Directly from the outside (one wall vent); Buildings 3 & 5: Two window vents (one inside the glazed balcony)
Unintended ventilation of glazed space	Very high tightness as compared to typical solution in Finland
Openness of the balcony glazing	Completely closed
Building air leakage coefficient	1 ACH
Designed heating capacity of hot water radiators	Heating capacity 140% of the building heat losses in Sodankylä
Heating system control curve position	Initial settings
Heating system summer shut-off	Summer shut-off in June, July and August
Building's heat delivery system	Hot water radiator heating system (70/40 system)
Heat losses from the heat delivery system	No heat loss to the flat
Specific heat capacity of balcony structures	880 J/(kg × K)
Lambda value of balcony structures	2.5 W/(m × K)
Density of balcony structures	2300 kg/m <sup>3</sup>
Surface absorptivity (balcony and exterior wall)	Base case: 0.95; Buildings 3 & 5A: 0.3
Surface emissivity (balcony and exterior wall)	0.95
Blinds in balcony glazing or window	No blinds

**Table 2**  
Results from the simulation of the base case.

Energy savings in base case		
Percentual ( $E_{\%,base}$ )	14.5	%
Kilowatt-hourly ( $E_{kWh,base}$ )	545	kWh
Balcony temperatures in base case		
Maximum ( $T_{max,base}$ )	41.3	°C
Minimum ( $T_{min,base}$ )	-11.1	°C
Average ( $T_{avg,base}$ )	13.4	°C

ing the interior temperature were (in the order of significance): the air leakage level of the balcony's vertical structures, the balcony's ability to capture solar radiation and the heat gain from an adjacent flat. The air tightness affected the measurements regardless of time, season, and position of balcony. In the temperature-wise worst situation, high outflow resulted in poor performance even if the solar absorption level and heat gain from the adjacent apartment were high. The significance of solar radiation level was especially evident from spring to autumn due to Finland's high latitude. Balconies were typically oriented to the southern sector between east and west and they absorbed solar radiation quite well (7/11 buildings of the study). Absorptivity could be improved by using dark surface colors, but the balconies of the studied buildings were painted light. The heat gain from the adjacent apartment had the smallest effect because the balconies were mostly protruding (16/17 glazed balconies), the thermal insulation level was rather good and the air tightness was quite poor.

### 2.2.2. Computer simulations

The simplified calculation method introduced in the current study has been developed with the help of simulation results produced in two previous studies [4,32]. The aim of the first study was to analyze the suitability of IDA Indoor Climate and Energy (IDA-ICE) 4.6.1 simulation software for the energy simulation of glazed spaces in theory and practice [32]. The purpose of the second study was to run a large-scale sensitivity analysis focusing on the impact of different types of glazed balconies on the energy consumption of buildings in northern climatic conditions [4]. The starting point for the second study was a glazed balcony in a typical Finnish block of flats from the 1970s, the impact of which on the energy consumption of the building was analyzed based on 156 different calculation cases. The purpose of the sensitivity analysis was to create a base model representing a typical situation in the Finnish building stock. The Flat 2B in Fig. 5 was selected to the study. Its structures are assumed to be typical to the construction decade. The use is considered to follow the standard given in the National Building Code, which corresponds to the typical use of a flat of this size and quality in Finland [33]. This flat represents a basic type that is, according to a recent study, the most common flat type amongst all Finnish flats from the 1960–80s with a share of 18.6% [29]. The use of this type is also justified by the fact that eight apartments of this kind were included in the field monitoring study. Three of their balconies were unglazed and five were glazed.

The results showed that the energy saving impact of a glazed space varies a lot between cases and depend, not only on the properties of the glazed space, but also on the building and its properties. The key variables in the energy engineering of a glazed space proved to be the integration of the space in the building's ventilation system; heat losses from the building to the glazed space and from the glazed space to outside air (balcony type and U-values of structures); air tightness of the balcony; and absorption coefficients of surfaces. The key properties of the building with regard to the energy saving potential of the glazed space were the total heating capacity of the hot water radiators and the adjustment of the heating system; the type of the ventilation system; the level of indoor

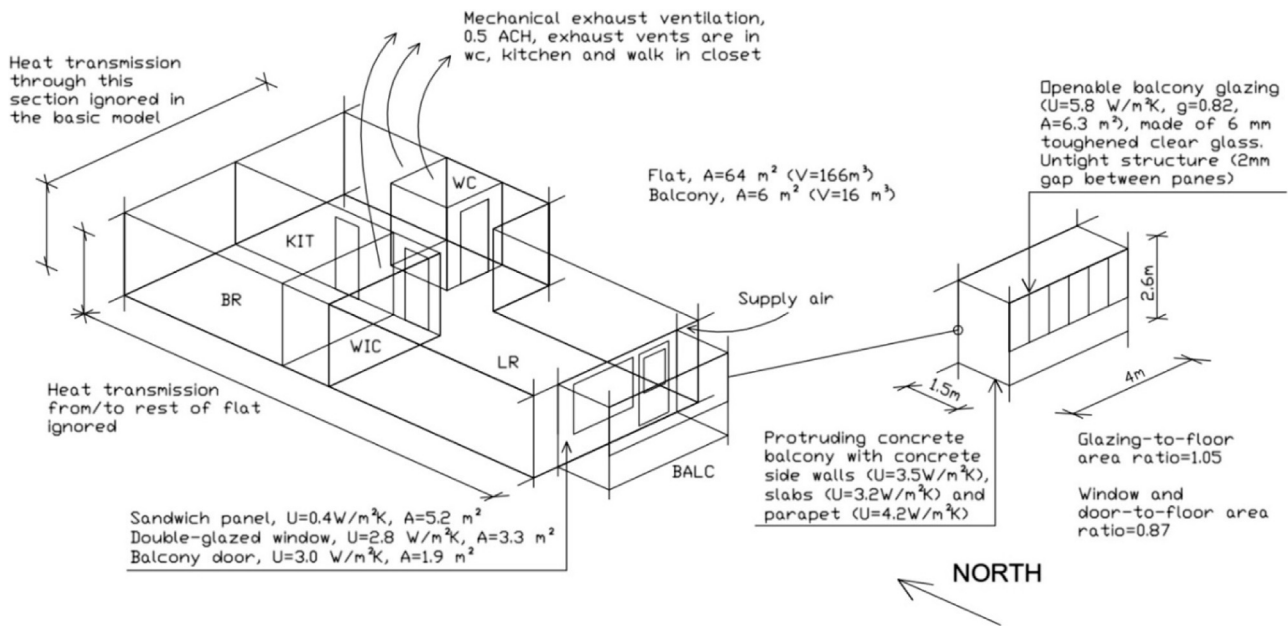


Fig. 7. An illustration of the simulated apartment [4].

temperature in the flat; and the flat's share of the building's energy consumption, which depends on the size of the flat and its location in the building. The findings also showed that the studied base case proved to be a very potential target for glazing installation due to the relatively tight balcony as a whole after glazing installation (1.5–2.6 ACH) and weak thermal insulation of the building envelope. This is especially true if balconies are towards south and their surfaces are painted dark, even though the buildings' supply air would not be drawn through the glazed space but outside it, as is the practice in the 1970s buildings. The study also showed that single glazing with air gaps and openable panes are a good option for balconies, especially in Finland, since the construction regulation requires untight solutions. To improve the usability of the research results in real building design, it is necessary to develop a simplified method for the assessment of the energy saving effect and interior temperatures of glazed spaces.

### 2.3. Methods for evaluating the energy saving potential and balcony temperature

By measuring the temperatures indoors, outdoors and in the balcony, it is possible also to figure out information on the temperature behavior of the balcony and the flat as well as on the heat loss reduction level (Eq. (1)) in the building section adjacent to the balcony as a whole (include balcony back wall, windows and door) after glazing installation. The results are reliable if the measuring devices are accurate enough, calibrated and the measurements conducted properly but, at a same time, very laborious and time consuming. A weakness of the method is the fact that it is only suitable for studying existing buildings.

$$\text{Heatlossreduction} = 1 - \frac{T_{\text{FLAT}} - T_{\text{BALCONY}}}{T_{\text{FLAT}} - T_{\text{OUTDOOR}}} \quad (1)$$

An alternative way to assess the temperature behavior of a balcony is to use calculation models. Standard ISO 13789 [34] introduces a general method for calculating the thermal performance of buildings, where transmission and ventilation heat coefficients and also solar radiation are accounted for. With a loss of accuracy, the method is quite simple to use without expensive simulation programs and it presents the most crucial factors affecting the heat

performance. The influence of solar radiation is quite evident for spaces with significant glazing surfaces, which also increases the uncertainty since the effect of solar energy is quite difficult to calculate manually. The simplifications of manual calculation usually disregard time variance and use static systems, which can have a major impact on the final outcome.

Another option for analyzing the interior temperatures and energy saving effects of glazed spaces is to use generally accessible steady-state or dynamic calculation tools, some of which have been analyzed by Wall with highly glazed spaces [18]. Also Poirazi's literature review [35] and dissertation [36] include useful information about the problematics of calculation when an extra layer of glazing has been added in front of a facade. The accuracy of the calculation software introduced in the aforementioned publications varies considerably according to level of detailing and purpose of the software. The rougher methods are based on manual calculus while the more precise ones are based on simulation. In addition, the coverage of calculation ranges from the level of components (e.g. Window Information System (WIS) software tool for complex windows and active facade calculation [37]) to that of the whole building. The most flexible methods can handle all of them [35,36].

The problem of simplified simulation methods has been that they usually overestimate the performance of glazed spaces as a means to achieve energy savings (balcony temperatures are higher than in real situations) [18]. This is due to the difference in the ways the programs handle solar radiation in comparison to more detailed simulations. To achieve more realistic results, a detailed analysis is needed, but this kind of applications are usually labor intensive and require expertise from the user (mastery of calculation principles and understanding of possibilities and limitations). These facts hinder the use of this type of simulation software, which is why more simplified computing applications should be developed further [18]. The aim of the current study is to develop a simplified method for analyzing the performance of different types of glazed spaces. The method enables analyses on energy savings and balcony temperatures as well as a quick and easy comparison of solutions in early design stages. The method is developed with the help of detailed calculations, but the final application may be used without in-depth knowledge on the used IDA-ICE software.

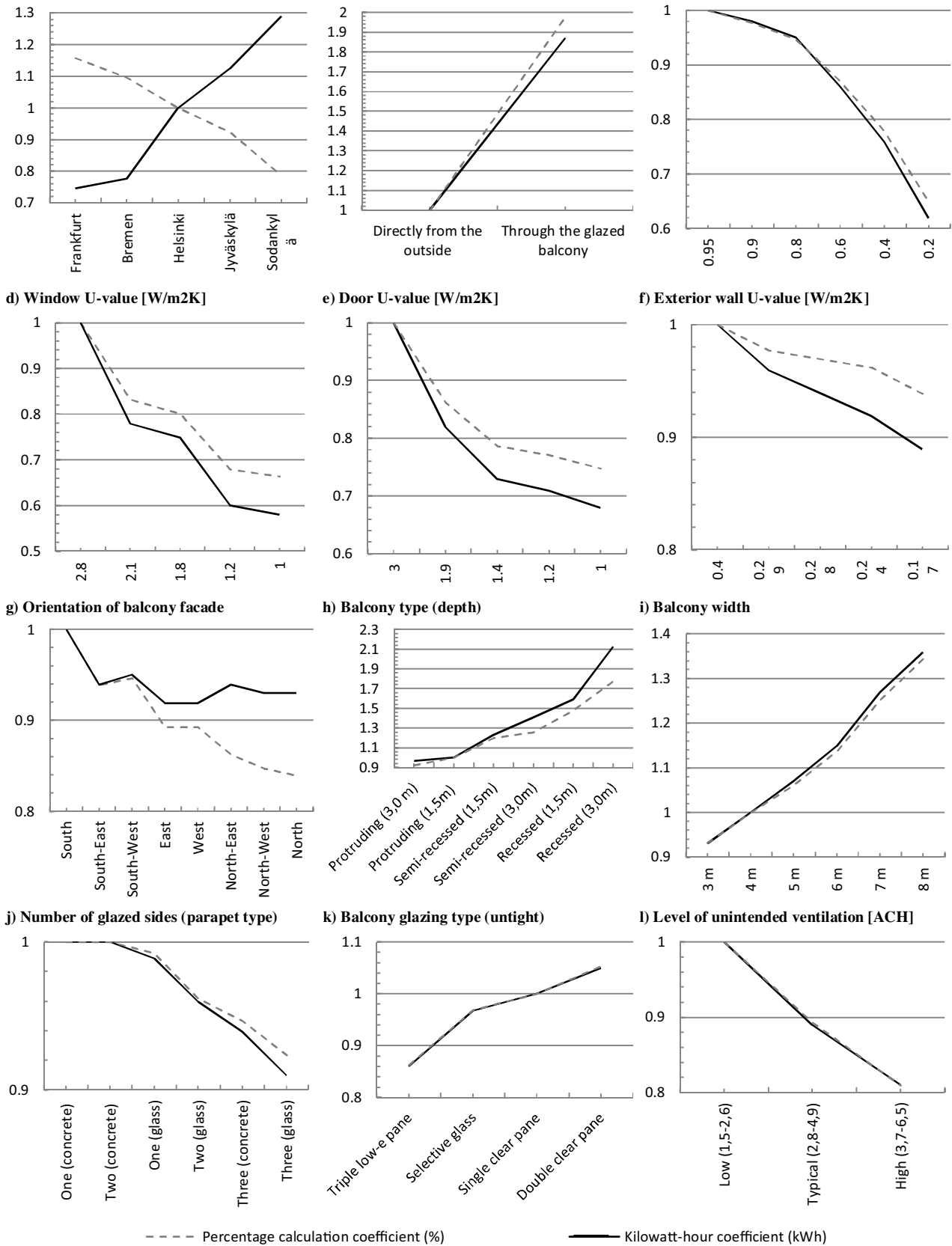


Fig. 8. Graphs a-l for energy saving calculations.



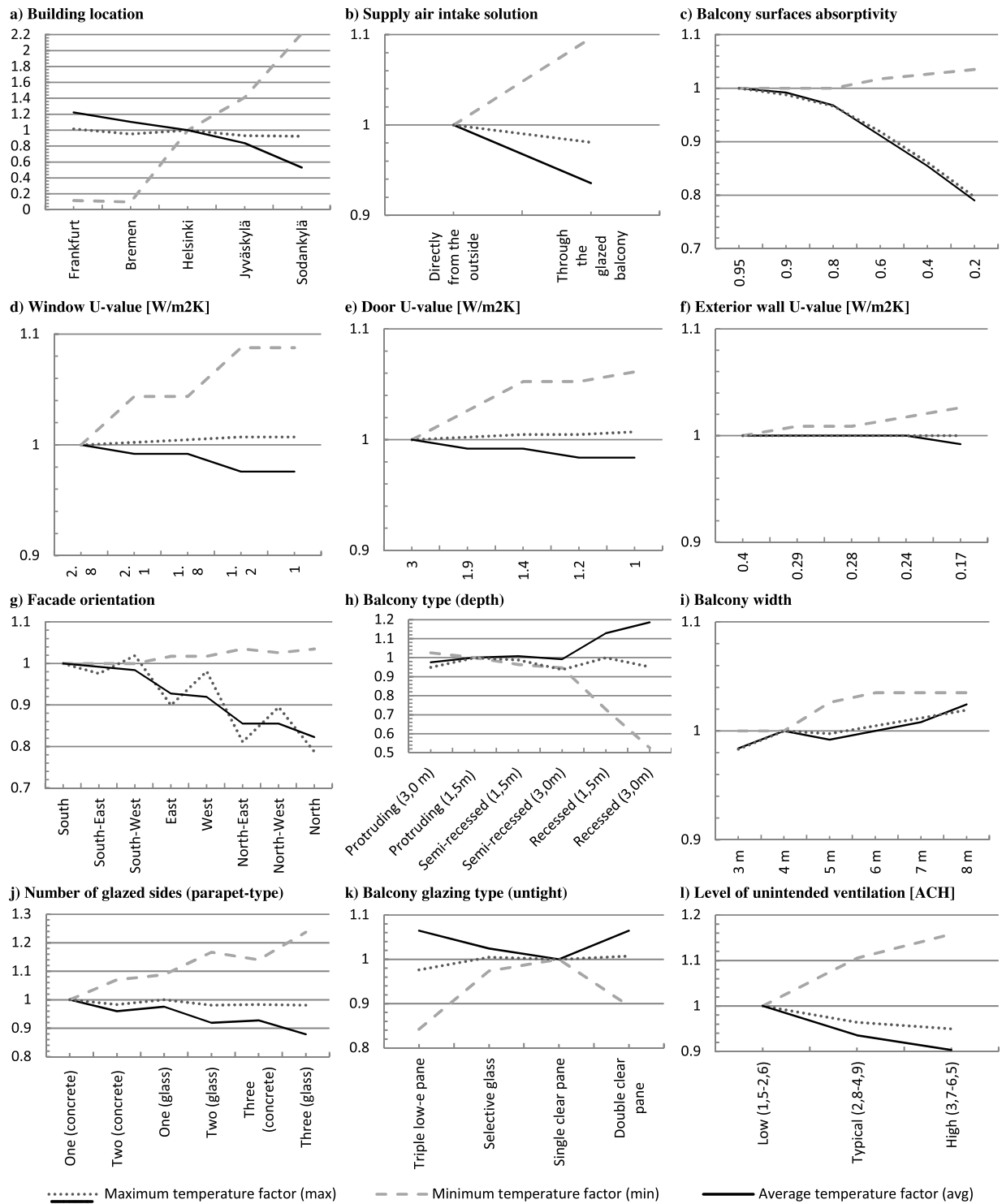


Fig. 9. Graphs a-l for balcony temperature calculations.

Table 3

The monthly average, maximum and minimum temperatures in different cities.

Month	Frankfurt (ASHRAE IWEC2) [°C]	Bremen (ASHRAE IWEC2) [°C]	Helsinki (ASHRAE IWEC2) [°C]	Jyväskylä (ASHRAE IWEC2) [°C]	Sodankylä (ASHRAE IWEC2) [°C]	Tampere (ASHRAE IWEC2) [°C]
Avg	10.2	9.2	6.0	3.8	-0.3	4.6
Absol. max	33.6	29.1	29.0	27.5	27.6	27.0
Absol. min	-10.9	-11.8	-22.7	-31.2	-38.8	-29.0

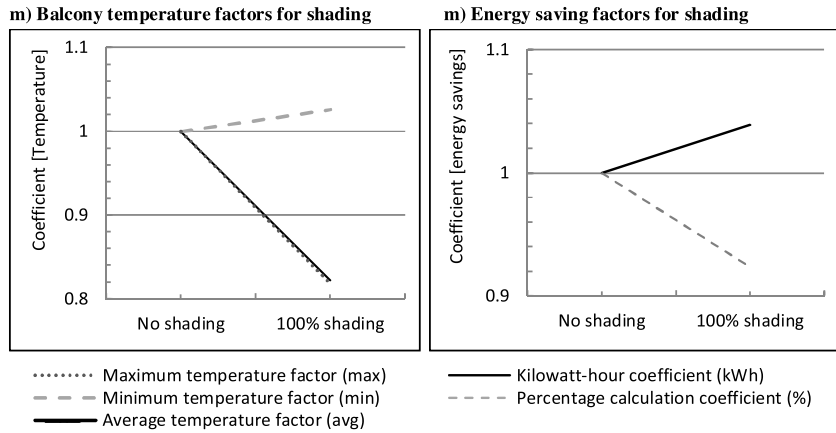


Fig. 10. Graphs m for energy saving and balcony temperature calculations.

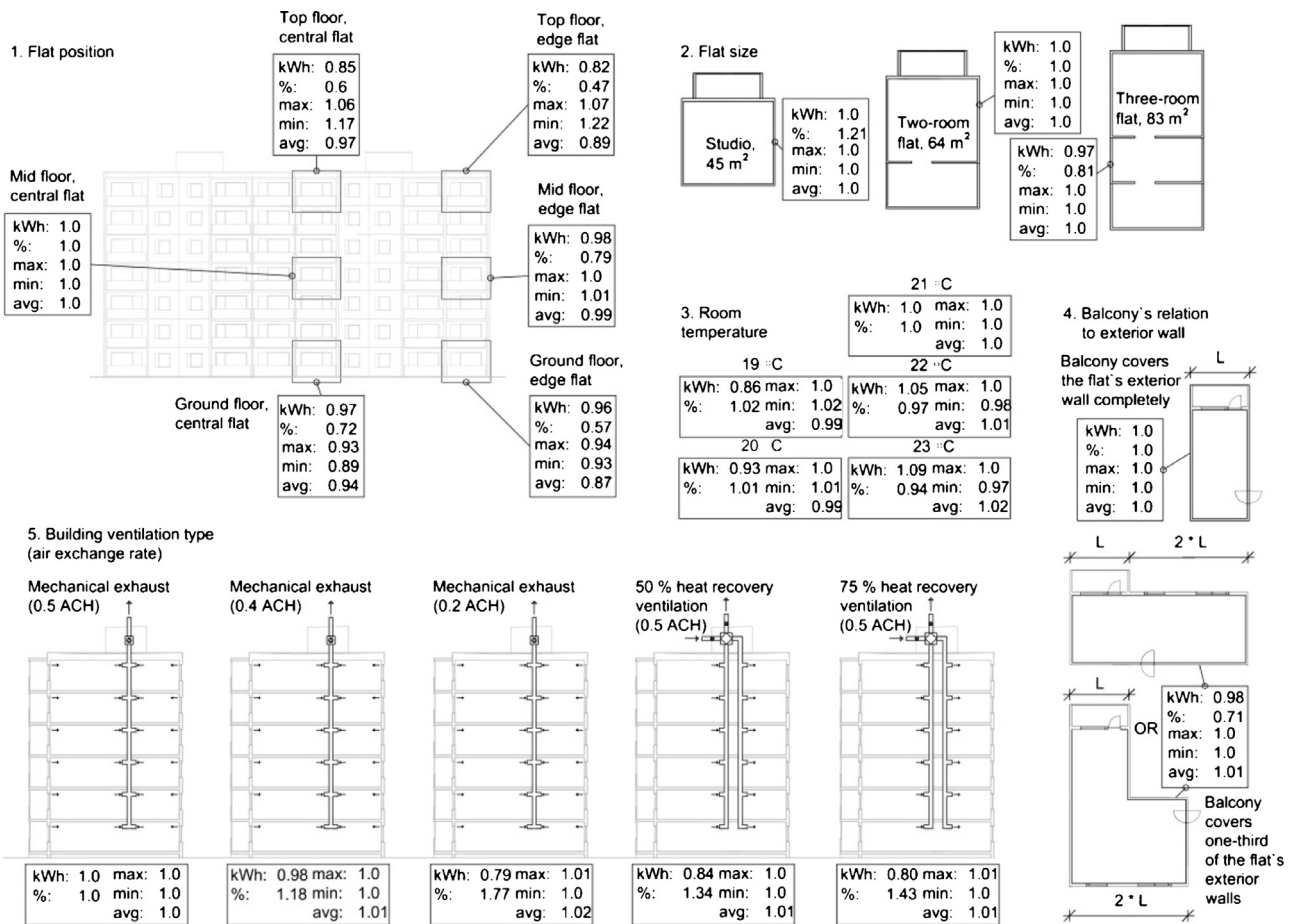


Fig. 11. Possible deviations from the flat of the base case.

### 3. Research materials and methods

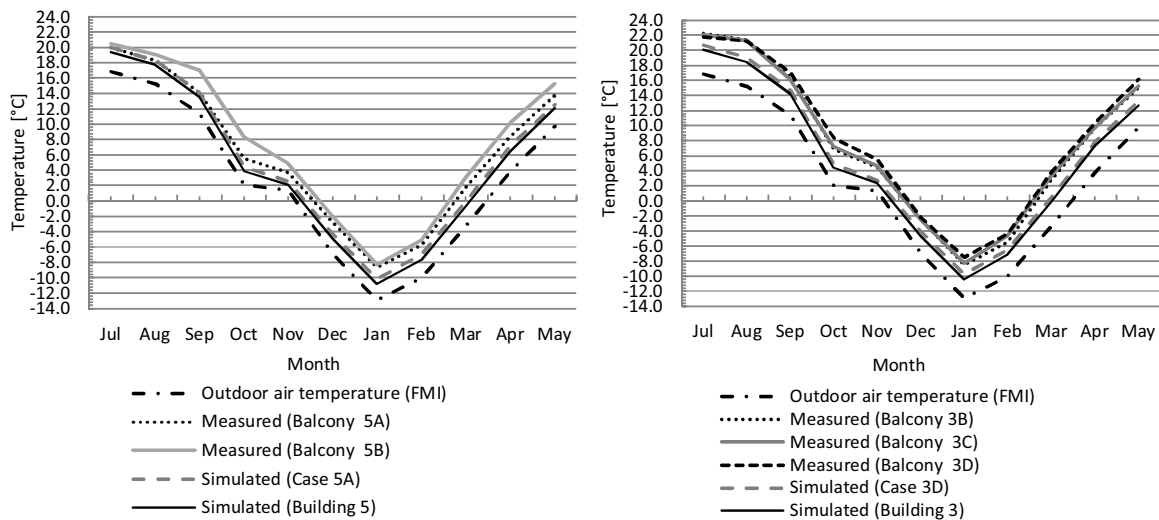
#### 3.1. Simplified calculation method: calculation principles

The calculation principles of the proposed method are specified in the following sections. These include the calculation of energy savings and inside temperatures of glazed balconies in northern climate conditions, which are heating-oriented. In principle, the method is intended for calculating the performance of individual glazed balconies in the preliminary design stage. It can be used for all types of glazed balconies and in all situations in which the cal-

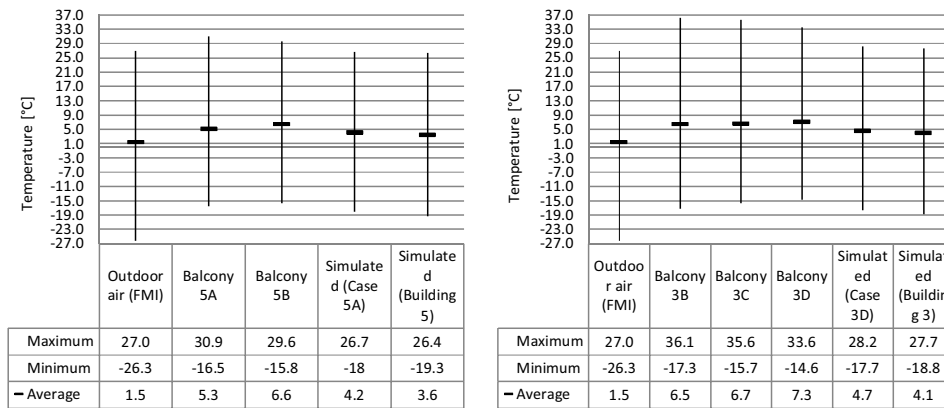
culatation factors are present and identifiable. The selected variables and their tolerance of variation enable calculating the energy saving potential and indoor temperature reliably in all situations. The accuracy of the results is affected by the number of changes made in relation to the typical 1970s apartment block in Finland, which was chosen as a starting point of the development. The method does not take cooling into account; thus the energy savings only denote the savings of heating energy. Sections 3.2 and 3.3 discuss the basis and basic structure of the method whereas Section 3.4 focuses on the accuracy of calculation.

**Table 4**  
Building-specific information about the field monitored blocks of flats [6].

Building number	Location	Building type, construction year, external wall structure and U-value [W/m <sup>2</sup> K]	Balcony type, dimensions (Number of glazed sides informed in parentheses)	U-values of windows and doors [W/m <sup>2</sup> K]	Balcony material (parapet material informed in parentheses)	Heat transfer by conduction ( $\sum U^*A$ ) from adjacent flat to balcony [W/K]	Solar absorption level of balconies (External obstruction informed in parentheses)	Overall tightness of the balcony (after user effect)
3	Hervanta	precast concrete, 1975, concrete sandwich panel, U=0.4	Protruding, w = 4.0m, d = 1.5m, h = 2.6 m (both 1 and 2)	U = 1.4 (windows), U = 1.2 (doors)	concrete balcony, (board parapet)	Typical, 9.5	High (building ≈50 m in front of facade)	High (typical)
5	Hervanta	precast concrete, 1979, concrete sandwich panel, U=0.29	Protruding, w = 4.0m, d = 1.5 m, h = 2.6 m (1)	U = 1.2 (windows), U = 1.2 (doors)	concrete balcony, (concrete parapet)	Low, 7.7	Very low (dense forest in front of facade)	Very high



**Fig. 12.** The measured and simulated balcony temperatures as well as reference outdoor temperatures. Measured balconies are identified by letter codes (in parentheses).



**Fig. 13.** Maximum, minimum and average temperatures of the outside air as well as those of the measured and simulated balconies. Measured balconies are distinguished by balcony codes.

The features affecting the glazed space's indoor climate and energy saving potential have been identified with the help of a sensitivity analysis [4]. For the simplified method, 13 main parameters regarding the balcony and 5 main parameters regarding the flat were chosen. The calculation coefficients, which depict the deviation from the base case, were derived by changing the simulation parameters one at a time and by proportioning the results to those of the base case. The derivation was simplified because all possible combinations of 13 balcony and 5 flat variables would have

been exorbitantly time-consuming to simulate. Consequently, the derived factors describe a situation where only one variable has been changed. Their concatenation will cause an error if the coefficients are dependent on each other. As some of the variables are likely linked, this uncertainty is discussed in Sections 4.1 and 4.2.

The temperature levels and energy saving effects of a building's balconies vary considerably due to their different locations on the façade (or on a different façade) and due to the properties of the apartment they are connected to. As said, the simplified

**Table 5**  
Specifications used in the comparisons of dynamic simulations and simplified calculations.

Cross tabulation case	Building location	Supply air intake through the balcony	Balcony surface absorptivity	Window U-value [W/m <sup>2</sup> K]	Door U-value [W/m <sup>2</sup> K]	Exterior wall U-value [W/m <sup>2</sup> K]	Facade orientation	Balcony type (depth) [m]	Balcony width [m]	Glazed sides (parapet type)	Balcony glazing type (All structures are untight)	Unintended ventilation of the glazed space [ACH]	External obstruction (% of total view)
1				1	1	0.17							
2	Bremen	Yes	0.2						8 m	3 (glass)		Very high	
3			0.4	2.1					6 m		Triple		
4	Bremen	Yes	0.2				East	Recessed (3.0 m)			Double		
5													
6	Jyväskylä	Yes	0.6	1.2	1.2	0.28	North	Recessed (1.5 m)		3 (glass)		Very high	
7					1	0.29							
8	Sodankylä						West	Semi-Recessed (1.5 m)	5 m	2 (glass)	Triple	Typical	
9		Yes	0.4	1.8	1.9	0.17	West	Semi-recessed (3.0 m)	3 m	2 (glass)	Selective	Typical	
10		Yes		1			East			2 (glass)		Very high	
11	Bremen	Yes	0.6		1.9		North	Recessed (3.0 m)	3 m		Triple	Typical	
12	Jyväskylä	Yes		1.2	1.4	0.17		Semi-recessed (3.0 m)		2 (glass)	Selective	Typical	
13					1.2	0.24							100%
14			0.2	1.8		0.24	East	Semi-recessed (1.5 m)	7 m	2 (glass)	Double		100%
15	Sodankylä								8 m				100%
Building 3	Tampere	Yes	0.4	1.4	1.2	0.29	South-West						25%
Building 5	Tampere	Yes	0.4	1.2	1.2		South-West						55%

**Table 6**

Specifications used in the comparisons of dynamic simulations and simplified calculations in the flat deviation study.

Cross tabulation case	Case to which additional case have made	Flat position	Flat size	Balcony's relation to exterior wall	Building ventilation type (air change rate)	Roomtemperature [°C]
4B	Case 4 (5 changes)+	Top floor, central flat		Balcony covers one-third of the flat's exterior walls	75% heat recovery (0.5 ACH)	
4C	Case 4 (5 changes)+	Ground floor, central flat		Balcony covers one-third of the flat's exterior walls	75% heat recovery (0.5 ACH)	
5B	Case 5 (5 changes)+	Ground floor, central flat	Studio		Mechanical exhaust (0.4 ACH)	
5C	Case 5 (5 changes)+	Top floor, central flat	Studio		Mechanical exhaust (0.4 ACH)	
6B	Case 6 (5 changes)+	Mid floor, edge flat	Three-room flat		Mechanical exhaust (0.2 ACH)	
6C	Case 6 (5 changes)+	Mid floor, edge flat	Three-room flat			19 °C
7B	Case 7 (7 changes)+	Top floor, edge flat	Three-room flat			
7C	Case 7 (7 changes)+	Ground floor, edge flat	Three-room flat			
8B	Case 8 (7 changes)+	Mid floor, edge flat			50% heat recovery (0.5 ACH)	
8C	Case 8 (7 changes)+	Mid floor, edge flat				23 °C
9B	Case 9 (7 changes)+	Ground floor, edge flat	Studio			
9C	Case 9 (7 changes)+	Top floor, edge flat	Studio			
10B	Case 10 (9 changes)+			Balcony covers one-third of the flat's exterior walls		
11B	Case 11 (9 changes)+				Mechanical exhaust (0.2 ACH)	
12B	Case 12 (9 changes)+	Top floor, edge flat				
12C	Case 12 (9 changes)+	Ground floor, edge flat				
13B	Case 13 (5 changes)+					23 °C
Case 3D	Building 3 (7 changes)+			Balcony covers one-third of the flat's exterior walls	Mechanical exhaust (0.4 ACH)	22.7 °C
Case 5A	Building 5 (8 changes)+			Balcony covers one-third of the flat's exterior walls	Mechanical exhaust (0.4 ACH)	23.6 °C

method is designed for the individual evaluation of a single glazed balcony. However, the combined effect of a building's all glazed balconies can also be calculated if the building's actual or estimated energy use is available. Summing up the results from individual calculations gives an estimation of the total energy saving in kilowatt-hours. Saving percentage can, then, be calculated by relating the result of the summation to the building's total energy use.

### 3.2. Base case

The base case is a starting point for the calculation. It represents a typical Finnish apartment with a balcony built in the 1970s. Like the majority of flats in Finnish apartment blocks, it is located in the middle of the building, not on the ground floor, top floor or on the building's gables. It is medium sized [38] and equipped with the most typically used ventilation type i.e. mechanical exhaust ventilation [39,40]. The chosen room temperature also represents the usual design value, i.e. 21 °C [33]. Fig. 7 shows the used simulation model and Table 1 presents the input parameters for the base case as well as for the simulation of Buildings 3 and 5. The level of electrical equipment in the apartment, flat usage habits and the operation of HVAC systems were altered to correspond to the national calculation guidelines of Finland. The values in the guidelines are based on the number of residents (3 W/m<sup>2</sup>); lighting (11 W/m<sup>2</sup>); electrical equipment (4 W/m<sup>2</sup>); the hours of the residents spend in the dwelling; and the hours the lighting and equipment are used [33]. The values correspond to the typical usage of a flat in Finland [41]. The climate data used for base case simulation was Helsinki ASHRAE IWEC2 Weather File, which is based

on measurements taken at least four times a day for up to 25 years and which originates from the National Climatic Data Center [42].

Numerous simulations were carried out during the development of the simplified method. The challenge was to find the most suitable modeling method for intended purpose. The aim was to make a model in which a) changes to all parameters would be possible, and b) to minimize obvious interdependencies identified by logical reasoning. Investigations were, for example, performed to establish the most suitable point of compass for the base model. Simulations were done for north and south facing balconies as well as with and without external shading. A south-facing base case was selected because its simplified calculation gave the best correlation with respect to the IDA-ICE simulation. This is because Finnish balconies are typically directed to south. The orientation is also desirable with regard to energy savings, indoor climate and usability. The elimination of interdependencies relied on a qualitative approach. A more detailed, quantitative analysis would have required the identification of stochastic variation in the parameters and the creation of a covariance matrix. Since the developed method is a simplified one, logical reasoning was considered to suffice.

### 3.3. The calculation procedure

In the simplified method, the calculation is performed by multiplying the factors determined from Figs. 8–11 with the values of the base case given in Table 2. Eq. (2) provides the formula for calculating energy savings and temperatures of a balcony, where X depicts the chosen variable ( $E_{\%}$ ,  $E_{kWh}$ ,  $T_{max}$ ,  $T_{min}$  or  $T_{avg}$ ). Eq. (3) is used for determining the average temperature difference  $\Delta T_{avg}$  as well

**Table 7**  
Calculation of the percentual savings according to the simplified method.

Cross tabulation case	Building location	Building supply air intake solution	Balcony surface absorptivity	Window U-value [W/m <sup>2</sup> K]	Door U-value [W/m <sup>2</sup> K]	Exterior wall U-value [W/m <sup>2</sup> K]	Balcony facade orientation	Balcony type (depth) [m]	Balcony width [m]	Glazed sides (parapet-type)	Balcony glazing type (All structures are untight)	Unintended ventilation of the glazed space [ACH]	External obstruction	The coefficients multiplied by each other	Calculated percentual energy saving [%]
1				0.66	0.75	0.94				0.92				0.47	6.7
2	1.10	1.98							1.34			0.81		2.00	29.1
3			0.65						1.14		0.86			0.71	10.2
4	1.10	1.98	0.78	0.83							1.05			0.70	10.1
5			0.65			0.89		1.78						2.14	31.0
6	0.92	1.98		0.68	0.77	0.97				0.92		0.81		0.51	7.4
7			0.87		0.75	0.98	0.84	1.48						1.07	15.5
8	0.72	1.98		0.80	0.86	0.94	0.89	1.20	1.06	0.96	0.86	0.89		0.60	8.7
9			0.78	0.66		0.94	0.89		0.93	0.96		0.89		0.96	14.0
10			0.87		0.86	0.94	0.89	1.26		0.96	0.97	0.81		0.81	11.8
11	1.10	1.98		0.68	0.86	0.94	0.84	1.78	0.93		0.86	0.89		1.73	25.1
12	0.92	1.98		0.68	0.79	0.94	0.84	1.26		0.96	0.97	0.89		0.96	13.9
13					0.77	0.96			1.25				0.92	0.89	12.9
14			0.65	0.80		0.96			1.34		1.05		0.92	0.62	8.9
15	0.72	1.98		0.77	0.77	0.98	0.89	1.20		0.96			0.92	0.68	9.8
Building 3	0.94	1.98	0.78	0.68	0.77	0.98	0.95						1.00	0.82	11.9
Building 5	0.94	1.98	0.78	0.68	0.77	0.98	0.95						0.96	0.68	9.9

as the minimum ( $\Delta T_{\min}$ ) and a maximum temperature differences ( $\Delta T_{\max}$ ).

$$X = \Pi_i(\alpha_i) \times \Pi_j(\beta_j) \times X_{\text{base}} \quad (2)$$

where  $X$  = estimated variable in actual design situation.  $\Pi$  = a symbol depicting product sequence.  $\alpha$  = calculation coefficient of balcony deviation (Section 3.3.1).  $\beta$  = calculation coefficient of flat deviation (Section 3.3.2).  $i$  = the index of balcony deviation calculation coefficient.  $j$  = the index of base case deviation calculation coefficient.  $X_{\text{base}}$  = the value of variable  $X$  for base case (Table 2).

$$\Delta T_{\text{avg}} = T_{\text{avg}} - T_{\text{average outdoor temperature}} \quad (3)$$

where  $\Delta T_{\text{avg}}$  = temperature difference between the glazed space and outdoor air.  $T_{\text{average outdoor temperature}}$  = yearly outdoor temperature of the city (Table 2).

If the intended calculation option is not included directly in the figures (e.g. the location of Tampere), the value can be estimated with the help of the other values (the values for Tampere are the averages of factors for Helsinki and Jyväskylä, because Tampere is located roughly halfway between them). The external shading (Fig. 10), which prevents the fall of solar radiation on the façades, must be estimated on the basis of the scene opening in front of the balcony. For example, if the building is situated in a fully open terrain, the obstruction level is 0% and in a fully closed scene it is 100%.

### 3.3.1. Balcony's deviation from the base case

The simplified method takes into account the following differences to the balcony of the base case (Figs. 8–10):

- Geographical location.
- Supply air solution (through the glazed balcony or directly from outside).
- Balcony surface absorptivity (The balcony's ability to store solar energy).
- U-values of balcony window.
- U-values of balcony door.
- U-values of building exterior wall.
- Orientation of balcony facade.
- Balcony type (including depth change).
- Width of balcony.
- Amount of glass in the parapet and balcony glazing.
- Glazing type (single, double or triple glazing).
- Structural tightness of balcony glazing as well as balcony other structures.
- Effect of external sun protection or shading.

The location-based temperatures needed in temperature difference calculations (Eq. (3)) are given in Table 3. All location-based weather information has been taken into account when the calculation factors were derived with the help of IDA-ICE, even though only temperature information is used in the simplified method.

### 3.3.2. Flat's deviation from the base case

The simplified method considers the following differences to the flat of the base case (Fig. 11):

- Position in the building (horizontal and vertical).
- Size.
- Room temperature.
- Balcony's relation to exterior wall.
- Ventilation type and exchange rate.

### 3.4. Reliability analysis

The reliability analysis of the simplified method consisted of two phases. First, the representativeness of the base model was estimated in relation to the reality with the measurements of Buildings 3 and 5; then, the reliability of the simplified method was studied by comparing the calculated and simulated results with each other.

#### 3.4.1. Field measurements vs. simulation

In the first phase, the field monitoring results of Buildings 3 and 5 were compared with simulations of their balconies. This is to say that deviations from the base balcony were taken into consideration but deviations from the base flat were not. Then, the base case was modified to accommodate also for the measured Flats' (3D and 5A) deviations from the base flat, and the comparison with their field measurements was repeated. The purpose of the investigation was to evaluate (a) how accurately the balcony's temperature level can be calculated without taking into consideration deviations from the base flat, and (b) how much the incorporation of those deviations will improve the results. The first simulations are referred to as 'Building 3' and 'Building 5' in Table 5, and the latter simulations as 'Case 3D' and 'Case 5A' in Table 6. Next, it is described how Buildings 3 and 5 differ from the base case, i.e. the model-specific characteristics.

Buildings 3 and 5 are located at a distance of 600 m from each other in the city of Tampere (61°29'53"N, 23°45'39"E). The original characteristics of the buildings were very similar, but after renovations in the 2000s, today there are some differences (Table 4). The most noticeable one is the replacement of the concrete balcony parapet in Building 3 with a parapet made of light-weight materials. There are also some differences between the thermal resistances of windows and walls, but most critical difference originates from the existence of external shading. Building 5 is surrounded by tall birch trees, which reduce the wind pressure and, most importantly, protect the facade from the sun's radiation. The reduction in incoming radiation reduces the inflow of thermal energy and results in lower temperatures in the balcony.

Weather data used in the simulation covering the period of field measurements was purchased from the nearest meteorological stations. The data that encompassed air temperature, relative humidity, wind speed and wind direction were obtained from the Tampere/Pirkkala airport (20 km west of the site) weather station EFTP (WBAN 99999). The data on solar radiation originated from the nearest Meteorological Observatory, Jokioinen (100 km south of the site).

#### 3.4.2. Simulation vs. simplified calculation

**3.4.2.1. Balcony deviation.** After the behavior analysis of the used simulation model was conducted, the effect of balcony deviations to the reliability of the simplified method was studied by comparing the calculated and simulated results with each other in 17 different cases (Table 5). Cases 1–3 include three changes; cases 4–6 and 13–15 five changes; cases 7–9 seven changes; and cases 10–12 nine changes. Cases 13–15 were designed to examine the impact of external shading to the results. In addition, the simulated and measured results of Buildings 3 and 5 were also compared. In the simulation model, the balcony's properties were modified to reflect the reality, but the flat was kept at default settings with a standardized air changes rate (0.5 ACH), 21 °C room temperature and the base case's room characteristics. This is because at this stage, the aim was to give an overview of balconies' temperature behavior and energy saving potential in general, not that of a specific balcony in a building. This kind of a review may be a useful starting point in a design situation in which,

for example, flats' sizes and room temperatures vary in abundance.

**4.1.2.2. Balcony and flat deviation.** Then, flat deviations were added to the Cases 4–13 and a total of 17 new calculations and simulations were performed. Cases 4B–6C include eight changes; cases 7B–9C nine changes; cases 10B–12C ten changes; and case 13B six changes. Cases 13–15 were designed to examine the impact of external shading to the results. The additional changes made to the cases 4–13 are presented in Table 6, where 16 cases of 17 have a total of 8–10 changes. In addition, the simulations and measurements of Cases 3D and 5A were compared. In the simulation model, the inclusion of the flats' properties meant that the model's flat was modified to extend across the building (balcony covers, thus, only one-third of the flat's exterior walls) and a second supply air vent was added (denoting that the amount of air incoming through the balcony is halved). The amount of ventilation was also dropped from 0.5 ACH to 0.4 ACH and the room temperature was raised from 21 °C to 22.7 in Case 3D and to 23.6 °C in Case 5A.

## 4. Results and discussion

### 4.1. Field monitoring vs. simulation model

Fig. 12 shows clearly that the temperatures the simulations produce are systematically slightly lower than the actual temperatures. The greatest difference between the simulated and measured balcony temperatures can be observed in Building 5 (flat deviation ignored) in the winter months, and the smallest difference occurs in the fall. The differences between the measured and simulated values are most likely caused by the difference in the relationship between the specific heat loss from the glazed space to the outside and specific gain from the building to the glazed space. As the simulated temperatures are clearly under the measured values throughout the year, the simulations likely overestimate the heat loss level from the glazed balcony to the outside air. This is clearly visible on all glazed balconies with Balcony 3A as an exception. The reason is the disruption on measurements on Balcony 3A whose door was open for long periods during the measurements [6].

The more detailed simulations (Cases 3D and 5A) raised the temperature level on the balconies by 0.6 °C on average (Fig. 13). This is due to the facts that a) changes in the ventilation rate and the number of supply air valves reduced the amount of intake air from the balcony (therefore, the balcony did not cool down as effectively) and b) raising the room temperature increased the temperature difference between the balcony and the flat (that is, heat losses from the flat to the balcony grew). The cooling effect is also decreased by the reduced air supply that follows from the dropped air change rate (from the standard 0.5 ACH to the actual situation of 0.4 ACH). This level is at least true for Building 5, whose ventilation rate has been shown to be under the required level in a previous study [43]. In addition, the base model assumes the room temperature to be lower (21 °C) than in reality (21.5–23.6 °C on average), and this causes incorrectness to the results, even though the simplification does not seem to have very significant implications. Balcony temperatures on Balconies 3A and 3B, for instance, were virtually the same during the coldest period of the year (January), although their measured average room temperatures differed by 2.1 °C being 21.1 °C in Flat 3A and 23.2 °C in Flat 3B.

The analysis shows that the simulations (both those that encompass only balcony deviation as well as those that encompass deviations from both the base balcony and the flat) gives results slightly lower than the reality, which means that the results are

**Table 8**  
Comparison of results from the simplified method and dynamic energy simulation in cases where the balcony deviates from the base case.

Cross tabulation case (number of changes in parenthesis)	Energy savings, percentual [%]				Energy savings, Kilowatt- hourly [kWh]				Balcony temperatures, maximum [°C]				Balcony temperatures, minimum [°C]				Balcony temperatures, average [°C]				
	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]	
1 (3)	6,7	2,8	4,0	144	191	76	115	152	42,1	42	0,1	0	-13,2	-13	-0,2	2	12,7	13	-0,1	0	
2 (3)	29,1	31	-1,5	-5	723	745	-22	-3	37,7	39	-1,3	-3	-1,5	-5,2	3,7	-71	12,2	13	-1,1	-8	
3 (3)	10,2	7,9	2,4	30	372	329	44	13	32,0	33	-0,5	-1	-13,9	-13,8	-0,1	1	9,7	9,8	-0,1	-1	
4 (5)	10,1	5,4	4,8	89	249	156	93	60	33,1	33	-0,3	-1	-1,0	-0,3	-0,7	246	13,1	14	-0,7	-5	
5 (5)	31,0	35,8	-4,8	-13	1300	1660	-360	-22	28,0	31	-3,4	-11	-6,1	-6,7	0,6	-9	11,7	12	-0,2	-2	
6 (5)	7,4	5,9	1,5	25	300	238	62	26	35,8	36	-0,1	0	-23,9	-23,8	-0,1	0	8,7	8,2	0,5	7	
7 (7)	15,5	16,4	-0,9	-5	508	582	-75	-13	30,0	29	1,0	3	-11,0	-13	2,0	-15	10,2	9,1	1,1	12	
8 (7)	8,7	7,4	1,3	17	625	529	97	18	34,0	36	-2,1	-6	-27,1	-25,7	-1,4	5	6,0	6,8	-0,8	-12	
9 (7)	14,0	13,2	0,7	6	458	507	-49	-10	36,6	38	-1,4	-4	-17,3	-17,6	0,3	-2	9,6	9,7	-0,1	-1	
10 (9)	11,8	13,1	-1,4	-11	391	455	-64	-14	27,7	31	-3,4	-11	-18,0	-16,8	-1,2	7	8,1	8,6	-0,5	-6	
11 (9)	25,1	30,5	-5,4	-18	790	961	-171	-18	24,5	26	-1,5	-6	-0,7	-1,1	0,4	-40	11,9	13	-0,7	-6	
12 (9)	13,9	19,6	-5,7	-29	520	712	-192	-27	33,6	35	-0,9	-3	-24,3	-21,9	-2,4	11	8,9	8,5	0,4	4	
13 (5)	12,9	11,2	1,7	16	494	484	10	2	34,5	34	0,6	2	-11,3	-11,9	0,6	-5	11,5	11	0,8	8	
14 (5)	8,9	6,3	2,6	41	330	279	51	18	27,6	26	1,2	5	-13,1	-14,1	1,0	-7	8,8	7,5	1,3	17	
15 (5)	9,8	8,9	0,9	11	794	623	172	28	27,2	25	2,2	9	-29,1	-28,6	-0,5	2	5,0	2,8	2,2	80	
Building (7)	11,9	12,7	-0,9	-7	425	470	-45	-10	32,4	30	2,2	7	-18,0	-18,7	0,7	-4	8,5	7,9	0,6	8	
Building (8)	9,9	9,5	0,4	4	341	335	6	2	31,0	29	2,2	8	-18,9	-19,6	0,7	-4	8,2	7,2	1,0	13	
Mean deviation, maximum deviation and 90 % fractile																					
Mean			2,4	29			97	27				1,4	5			1,0	29			0,7	12
Max			5,6	127			341	140				3,1	10			3,5	239			2,0	73
90 %			3,2	60			104	40				2,2	7			1,4	9			1,2	15

**Table 9**  
The absolute and proportional differences of the cases including 3, 5, 7 or 9 changes in relation to the base case.

Number of changes	Energy savings, percentual [%]				Energy savings, Kilowatt-hourly [kWh]				Balcony temperatures, maximum [°C]				Balcony temperatures, minimum [°C]				Balcony temperatures, average [°C]			
	3	5	7	9	3	5	7	9	3	5	7	9	3	5	7	9	3	5	7	9
Absolute difference																				
Mean deviation	2,1	3,5	0,8	1,8	46	194	71	52	0,5	1,4	1,2	1,0	1,7	0,4	1,1	1,0	0,5	0,4	0,7	0,4
Max deviation	3,1	5,3	1,3	2,7	70	292	106	78	0,8	2,1	1,9	1,5	2,6	0,7	1,7	1,5	0,7	0,7	1,0	0,7
90% fractile	3,7	4,1	1,2	-2,2	101	87	68	-85	0,0	-0,2	0,5	-1,0	2,9	0,5	1,6	0,1	-0,1	0,4	0,9	0,2
Percentual difference																				
Mean deviation	58	37	7	7	65	29	13	5	1	5	4	3	32	111	8	22	3	4	8	5
Max deviation	88	55	11	10	98	43	20	7	2	7	6	5	48	167	11	33	5	7	12	7
90% fractile	121	76	15	-12	124	53	13	-15	0	-1	2	-3	1	197	4	10	-1	5	10	2

on the safe side. The main reason for this is the overestimated heat loss level from the glazed balcony to the outside. As seen in Figs. 12 and 13, flat deviations, such as modifications to the air change rates, room temperatures and the number of air inlet vents bring the simulated results closer to the measured values, but the improvement of accuracy is not very significant. This is because the flat deviations do not affect the simulation's basic source of error, i.e. the exaggerated heat loss from the balcony. Thus, the results are on the safe side in both situations (flat deviation omitted or included).

4.2. Simulation vs. simplified calculation

4.2.1. Balcony deviation

This section demonstrates the use of the simplified method by giving the calculation results for the percentual energy savings, and by comparing the results calculated for percentual and kilowatt-hour energy savings as well as maximum, minimum and mean temperatures with those acquired through simulation.

The differences between the calculation cases are given in Table 5; the corresponding coefficients have been read from

Figs. 8–10 in Section 3.3.1 and are recorded in Table 7. The total impact of the changes has been calculated to the second last column of the table by multiplying the coefficients together. The final results have been obtained by multiplying the overall coefficient by the percentual base values of the base case (Table 2).

Table 8 gives the results from comparing the calculations with the simulations. The reliability of the simplified method's results is evaluated in terms of absolute and proportional changes in relation to the simulated values. The proportional change indicates how much the difference of the calculated and simulated value is in relation to the simulated value. The four largest proportional and absolute deviations between the methods are highlighted in dark gray. The bottom of the table summarizes the mean deviation, maximum deviation and 90% fractile of the calculated difference. In terms of the method's reliability, proportional errors are more critical than absolute errors. Therefore, the paper focuses from now on comparing the relative errors and analyzing the reasons behind them.

The largest relative errors tend to be in situations where the energy savings have been small, and the largest absolute errors in situations where the energy savings have been great. The most



**Table 10**

Comparison of results from the simplified method and dynamic energy simulation in situations where both the balcony and the flat deviate from the base case.

Cross tabulation case (number of changes in parenthesis)	Energy savings, percentual [%]				Energy savings, Kilowatt- hourly [kWh]				Balcony temperatures, maximum [°C]				Balcony temperatures, minimum [°C]				Balcony temperatures, average [°C]			
	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]	Table calculated	Energy simulated	Difference	Proportional change [%]
4B (8)	6,2	0,6	5,6	906	166	25	141	564	35,4	34	1,6	5	-1,2	-3,2	2,0	-62	13,0	13	0,3	2
4C (8)	7,4	3	4,4	148	190	114	75	66	31,1	31	-0,2	-1	-0,9	0,1	-1,0	-1024	12,6	13	-0,6	-4
5B (8)	31,9	28,4	3,6	13	1236	134	-105	-8	26,0	26	-0,2	-1	-5,4	-3,8	-1,6	43	11,1	11	0,2	2
5C (8)	26,6	16,1	10,5	65	1083	800	283	35	29,9	29	0,6	2	-7,1	-10,9	3,8	-34	11,4	9,6	1,8	19
6B (8)	8,4	9,0	-0,6	-7	226	227	-1	0	36,1	36	-0,3	-1	-24,1	-24	-0,1	0	8,8	8,3	0,5	6
6C (8)	4,8	4,5	0,4	9	245	210	36	17	35,8	36	-0,4	-1	-24,6	-24,1	-0,5	2	8,6	8,2	0,4	4
7B (9)	5,9	6,3	-0,4	-6	404	463	-60	-13	32,1	31	0,8	3	-13,5	-15,4	1,9	-13	9,1	8,8	0,3	3
7C (9)	7,2	2,5	4,7	189	473	350	122	35	28,2	26	2,6	10	-10,3	-11,6	1,3	-12	8,9	8,3	0,6	7
8B (9)	9,2	9,6	-0,4	-4	515	740	-225	-30	34,0	36	-2,3	-6	-27,4	-25,8	-1,6	6	6,0	6,7	-0,7	-11
8C (9)	6,4	7,8	-1,3	-17	668	683	-15	-2	34,0	36	-2,2	-6	-26,6	-25,8	-0,8	3	6,0	6,7	-0,7	-10
9B (9)	9,6	4,5	5,2	115	440	134	306	228	34,4	36	-1,9	-5	-16,1	-17,3	1,2	-7	8,4	9,4	-1,0	-11
9C (9)	7,9	4,2	3,8	91	376	131	245	187	39,1	41	-1,4	-3	-21,1	-19,1	-2,0	11	8,6	9,8	-1,2	-13
10B (10)	8,3	7,9	0,5	6	383	274	110	40	27,7	31	-3,5	-11	-18,0	-16,6	-1,4	9	8,2	8,7	-0,5	-6
11B (10)	44,5	40,9	3,6	9	624	589	36	6	24,7	27	-2,0	-7	-0,7	-0,5	-0,2	32	12,1	13	-1,0	-7
12B (10)	6,5	9,8	-3,2	-33	426	635	-208	-33	36,0	38	-1,5	-4	-29,6	-23,4	-6,2	27	7,9	8,6	-0,7	-8
12C (10)	7,9	11,6	-3,7	-32	499	722	-223	-31	31,6	31	1,1	4	-22,6	-20,6	-2,0	10	7,7	7,8	-0,1	-1
13B (6)	12,2	10,1	2,1	20	538	500	39	8	34,5	34	0,6	2	-11,0	-11,7	0,7	-6	11,8	11	0,9	8
Case 3D (10)	9,4	6,9	2,5	37	408	320	87	27	32,4	31	1,2	4	-17,4	-17,7	0,3	-1	8,9	8,5	0,4	4
Case 5A (11)	7,6	5,5	2,1	38	328	239	88	37	31,0	30	1,4	5	-18,1	-18,4	0,3	-2	8,6	7,8	0,8	10
Mean deviation, maximum deviation and 90 % fractile																				
Mean			2,7	110			117	85			1,3	4			1,5	103			0,7	7
Max			8,4	824			267	505			3,2	11			5,9	971			1,9	19
90 %			5,2	157			253	195			1,4	5			1,9	28			0,8	8

accurate results are obtained in cases that deviate only slightly from the base case. In practice, this means that large energy savings are underestimated and small savings overestimated. A similar trend has been observed in results regarding temperatures, although it is not as evident. Due to this trend, absolute and relative errors occurred often in different cases (Table 8). The largest relative deviations (Table 9) were associated with the energy consumption, where the kilowatt hourly errors were slightly higher than the percentual errors. Interestingly, in many cases the percentage and kilowatt hourly error had the same order of magnitude. This suggests that the same factors were behind the error. When it comes to temperature calculations, the greatest uncertainty occurred with minimum temperatures, which was especially evident in Case 4. In contrast, the maximum and average temperatures could be determined with good accuracy in all cases.

The accuracy is not highly dependent on the number of variables changed, since cases 7–12 do not account for the most of the highest relative errors (Table 8). More likely, the accuracy is affected by some individual factor or a combination of a few. The factual underlying reason for the inaccuracy was not found. As discussed in Section 3.1, the calculation method relies on a simplified derivation of coefficients due to practical reasons. This simplification is likely the main cause of inaccuracies. The reason is that (a) some variables are dependent on each other, which is why the effect of some factors is inadvertently calculated multiple times, and (b) when the calculated case differs significantly from the base case, the true interdependencies of the variables also change, and the method is not able to take this into consideration. This can be seen clearly by examining the results of Tables 8 and 9. Table 9 shows that the largest error with regard to energy savings occurred in cases that had only three deviations from the base case, and the greatest error from the simulated minimum temperatures occurred

with five deviations. Major errors arise in situations where either the building's overall energy consumption level (e.g. clearly different location than in the base case) or the balcony's heat balance (increased heat loss from balcony to outside, reduced heat loss from flat to balcony and/or reduced solar energy absorption) is significantly different in comparison to the base case. The reason for a large error in Case 1 was the simultaneous significant changes to the U-values of the balcony window (from 2.8 to 1.0), door (from 3.0 to 1.0) and exterior wall (from 0.4 to 0.17). In Case 4, the cause was the change of geographical location (which reduces the temperature difference between the outside air and the apartment) in connection with the changes to the absorptivity of the balcony's surfaces, the number of layers in the glazing and the glass's properties (triple solar protection glazing).

A significant improvement of the thermal insulation also reduced the accuracy of the minimum temperatures and caused the highest deviation between the calculated and simulated minimum temperatures (Case 4). The second largest error occurred in a situation where the location was changed, the number of glazed sides was increased from one to three, and the air supply was taken through the balcony (Case 2). The basic reason in this case is, however, the deviation of location, because the magnitudes of the calculation factors are highly dependent on the location (for example, the effect of U-value changes is, in reality, lower in Bremen than in Helsinki). The largest errors to average temperatures were caused by a difference in external shading when it occurred together with either that of the absorption coefficient (Case 14) or a different balcony orientation (Case 15). In both situations, the effect of weakened solar energy absorption is taken into account partially twice. This should be avoided when calculating cases where at least two of the following variables deviate from the base case: balcony surface absorptivity, orientation and external shading. To

avoid this overlap, one option is to reduce external shading from the real situation.

#### 4.2.2. Balcony and flat deviation together

Deviations from the flat's properties in the base case do not seem to have major implications for mean and maximum temperatures, but they do have clear impacts on percentual and kilowatt hourly energy savings as well as on minimum temperatures. This can be seen by comparing the maximum errors in Tables 8 and 10. The results also show that the magnitude of the error is directly proportional to the number of flat deviations from the base case (Table 11). The cases with only one deviation to the flat's variables result in only minor additional error, but already two and three deviations can increase the error clearly if the balcony also deviates significantly from that of the base case. In all, flat deviations cause larger calculation error than balcony deviations.

Table 10 also shows that cases that already include a lot of error due to balcony deviation (such as Case 4) can lose accuracy even more if flat deviation is added (as in Cases 4B and C). In those cases, the systematic error of the calculation method is multiplied. On the other hand, Table 10 shows that changing the flat's size and position on the facade simultaneously can, too, be a major source of uncertainty (e.g. Cases 5B,C, 7B,C, 9B and C). In addition, major differences with regard to ventilation (e.g. supply and exhaust ventilation with heat recovery) coupled with significant deviation from the base case's energy consumption (e.g. location in Bremen) can cause clear error to the results.

In other words, further deviations from the base flat exacerbate these errors. The simplified method may even give them incorrect ranking if, in connection with several balcony deviations, two or more changes are made to the flat. Three cases behaved like this. The first was Case 7C with regard to the percentual energy savings: according to the simplified method, percentual savings increase in comparison to Case 7B, but according to the simulation, they should have decreased. A similar phenomenon was noticed in the average temperatures between Cases 4B and C as well as Cases 5B and C. This indicates that the simplified method is not, in principle, designed for comparing the performance of balconies in different parts of the building or belonging to flats of different sizes, but for optimizing the energy performance of a balcony, whose flat is already known. In the latter situation, the method is capable of indicating the correct ranking of different options, even though the quantified results do withhold some uncertainty.

#### 4.3. Possibilities and limitations of the simplified method

The accuracy of the method is best in Finland and in other similar climatic conditions, since the base case is based on Finnish construction methods and Finland's latitudes. The uncertainty analysis, however, indicates that the calculated case can also differ from the base case. With regard to the method's accuracy, the most significant factor is not the number of deviations but how extensive they are in comparison to the base case. If the properties of the calculated flat do not deviate from the base case, the most critical variables are those that affect the energy performance the most, such as the geographical location, U-values, air tightness and exposure. The method is, however, more sensitive to deviations from the base flat: for instance, if the flat's size and position deviate, the error is exacerbated if further deviations from the base balcony are made. The simplified method is, nevertheless, within the limits of reasonable reliability if it is not used for comparing balconies with different positions or flat sizes but for optimizing the energy performance of a chosen balcony. One should, however, note that the relative error increases the more the design deviates from the base case. As a general rule, the systematic error of the method does not grow too large if the total amount of deviations is no more than

nine while a maximum of one deviation is made with regard to the flat. If the design includes two or three deviations from the base flat, the total number of changes should respectively be limited to seven and five.

Despite the fact that the simplified calculation method is not intended for the simultaneous optimization of both the properties of a balcony and its position on the facade, this can be done with the help of the method if a three-stage procedure is followed. First, the position of the balcony should be optimized by comparing different positions while keeping the balcony's properties constant. Secondly, the properties of the balcony should be optimized by comparing different options while keeping the balcony's position constant. Finally, the combined effect of the balcony's properties and position can be calculated if there is a need to quantify, for instance, the energy savings. It is also important to remember that the results represent, in principle, the order of magnitude rather than the precise truth.

A critical evaluation of the method reveals also some shortcomings, some of which can be observed in the results of Table 8. One major deficiency is the calculation method for the heat losses between the building and the balcony, the effect of which Case 1 illustrates well. In the simplified method, the heat loss level changes are examined separately for windows, doors and back walls, although observing the total heat loss levels would give more accurate results. In the simplified calculations, the multiplied effect of those changes results in higher balcony temperatures than simulations do. The joint effect can also produce errors when the balcony type or size or the U-values of windows, doors or walls are changed. This is because the proportional changes of U-values are compared to the base model situation, which is a 4 m wide protruding balcony. In recessed balconies, for instance, there are more running meters of exterior walls, and windows and doors represent smaller proportions of their total heat losses. The coefficients of the simplified method cannot take these differences into account, which is why the method underestimates the change of the U-value but overestimates the effect of windows and doors in recessed balconies. Error can also occur if the length of the balcony differs from the base case but the proportion of windows and doors does not change in the same proportion. However, recessed or very wide balconies are rather rare in Finland, whereby the reliability is good for typical cases. In addition, it was necessary to provide the U-values separately for windows, doors and back walls, because these structural parts are often renovated independently of each other.

Another factor causing uncertainty to the method is the supply air inlet solution, because its proportional effect with a protruding balcony (base case) is less than that of a recessed or semi-recessed balcony. This effect would have been possible to rectify with a correction factor, but it has not been done in order to retain the simplicity of the method. In addition, variables linked to angle-dependent solar radiation, like the balcony surface absorption coefficient; balcony orientation; external sun protection or obstruction; and building location are critical. For example, external shading and orientation are the more critical the darker the surface, and vice versa. In this case, the change in the availability of solar radiation (either by an external shading or a change of orientation), together with the change in the absorption coefficient, gives a slightly distorted result. When it comes to external shading, it should be remembered that the availability of solar energy is also directly commensurate to the orientation of the facade, which results easily in calculating the same effect two times. For example, a north-oriented recessed balcony does not receive solar radiation, even though the building would be situated in a totally open terrain. If both factors are taken into account, an error occurs, because they are modeled separately and proportionally to the south-facing balconies in the sensitivity analysis. As a result, the combined effect is more than the actual situation.

**Table 11**

The absolute and proportional differences of the cases including 8–10 changes in relation to the base case.

Number of changes	Energy savings, percentual [%]			Energy savings, kilowatt-hourly [kWh]			Balcony temperatures, maximum [°C]			Balcony temperatures, minimum [°C]			Balcony temperatures, average [°C]		
	8	9	10	8	9	10	8	9	10	8	9	10	8	9	10
<b>Absolute difference</b>															
Mean deviation	2,9	2,6	2,7	95	162	144	0,6	1,6	1,3	1,6	1,5	1,9	0,5	0,6	0,3
Max deviation	6,5	3,3	4,3	212	287	181	1,4	3,3	2,6	3,3	2,1	3,8	1,4	1,0	0,5
90% fractile	8,0	4,9	2,6	212	275	88	1,1	1,7	0,3	2,9	1,6	−0,5	1,2	0,4	−0,2
<b>Percentual difference</b>															
Mean deviation	239	70	20	151	93	27	2	5	5	282	8	10	5	7	2
Max deviation	717	128	21	452	160	45	4	12	8	845	13	13	14	13	5
90% fractile	527	152	8	315	208	30	3	6	1	23	8	30	13	5	−3

Due to this challenge with the assessment of the effect of the external shading and orientation, the simplified method takes shading into account as an optional parameter separated from the basic variables. When using it in calculations, it is necessary to keep the aforementioned effect in mind. Another way to use those figures is to utilize them together with the figures for the unintended balcony ventilation and to evaluate the effect the air movement and external shading have on summer time maximum internal temperatures of the glazed balcony. The figure for unintended ventilation can also be used for assessing how much summertime maximum temperatures can be affected with ventilation and external shading.

Although it was not possible to eliminate the variables' dependence of each other totally, the development of simplified method is favored by its benefits, such as clarity, understandability and the speed of calculation. For example, Figs. 8–11 show the effects of different variables in a very graphic manner. If they are taken into account in balcony design from the start, the number of changes required to the base case is reduced so that it rarely exceeds seven. In other words, the key factors for energy savings and interior temperature of glazed spaces are easy to understand and this information can be taken advantage of even without conducting calculations. Furthermore, using the simplified method does not require in-depth knowledge of building physics or a deep understanding of the simulation software. Instead, an engineer's or an architect's basic education is sufficient for performing the calculations. This promotes the use of method in practical design work, allowing easy energy engineering of glazed spaces.

## 6. Conclusion

The purpose of this study was to develop a simplified method for the assessment of energy saving effects and interior temperatures of glazed balconies. The aim was to create a quick and simple way to rank different design options in the preliminary design stage of a construction project. The development of the method was based on the materials and results produced during previous studies [4,6,32,43].

As a result of preselected variables and their pre-calculated coefficients, the use of the method is quick. After a few hours of experience, any architect or structural engineer can absorb the method and take advantage of it in their daily work. It is not even necessary to always make the calculations: the user can learn a lot about the energy saving and interior temperature design of glazed spaces simply by looking at the participating factors in Figs. 8–11 given in Section 3.3 and by utilizing this knowledge in the design work. However, the method enables making real calculations easily and designing energy-optimized glazed spaces by comparing different options in the preliminary design stage. Even though the method has some shortcomings that result in a degree of uncertainty, the accuracy of the tool is sufficient for this purpose.

## References

- [1] Statistics Finland, Buildings and Helsinki free-time residences. Available from [http://www.stat.fi/til/rakke/2012/rakke\\_2012-05-24\\_kat\\_002\\_en.html](http://www.stat.fi/til/rakke/2012/rakke_2012-05-24_kat_002_en.html), 2012 (assessed 9.10.2015).
- [2] Statistics Finland, PX-Web Database in English. Available from [http://pxweb2.stat.fi/database/StatFin/databasetree\\_en.asp](http://pxweb2.stat.fi/database/StatFin/databasetree_en.asp), 2015 (accessed 9.10.2015).
- [3] Statistic Finland, Finnish block of flats with apartment balcony by the year of construction and tenure status [Unpublished], 2014 (accessed 9.10.2015).
- [4] K. Hilliaho, E. Mäkitalo, J. Lahdensivu, Energy saving potential of glazed space: sensitivity analysis, *Energy Build.* 60 (2015) 87–97.
- [5] I. Kummala, Parvekerakentamisen Nykytila Suomessa (Present State of Balcony Construction in Finland), Bachelor's Thesis, Tampere University of Technology, Tampere, 2014, pp. 33 (in Finnish).
- [6] K. Hilliaho, A. Köliö, T. Pakkala, J. Lahdensivu, J. Vinha, Effects of added glazing on the balcony indoor temperatures – Field measurements, *Energy Build.* (Under the review process in Energy and Buildings journal).
- [7] A.R. Rempel, A.W. Rempel, K.V. Cashman, K.N. Gates, C.J. Page, B. Shaw, Interpretation of passive solar field data with EnergyPlus models: un-conventional wisdom from four sunspaces in Eugene Oregon, *Build. Environ.* 60 (2013) 158–172.
- [8] O.B. Joergensen, L.T. Nielsen, Monitored results from yellow house, in: Proceedings of the EuroSun2000 ISES-European Solar Conference, Copenhagen, Denmark 19–22 June, 2000.
- [9] S.T. Elias-Ozkan, F. Summers, Ö. Taner, Energy efficiency of building with a solar space: two case studies from the Anatolian plateau, in: Proceedings of the International 26th PLEA Conference, Montreal, Canada 22–24 June, 2009.
- [10] O.B. Joergensen, L.T. Nielsen, Monitored results from an innovative solar renovation of multi-storey housing-EU SHINE-Engelsby, Flensburg, in: Proceedings of the EuroSun2000 ISES-European Solar Conference, Copenhagen, Denmark 19–22 June, 2000.
- [11] G.J. Schoenau, A.J. Lumbis, R.W. Besant, Development and verification of a simulation model for predicting the thermal behavior of attached sunspaces, *Energy Convers. Manag.* 32 (4) (1991) 319–331.
- [12] J.-M. Mottard, A. Fissore, Thermal simulation of an attached sunspace and its experimental validation, *Sol. Energy* 81 (3) (2007) 305–315.
- [13] J.J. Roux, C. Teodosiu, D. Covalet, R. Chareille, Validation of a glazed space simulation model using full-scale experimental data, *Energy Build.* 36 (6) (2004) 557–565.
- [14] A.H. Abdullah, Q. Meng, L. Zhao, F. Wang, Field study on indoor thermal environment in an atrium in tropical climates, *Build. Environ.* 44 (2) (2009) 431–436.
- [15] A. Laouadi, M.R. Atif, Comparison between computed and field measured thermal parameters in an atrium building, *Build. Environ.* 34 (2) (1998) 129–138.
- [16] A. Haller, Improvement of solar Renovation concepts and systems, in: A Technical Report of IEA SHC Task20 Solar Energy in Building Renovation, Ernst Schweizer AG, Metallbau Hedingen, 1999 (pp. 42, 49, 50, 70 and 71).
- [17] K.M. Bataineh, N. Fayed, Analysis of thermal performance of building attached sunspace, *Energy Build.* 43 (8) (2011) 1863–1868.
- [18] M. Wall, Climate and Energy Use in Glazed Spaces, Report No TABK-96/1009 (PhD Thesis), Lund University, Lund, 1996404.
- [19] G. Mihalakakou, On the use of sunspace for heating/cooling in Europe, *Renew. Energy* 26 (3) (2002) 415–429.
- [20] G. Mihalakakou, A. Ferrante, Energy conservation and potential of a sunspace: sensitivity analysis, *Energy Convers. Manag.* 41 (12) (2000) 1247–1264.
- [21] C. Boonstra, Glazed Balconies in Building Renovation, Brochure, James and James, London, UK, 1997, pp. 16.
- [22] J.S. Mattila, Effect of balcony glazing on the durability of concrete structures in Nordic Climate, in: Proceedings of Sustainable Construction, Materials and Practice Conference, Portugal, 2007.
- [23] G. Shoenu, A. Lumbis, R. Besant, An examination of operating strategies for energy efficient operation of attached sunspaces in cold climates, *Energy Convers. Manag.* 33 (1) (1992) 23–36.
- [24] G. Oliveti, N. Arcuri, M.D. Simone, R. Bruno, Solar heat gain and operative temperature in Attached sunspaces, *Renew. Energy* 39 (1) (2012) 241–249.
- [25] E. Mäkiö, Kerrostalot 1960–1975 (Block of flats from 1960 to 1975), first ed., Rakennustieto Oy, Helsinki, 1994, pp. 271 (in Finnish).

- [26] T. Kaasalainen, S. Huuhka, The homogenous homes of Finland: 'Standard' flats in non-standardized blocks, *Build. Res. Inf.* 44 (2016) 229–247.
- [27] S. Huuhka, T. Kaasalainen, J.H. Hakonen, J. Lahdensivu, Reusing panels from building for building: potential in Finnish 1970 mass housing Resources, *Conserv. Recycl.* 101 (2015) 105–121.
- [28] H. Achren, Asunnon julkinen huone: joustavuutta lähiöasumiseen, in: *Julkaisu 2, Tampereen teknillinen yliopisto, Tampere, 2015* (Available from <http://urn.fi/URN:NBN:fi:tty-201505061259>).
- [29] T. Kaasalainen, S. Huuhka, Properties of 320 blocks of flats from 1968–1985, Unpublished raw data, 2014.
- [30] Kerrostalot 1880–2000 (Block of flats from 1880 to 2000), in: P. Neuvonen (Ed.), first ed., *Rakennustieto Oy, Helsinki, 2006*, p. 288 (in Finnish).
- [31] J. Lahdensivu, S. Varjonen, A. Köliö, Betonijulkisivujen Korjausstrategiat (Repair Strategies of Concrete Facades and Balconies), Research Report 148, Tampere University of Technology, Tampereen teknillinen yliopisto, Tampere, 201079 (in Finnish).
- [32] K. Hilliaho, J. Lahdensivu, J. Vinha, Glazed space thermal simulation with IDA-ICE 4.61 software-Suitability analysis with case study, *Energy Build.* 89 (2015) 132–141.
- [33] D3, Rakennusten energiatehokkuus: määräykset ja ohjeet 2012 (Energy management in buildings: regulations and guidelines 2012), in: *The National Building Code of Finland, Part D3, Ministry of the Environment, Helsinki, 2011*, pp. 27 (in Finnish).
- [34] SFS-EN ISO 13789, Thermal Performance of Buildings – Transmission and Ventilation Heat Transfer Coefficients – Calculation Method, Finnish Standards Association SFS, Helsinki, 2008, pp. 22.
- [35] H. Poirazis, Double skin facades for office buildings: a literature review, in: *A Report of IEA SHC Task 34 ECBCS Annex 43, Lund University, Lund, 2006*, pp. 247.
- [36] H. Poirazis, Single and Double Skin Glazed Office Buildings: Analyses of Energy Use and Indoor Climate, Report EBD-T-08/8 (PhD Thesis), Lund University, Lund, 2008405.
- [37] D. van Dijk, H. Oversloot, WIS, the European tool to calculate thermal and solar properties of windows and window components, in: *Proceedings of Building Simulation '03, The Netherlands, 2003*.
- [38] A. Tiihonen, Asumisväljyys Lisääntyy Hitaasti (Living Space Is Increasing Slowly), Statistics Finland, 2011, Available from <http://www.stat.fi/tup/vl2010/art.2011-10-18.001.html>, (accessed 9.10.2015). (in Finnish).
- [39] J. Säteri, K. Kovanen, M.-L. Pallari, Kerrostalojen Sisäilmaston Ja Energiatalouden Parantaminen (Improvement of Indoor Air and Energy Efficiency in High-rise Residential Building), Technical Research Center of Finland, Espoo, 1999, pp. 82 (Available from <http://www.vtt.fi/inf/pdf/tiedotteet/1999/T1945.pdf>).
- [40] J. Palonen, Asuntoilmanvaihto (Ventilation in Residential Buildings), in: A. Koskenvesa (Ed.), *Rakennustieto Oy, Helsinki, 2004*, p. 1088 (Available from <https://www.rakennustieto.fi/Downloads/RK/RK040402.pdf>).
- [41] Kotitalouksien sähkönkäyttö 2011 (Electricity consumption in household 2011), Research report, Ministry of employment and the economy, Helsinki, 2013, pp. 52. (in Finnish).
- [42] International Weather for Energy Calculations 2.0 (IWEC2), ASHRAE, Available from <http://ashrae.whiteboxtechnologies.com/faq>, 2015 (accessed 18.2.2015).
- [43] K. Hilliaho, Parvekelasituksen Energiataloudelliset Vaikutukset (Energy Saving Effects of the Balcony Glazing), Master of Science Thesis, Tampere University of Technology, Tampere, 2010, pp. 147 (in Finnish).

**V**

**ENERGY SAVING AND INDOOR CLIMATE EFFECTS OF AN  
ADDED GLAZED FAÇADE TO A BRICK WALL BUILDING: CASE  
STUDY**

by

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# Energy saving and indoor climate effects of an added glazed facade to a brick wall building: Case study



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## ABSTRACT

This study is focused on the energy saving and indoor climate analysis of the renovation of a 1930's brick-walled building in the moderately cold climatic conditions of Malmö in southern Sweden. Three facades of the building were glassed in and the ventilation system was renewed. The purpose of this study was to investigate the effect the added glazing would have on the building's energy demand and indoor climate. Measurements were taken on site and were used as the input for computational studies performed with the help of IDA Indoor Climate and Energy software (IDA-ICE).

The study showed that the heating energy demand was reduced after the glazing installation by between 5.6% and 25.3%. In addition, the mean annual temperature difference between the cavity space and the outside air was from 5.2 °C to 11.4 °C higher, depending on the design. A number of different design options were explored for the winter and also summer case-studies, as it was apparent that adding glazing decreased the level of comfort in the building's indoor environment in summer time. This problem could be solved by increasing the cavity air flow or adding new solar shading to the front or back of the glazing.

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## 1. Introduction

In order to save energy in existing buildings different measures can be taken e.g. building technical solutions, such as adding insulation to the building envelope, and building services solutions, such as adding heat recovery to the ventilation system. Other solutions may also be applied if special requirements are to be met, cultural heritage considerations could be one example. In these situations, the façade can be protected with a transparent glass layer construction added in front of the façade.

In this study, an old hospital area in Malmo was being renovated. The renovation had a sustainable profile. One of the houses was a small flat brick building which was first intended to be externally insulated. However, the exterior was not allowed to be altered too much so instead it was decided to construct a glazing on the façade, creating an air cavity between the old brick wall and the glazing. This technical measure was chosen as it improves the insulation of the building envelope by reducing the heat transmission losses through the exterior walls, and it warms the building by capturing the solar energy absorbed by the brick wall and could also be used for pre-heating of the ventilation air. In line with its strategy of achieving sustainable solutions, the city of Malmö planned and installed an extensive amount of measurement sensors at various points in the building to enable evaluation and control of the technical solution. The study of the energy demand and indoor climate performance of the building was the main objective of this study, and the intention was to estimate the energy needed for different design solutions, and their effects on the indoor climate. The objectives for this study can therefore be specified as being to:

1. Investigate how effective the chosen renovation method was regarding energy and thermal comfort.
2. Build an IDA-ICE model and use measurements from the real building to validate that the IDA-ICE model behaves in a qualitatively realistic way compared to the renovated building.
3. Investigate other possible renovation choices with the IDA-ICE model for both winter and summer conditions.

Measurements were made on site and were used as inputs for computational studies performed with the help of IDA Indoor Climate and Energy software (IDA-ICE) 4.6.2. Software validation was carried out by comparing the field measurement results to the simulations during one week in winter, one in summer and one in spring. After creating a valid model, a total of 63 whole-year simulations were conducted in order to analyse the impact of different glazing and ventilation modes on the building's energy demand. In addition, the building's indoor temperatures in summer were also analyzed. The heating energy-saving studies (winter mode) included different amounts of glazing (one, two and three glazed façades), various glazing solutions (single, double and triple glazing) and two air inlet modes (through the cavity space or directly from outside). The summer conditions studies (cavity cooling mode) included evaluation of the cavity window ventilation, the cavity mechanical exhaust ventilation (FF2-fan) and

supply by the ground duct system (TF1-fan) as well as internal and external blinds for the cavity glazing. Calibration studies were made without tenants in residence, and a simulation analysis was performed using the standardized living habits of tenants, which was the only difference between the analyses of the calibration and the simulation. The building is structurally homogeneous, like a typical brick-walled building in Sweden, which makes it possible to apply the results to similar buildings.

## 2. Background

In general, a double skin façade (DSF) can be defined as multiple layer skin construction [1] and is considered to be a promising energy conservation measure for buildings [2]. New multi-story office buildings are sometimes built with a DSF [3]. Solutions applied to residential buildings such as [4–6] are clearly less commonly studied, and those studies which have been carried out have mainly focused on multi-story buildings. DSFs have rarely been studied as a method of protecting the façades of architecturally significant buildings [7], especially with regard to protecting smaller buildings, as in [8].

Typically, a DSF is composed of an external and an internal layer, as well as the cavity space, which acts as a buffer and can be used for controlled ventilation and solar protection [9]. Typically, the inner and outer layers are glazed structures [10]. The inner skin consists of double- or triple-pane glass filled with air, argon or krypton, while the external skin is single glazing [3]. Controllable shading systems have been typically located inside the cavity [11] and cavity depths have varied from 0.2 to over 2.0 m [3]. There have been few field-measurements or simulations where the internal skin consists of material with a high thermal mass [12]. Measures for adding glazing to protect old facades while they are being renovated [7] have also received little attention. Energy savings in a cooling-dominated climate are mostly connected to glazing solutions with a low solar factor and low U-value in order to minimize the cooling load of the building [13]. Conversely, in a heating-dominated climate, a high solar factor is recommended – especially in the situation where the added cavity is also utilised to pre-heat the ventilation air [14], because this allows the highest available amount of passive solar heat gain.

Ventilation of the cavity could be natural, forced or mixed. It is also possible to integrate it with the naturally- or mechanically-driven ventilation system inside the building. The results of Ref. [7] shows that a DSF which is connected to naturally-ventilated buildings is a valuable renovation solution and may reduce the energy demand by up to 12%. The work of [15] also supports the fact that DSFs with natural ventilation minimize the use of cooling energy and enhance thermal comfort. Stec and van Paassen [16] have underlined the importance of integrating a DSF into the building's ventilation unit. Saelens et al. [17] suggest a changeable system whose settings can be adjusted according to the climatic conditions, if traditional glazing solutions with external shading deemed to be inadequate. This means, for example, that it should be possible to change the system's mode of operation between

winter and summer. In addition, it has been observed that heat recovery will lower the overall yearly benefits of having the air inlet through the cavity, and may even, at certain times of the year, increase the energy demand compared to solutions without any air inlet [14]. The reason for this is the high-efficiency of the heat recovery. The heat recovery unit could cover the heating energy demand even if the outdoor air is not first passed through the cavity in, for example, the month of April. "In this case, the intake air should have been bypassed the cavity, since maintaining the thermal buffer is most energy efficient in this case" [14]. DSFs connected to ground-coupled heat exchangers have also been evaluated [18] and their benefits in winter conditions have been clarified. However, based on the literature survey, it appears that earth-to-air heat exchange units have very rarely been connected to DSF.

Typically, DSF constructions have been categorized into four groups: Box Window facades, Shaft-box facades, Corridor facades and Multi-story facades [19,20]. Of these, high multi-story facades with one cavity covering the whole façade from the bottom to the top of the buildings have been the typical solution in Sweden and Finland [21]. Typically, openings have been closed during the winter for extra insulation and opened during the summer for heat extraction. Another common solution is the use of shading devices, usually venetian blinds, placed inside the cavity [21]. According to the introduced design strategies [22,23], previous design solutions do not seem to have been fully optimized. The work of [24] also underlines how few full-scale measurement studies have been made in real buildings [25–27]. The study presented here aims to make up for this by presenting full-scale measurement and simulation studies from the unique perspective offered by Nordic climatic conditions. The particular contribution this study makes to the subject is that our double façade has been constructed in a different way than is common practice in Finland and Sweden. Furthermore, the location offers results from a northern, heating oriented climate, whereas most of the buildings studied in the literature are situated in a more cooling-oriented climate. Another special feature is that it is a one-storey house to which glazing has been added to protect the old façade, and whose cavity space is connected to the detailed, mechanically-controlled ventilation system, which allows various control setpoints to be used at different times of the year. Also, the uniform cavity space around three out of four of the building's facades includes a cavity air circulation unit, as well as a separate cooling option with a mechanical air supply through the ground ducts, a mechanical exhaust from the south-side cavity, and two openable windows in the south façade, all of which makes this solution almost unique. Using several technical measures at the same time, including two mechanical ventilation systems, a ground duct system, and

opening and closing windows, is rarely found in real buildings. This provides us with a unique opportunity to learn more about the performance of these types of solutions and how they work in combination. Both the extensive renovation work, and the comprehensive installation of measurement sensors gave rise to the opportunity to validate our simulations with measurements from the real conditions. It has thus been possible to explore how the performance of the renovation solutions can be optimized by performing calculations for several alternatives. In this study, a very detailed model was implemented. The fact that both passive measures, such as preheating of the ventilation air and opening and closing the windows, and more active measures, such as the mechanical ventilation system are applied is also interesting from the sustainability perspective.

### 3. Research materials and methods

#### 3.1. The studied building

##### 3.1.1. Description of the building

The brick building with 1½-stone walls was erected in the 1930's. In 2010–2011 the building was renovated by adding glazing at a distance of roughly 0.75 m from the south, east and west façades of the building (Fig. 1). The vertical glazing added to the brick façade is single 8 mm clear glass and the horizontal glazing added on top of the cavity is clear argon-filled double glazing. The front of the building has a south-east orientation (30° east of south). The building is heated with radiators by a hydronic heating system and it is ventilated by two independently working ventilation systems; 5701 for the building and 5702 for the cavity (Fig. 2).

##### 3.1.2. Description of the building ventilation system

A mechanical air supply and exhaust ventilation system was installed in the building during the renovation. The ventilation unit; a Systemair VR 700 DC, located in the attic, included filters, a rotary heat exchanger, a heating coil and fans. The ventilation system was designed by consultants to the building owner before the research study started. The operating modes and set points that were defined by the designers have been used in this study, to allow evaluation of the existing system, as well.

The intention is that when the supply air needs heating, the outdoor air is passed through the cavity before it is supplied to the ventilation unit (Fig. 2). During non-heating periods the outdoor air is supplied directly to the ventilation unit from outside. The different modes have been defined in the system as shown in Fig. 2. When the temperature of the sensors located on the south

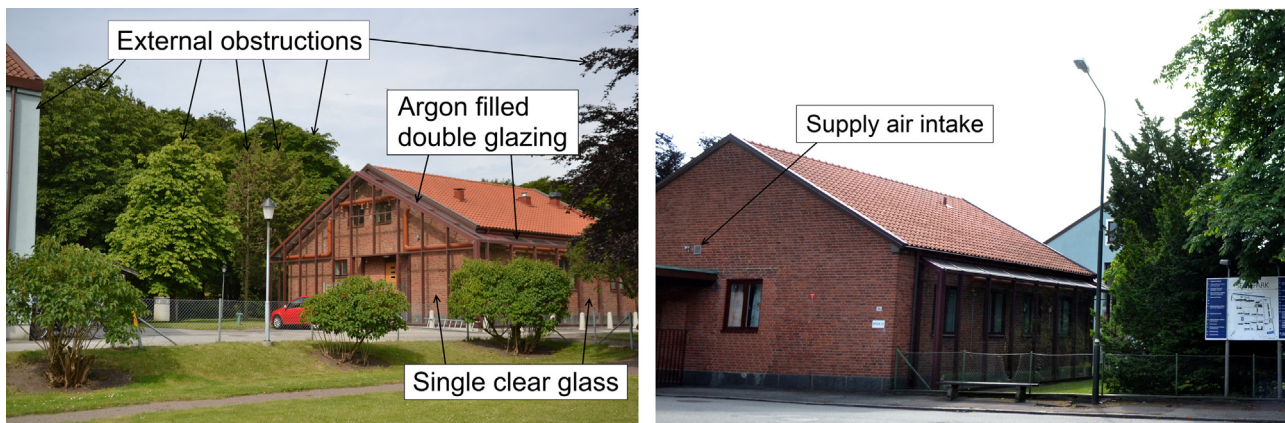
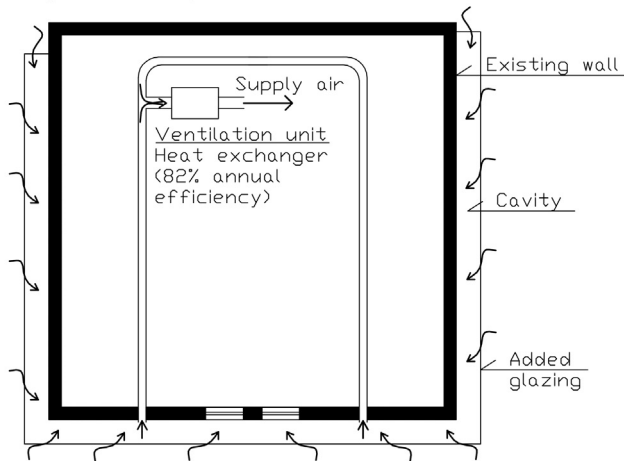


Fig. 1. The outside view of the south and east facade (left photo) and north and west facade (right photo).

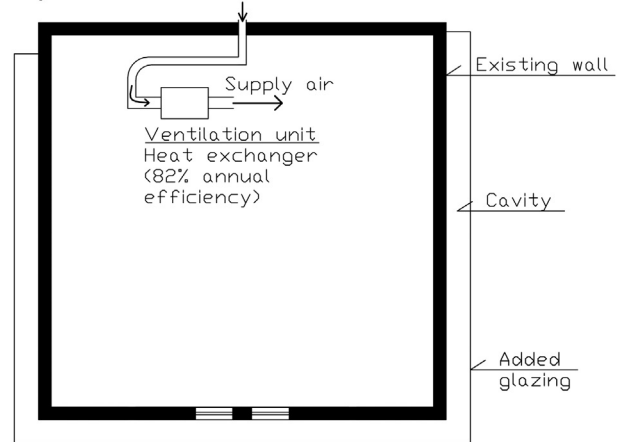


Heating period (winter case) - system 5701

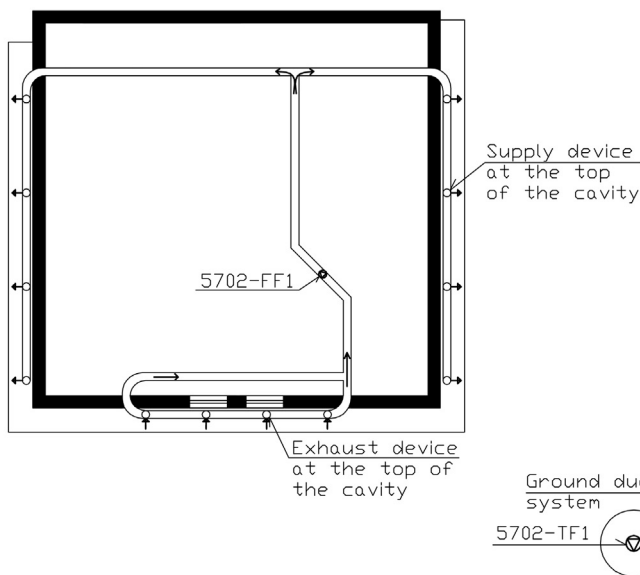
If the temperature of two south cavity sensors (GT31, GT32) is below 20°C, supply air comes through the cavity.

Non-heating period (summer case) - system 5701

If the temperature of two south cavity sensors (GT31, GT32) is above 20°C, supply air comes directly from outside.

Heating period (winter case) - system 5702

If the mean temperature of two south cavity sensors (GT21:1, GT21:2) are above east (GT31:1, GT31:2) or west (GT32:1, GT32:2) cavity sensors mean value, the air circulation starts (fan 5702-FF1).

Non-heating period (summer case) - system 5702

If the mean temperature of two south (GT21:1, GT21:2), east (GT33:1, GT33:2) or west (GT34:1, GT34:2) cavity sensors are above 20 °C, the supply (5702-TF1) and exhaust (5702-FF2) fan starts. If the sensor GT41 temperature is above 23 °C, cavity windows also open.

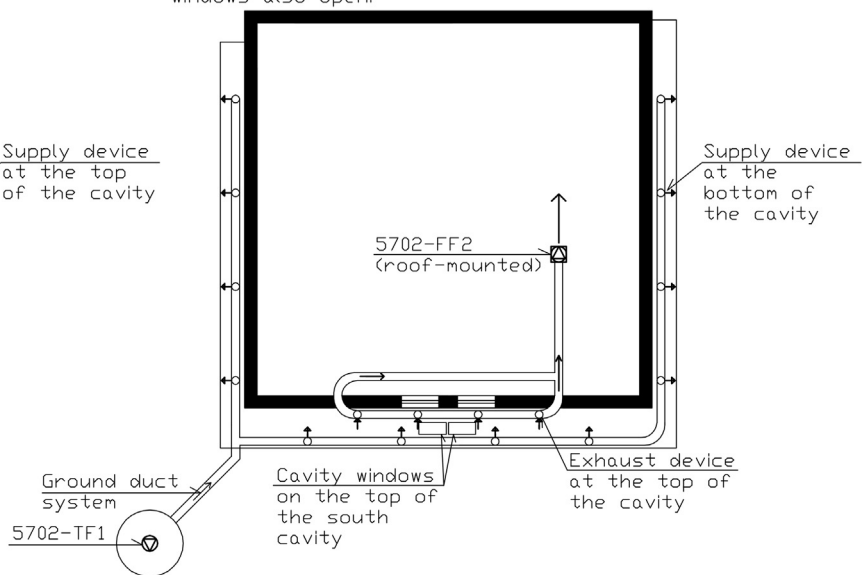


Fig. 2. The four principle operating modes for the two ventilation systems 5701 (supplying the building) and 5702 (supplying the cavity).

façade of the cavity (GT31 and GT32) both exceed 20 °C, the outdoor air is taken directly from the air intake on the north façade. When these temperatures drop below 18 °C, the outdoor air is once again passed through the cavity. The temperatures in the cavity may also rise above 20 °C during wintertime. The reason for preventing the air from passing through the cavity at 20 °C is probably because this is an adequate air-supply temperature. If the outdoor air is heated to higher temperatures in the cavity, the air movement inside the rooms may suffer as the air will tend to stay close to the ceiling and not mix with the rest of the air in the room, meaning that any pollutants cannot easily be removed from the rooms.

In the mode of air supply through the cavity, the outdoor air enters the cavity through leakage air gaps on the east, south and west facade. These are horizontal gaps located between the added glazing and the ground and vertical gaps between the brick wall and the glazing. These gaps could have been sealed but are not, as

the outdoor air is intended to pass through them. The gaps vary from a few millimeters up to 10 millimeters, so a mean distance of 6.5 mm was set for the simulations. The air is then transported from the cavity via two air intakes on the south brick wall (marked "Air supply to ventilation unit" in Fig. 3) to ducts in the attic connecting to the ventilation unit. The supply air is then supplied through insulated ducts to each room. The system is also shown in Figs. 4 and 5.

### 3.1.3. Description of the cavity ventilation system

The other ventilation system, numbered 5702, is installed for the cavity. This works independently from the main ventilation system. This system also has different modes for heating and cooling purposes (Fig. 2). During heating periods, the aim has been to attain as high heating of the cavities as possible by using a fan (5702-FF1) to move the air from the south cavity to the east and west cavities whenever the south one has a higher temperature.

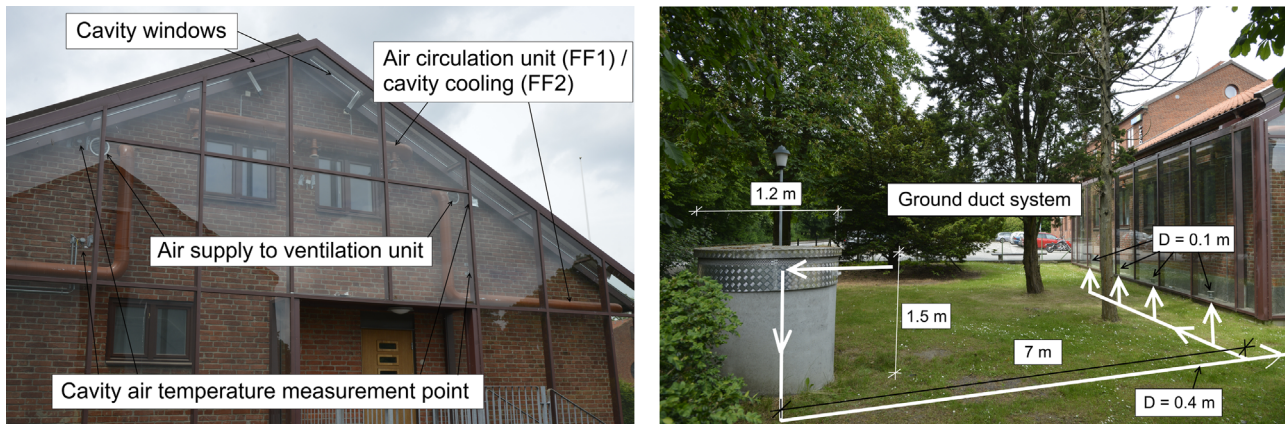


Fig. 3. South façade (left photo) and ground duct system (right photo) with description of the visible system components.

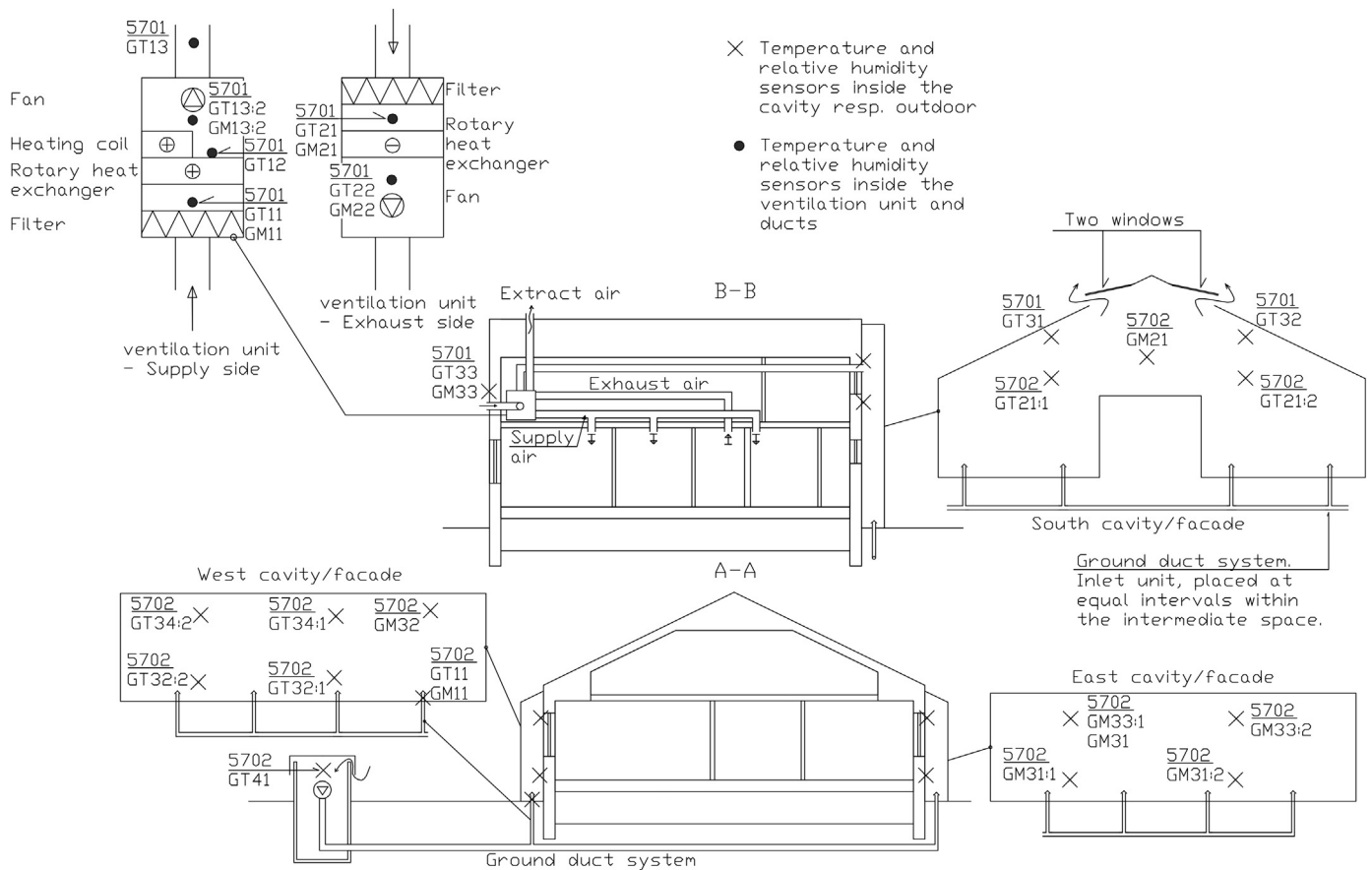


Fig. 4. Schematic drawing of the measurement arrangements.

There are no partitions between the different cavities, which mean that the air can be exchanged directly between the different sides, as well.

During cooling periods (summertime) a fan (5702-TF1) located at the beginning of the vertical concrete duct (Fig. 3) starts to cool down the cavity whenever the mean temperature in the upper part of any of the cavities is above 20 °C by passing outdoor air through a ground duct system and supplying it to the cavity. The fan stops when the temperature drops below 18 °C. The air supply passes through the cavity and leaves either through an exhaust fan (5702-FF2) or through the two cavity windows at the top of the south façade (this air is not supplied to the building). The windows (Fig. 3) open when the outdoor temperature sensor located at the start of the concrete duct is above 23 °C, and close again when the

temperature drops below 20 °C. The outdoor air used in the building during the cavity cooling mode is supplied to the building from the north façade (Fig. 1). (Article V).

Outdoor air is supplied to the ground duct via a large concrete pipe with an outside diameter of 1.2 m (Fig. 3) and a height of 1.5 m above the ground. The underground ducts are 400 mm in diameter and the distance from the concrete pipe to the bottom of the glazed space is 7 m. There are 4 air inlets of 100 mm diameter in each of the east, west and south sides of the cavity (a total of 12 inlets) at the bottom of the cavities. The two cavity windows are both about 0.5–0.7 m<sup>2</sup> in size.

It is worth emphasizing that the air that is cooled down in the ground does not enter to the building but only passed through the cavity. Otherwise the increased relative humidity of the air could

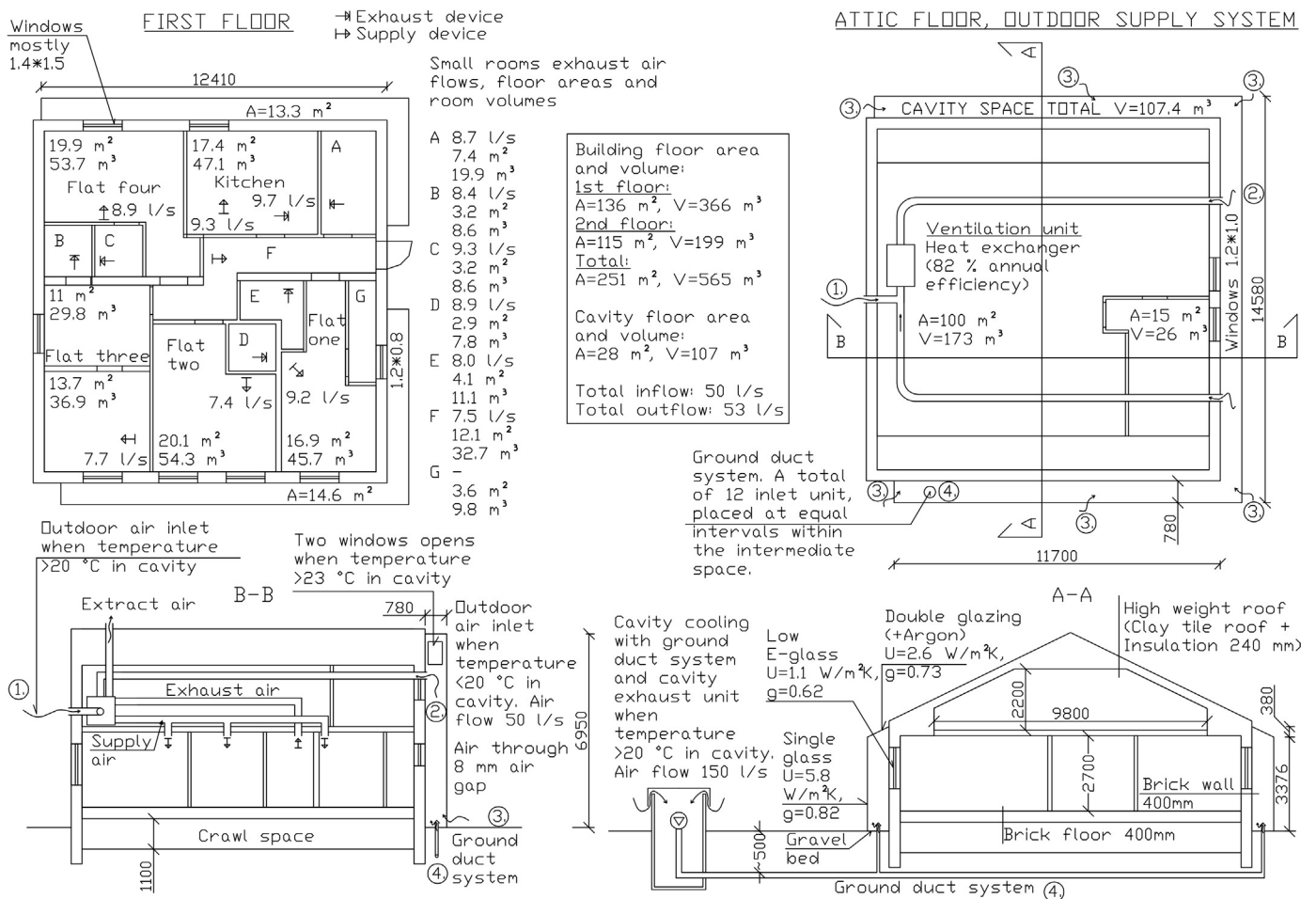


Fig. 5. Illustration of the simulated building.

possess a risk in terms of moisture for indoor air quality reasons [28]. When the fans TF1 and FF2 are not working (during wintertime), a very low natural air flow may, however, occur in the ground ducts and mix inside the cavity with the outdoor air flow passing through the leakage gaps to the cavity. This has been taken into account in the IDA-ICE model. However, the higher pressure drop in these 7 m long ducts compared to the 8 mm air gaps in the cavity implies that this air flow will be small when the fans are not working. This is captured in the simulations, as 98–100% of the air flow comes through the air gaps and only 0–2% through the ground ducts during wintertime. The ratio is reversed for the cooling case when the fan in the ground duct is working.

### 3.2. Measurement arrangement

The building has been equipped with a measurement system (Fig. 4). Sensors for temperature, relative humidity, air flow and other parameters have been installed at various points in the building, in the cavity, in the ventilation unit, and in the ventilation ducts. Inside the cavity, the temperature is measured at 4 different points on the south façade, 4 points on the east façade and 5 points on the west façade. These sensors have been attached to the brick wall and shielded with aluminum foil. 10 temperature measurement points are installed for the main ventilation system, and the cavity system has a total of 15 temperature points. The two sensors used for calibration of the simulation model are 5701-GT31 and GT32. The main purpose of the monitoring is to evaluate and control the operation of the building's HVAC system. The accuracy of the sensors (PT1000) were  $T = \pm 0.3$  °C and  $RH = \pm 3\%$

RH at 0 °C.

All the sensors are connected to a Programmable Logic Controller (PLC) located in the HVAC room in the attic. This is also connected to the city of Malmö's overall monitoring system for all public buildings. The temperature values are stored for each time step (the selected time step is considered to be 1 min). The monitoring period which has been analyzed covers 15 months, from the 28th of October 2013 to the 10th of February 2015. The main focus of the analysis is on the 10 months between the 7th of April 2014 and the 10th of February 2015. The building was unoccupied during the whole measurement period except for one week in August 2014 (from 15th to 23th of August). Human behavior has not, therefore, influenced the building's indoor climate or its energy balance. It should be noted that the ventilation units have been shut down each night.

### 3.3. Dynamic energy simulations with IDA Indoor Climate and Energy (IDA-ICE) software

The energy analysis of the glazed spaces is a special calculation case, for which purpose no commercial energy simulation software has been specifically designed. Thus, it was important to validate and calibrate the used simulation software before using it to draw conclusions about the building design. The most important parameters for a dynamic simulation of a glazed space are a precise geometrical description of the building, hourly-based weather logs, detailed solar radiation processing and the models of the windows. The solar radiation model should take into account direct and diffuse radiation separately, and handle solar radiation

distribution into the space, the adjoining building and the window structures. Surface resistances must be calculated using temperature-dependent variables with regard to the long-wave sky radiation [29]. The IDA-ICE software used (version 4.6.2) incorporates those features [30] and has proved itself reliable in many validation studies [31–41].

Challenges in performing the IDA-ICE modeling in this study occurred when it was found that the current software package did not include the possibility to connect an adjacent zone to the ventilation unit (air supply from the cavity) nor any model to handle the existing ground duct system. This meant that the air supply through the cavity was simulated by placing an extra exhaust ventilation unit inside the cavity space and connecting it to the attic ventilation unit. The ground duct system, in turn, was modeled as nine small underground zones connected to each other. By doing this, the real impact of the ground duct system could be treated to some degree. A detailed window structure (Detwind) and a simplified zone model (Energy) were used in the simulation.

The energy simulations were made in three steps. In the first step, a detailed model was created including modeling of the shading from nearby trees. Secondly, the detailed model was validated by comparing the results from the simulations with the field measurements. Thirdly, 63 calculation cases from the whole-year weather log (year 2014) were performed, and the impact of different glazings and ventilation modes on the building's energy demand and the summertime indoor temperatures were analyzed.

### 3.3.1. Model description

The building used for this study is a two-storey student house with four flats on the first floor, where there also is a communal kitchen and a storage facility (Fig. 5). The floor area of the building is 251 m<sup>2</sup> (V=565 m<sup>3</sup>) and the flats vary in size from 16.7 m<sup>2</sup> to 27.9 m<sup>2</sup>. The floor area of the cavity space is 28 m<sup>2</sup> and the air volume is 107 m<sup>3</sup> (glazing to floor area is ~1.8). For the added vertical single glazing, a U-value of 5.8 W/m<sup>2</sup>K (g=0.82) is given,

and the horizontal double glazing has a U-value of 2.6 W/m<sup>2</sup>K (g=0.62). The red brick wall's U-value is estimated to be U=1.35 W/m<sup>2</sup>K and its solar absorptivity  $\alpha=0.75$ . Additional information about the building, the measurement arrangements and the monitoring results can be found in the following publications [8,42,43].

For the yearly energy simulations (not the validation simulations) user-related energy figures such as the number of occupants, lifestyle habits and the use of lighting and electrical device have been standardized after the calibration by using the Finnish standardized reference values [44]. As a result, the energy used by the building's lighting, the operation of the fans and electrical equipment (radio, television, etc.) are similar for all simulation cases. Also, the consumption of tap water (600 l/m<sup>2</sup>) and the number of tenants (0.0357 no./m<sup>2</sup>), as well as the inhabitant's behavior are the same in all the different cases. In contrast, the case-specific parameters are represented by the amount of energy delivered to the hot water radiators and the energy demand for the ventilation air and for the electricity needed to operate the rotary heat exchanger. The building's air leakage coefficient was assumed to be 1 air changes per hour (ACH) at a 50 Pa pressure difference. More detailed information about the building, its characteristics and the simulation software's main input parameters are described in Fig. 5 and Table 1.

As only the outdoor air temperature and the relative humidity was measured on site the solar data files used in the simulations were assembled through the use of services provided by the Swedish Metrological and Hydrological Institute (SMHI). The time period used in the annual simulations is the year of 2014; from 1st of January 2014 to 31st of December 2014 with hourly values. Through the service of MetObs [45], data on the air temperature, relative humidity, wind direction and wind speed were acquired for Sturup (Malmö Airport). From the same service, data on precipitation and global radiation were acquired for Malmö and Lund, respectively. The direct solar radiation has been calculated through SMHI's service Strång [46–48]. Diffuse solar radiation has been

**Table 1**  
Simulation model key input parameters.

<b>Location (climate condition)</b>	Malmö (55.59056 N, 12.99145 E), Sweden
<b>Orientation</b>	SE (30° from South)
<b>Wind profile</b>	City center
<b>External obstruction</b>	Some trees and buildings (see Fig. 1)
<b>Building size</b>	A=251 m <sup>2</sup> and V=565 m <sup>3</sup>
<b>Size of the cavity space</b>	A=28 m <sup>2</sup> , V=107 m <sup>3</sup> and mean depth 0,75 m
<b>Air temperature inside flat</b>	21 °C (system set point i.e. mainly during heating season)
<b>Equipment</b>	Lighting 11 W/m <sup>2</sup> and equipment 4 W/m <sup>2</sup> (in the first floor)
<b>Number of occupants</b>	0.0357 no./m <sup>2</sup> (totally 4.7 people), activity level 1.2 and clothing 0.85 (in the first floor)
<b>Building ventilation type (air change rate)</b>	Mechanical supply and exhaust ventilation with 82% heat recovery (0.5 ACH)
<b>Supply air to ventilation unit</b>	From the cavity or directly from outside (See Figs. 1 and 3)
<b>Building windows properties</b>	U=1.1 W/m <sup>2</sup> K, g=0.62, internal venetian blinds (g <sub>shading+window</sub> =0.2)
<b>Cavity glazing (vertical)</b>	Single clear glass, 8 mm, U=5,8 W/m <sup>2</sup> K, g=0.82
<b>Cavity glazing (horizontal = ceiling)</b>	Argon-filled double glazing, U=2.6 W/m <sup>2</sup> K, g=0.73
<b>Air gaps of the glazing structure</b>	Air gaps between glazing frames and basement as well as between vertical frame structures and brick wall; mean distance 6.5 mm. Correspond to 1,6 air change per hour (ACH) in average (fluctuation 1,3–2,5 ACH)
<b>Building air leakage coefficient (at 50 Pa pressure difference)</b>	1 ACH
<b>Heating system and heat delivery</b>	District heating connected to hydronic heating system with radiators (60/40 system)
<b>Control curve position of the heating system</b>	According to current settings in the building [42]
<b>Summer shut-off; heating system</b>	No summer shut-off
<b>Heat gain to zones from the heat distribution system losses</b>	5%
<b>Properties of the brick wall</b>	Density=2300 kg/m <sup>3</sup> , Lambda=0.7 W/(m*K), Specific heat=1050 J/(kg*K)
<b>Absorptivity and emissivity of the brick wall surface</b>	Emissivity=0.9, Absorptivity=0.75
<b>Summer cooling air flow through cavity</b>	150 l/s, both supply air via ground duct (TF1) and exhaust air via roof fan FF2
<b>Blinds of the added glazing structures</b>	No blinds in the basic case
<b>Used weather file</b>	Available climate information about the Malmö/Lund from the year 2014. Assembling method is described in this subsection.

**Table 2**

Monthly mean values of the used 2014 weather file.

	Dry-bulb temperature [°C]	Relative humidity of air [%]	Direction of wind [°]	Speed of meteorological wind [m/s]	Direct normal radiation [W/m <sup>2</sup> ]	Diffuse radiation on horizontal surface [W/m <sup>2</sup> ]
Jan	0.8	88.8	148.9	6.5	5.0	11.0
Feb	3.1	91.1	172.0	4.8	42.5	32.9
Mar	5.2	82.4	202.0	4.7	120.0	53.0
Apr	8.3	73.2	162.4	4.5	159.7	83.8
May	11.8	78.2	197.2	3.7	185.3	114.9
Jun	14.7	75.6	208.2	3.3	212.5	116.5
Jul	19.6	72.5	156.4	3.6	281.2	87.3
Aug	16.2	78.1	203.3	4.1	153.8	93.5
Sep	14.2	83.8	156.6	3.8	150.4	68.3
Oct	11.5	90.6	150.2	4.0	48.0	30.8
Nov	7.4	90.4	126.0	4.4	17.9	14.4
Dec	2.6	90.3	210.0	4.9	15.8	9.6
Yearly average	9.6	82.9	174.6	4.4	116.4	59.8

calculated using the following formula:

$$E_{dif} = E_{glo} - E_{dir.norm.} \cdot \sin(\alpha_{sol})$$

where

$E_{dif}$  = the diffuse solar radiation [W/m<sup>2</sup>],

$E_{glo}$  = the global radiation [W/m<sup>2</sup>],

$E_{dir.norm.}$  = the direct normal solar radiation [W/m<sup>2</sup>],

and  $\alpha_{sol}$  = the solar elevation [degrees].

The solar elevation was calculated with [49], based on the latitude, longitude and the elevation of the simulated location. Missing data have been interpolated. The monthly mean values of the 2014 weather log are shown in Table 2.

Before the simulation, the outdoor temperature data measured on site was compared with the files produced through the above-described technique to ensure that the produced weather file was truly representative of the site conditions. A time zone correction, due to daylight saving time (DST), was also made, moving all data one hour forward in the produced weather file to allow direct comparison with the actual temperature.

### 3.3.2. Model validation

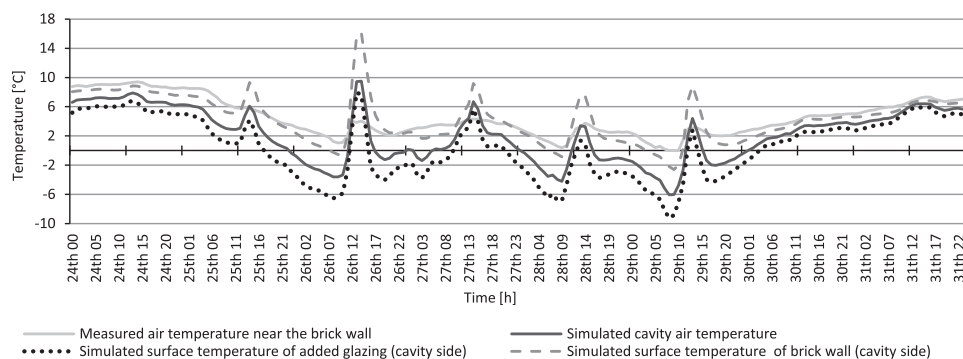
The purpose of the validation was to ensure that the IDA-ICE model behaved in a qualitatively realistic way (“good enough”) compared with the actual building. This meant that the objective was not to make a parameter fitting of the model to replicate the results exactly.

The model validation was made by comparing the measured air temperature of the top gable on the south façade (two measurement point average) with the simulated temperatures during one week in winter (24/12–31/12 2014), one in summer (24/7–31/7 2014) and one in spring (15/4–20/4 2014). The temperatures in the

cavity were used as the cavity was the most interesting part of the building and the most difficult one to model. The purpose of the winter week validation (Fig. 6) was to adjust the heating mode correctly and the purpose of the summer week simulation (Fig. 7) was to verify the operation of the cooling mode. The spring week simulation (Fig. 8) demonstrated the overall behavior of the model, because the cavity control mode changed many times from winter mode (air supply through the cavity) to cooling mode during that period. During the winter week the cavity temperature was below 20 °C, which meant that ventilation air passed through the cavity before coming into the ventilation unit. During the summer week the outdoor air temperature was consistently over 23 °C. This meant that the cavity windows were open and the cavity cooling unit (ground duct system and cavity exhaust ventilation unit) were working. The period which best fulfilled the criteria for “cavity mix use” was in the spring. During this period, the cavity temperature ranged from 5 °C to 33 °C and the cavity control mode frequently changed between cavity cooling and ventilation air supply through the cavity to the ventilation unit.

The temperature sensors were covered with aluminum foil (to prevent exposure to direct sunlight) and were placed close to, but not in direct contact with, the brick wall. The temperature sensor itself (PT1000) was mounted in a plastic shell. It was therefore assumed that the measured temperature was a certain weighted average of the temperatures of the: cavity air, the external surface of the brick wall inside the cavity and the internal surface of the glazing. The weighting depended mostly on the air speed and the solar radiation in the cavity. Thus, the main problem was to determine which of the simulated temperatures were closest to the measured “cavity” temperature.

Figs. 6–8 show the measured temperature, the temperature of



**Fig. 6.** Winter validation week between 24th and 31st of December 2014.

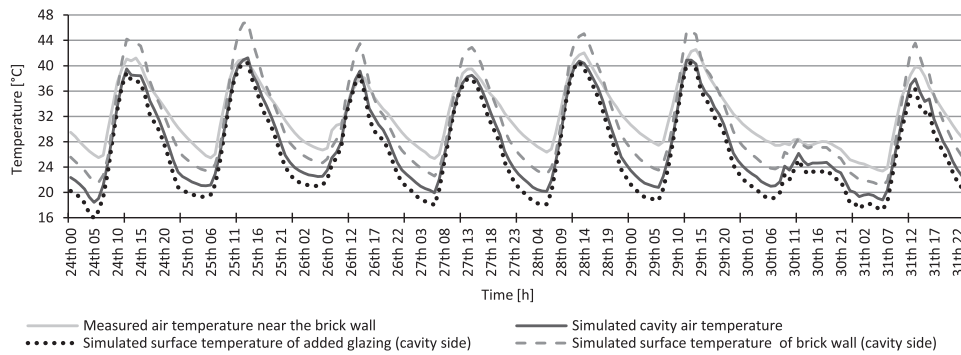


Fig. 7. Summer validation week between 24th and 31st of July 2014.

the cavity air, the brick wall (two point average) and the temperature of the internal surface glazing. The figures indicate that the measured temperatures were indeed a mix of the brick wall and air temperatures. The sun would still heat the aluminum foil, but the assumption was that the solar impact was reduced by the foil. The best fit for the spring and summer situations were with the measured cavity temperature and the simulated outer surface temperature of the brick wall, which indicates a low air speed behind the aluminum foil (Figs. 7 and 8). It should be noted that the simulated external surface temperature of the brick wall takes into account both the direct and the diffuse sunlight reaching its surface. The aluminum foil did, however, provide shade from direct sunlight. This might be the reason that the simulated outer surface temperatures, in the summer, are higher than the measured temperatures (Fig. 7).

The measured and simulated temperatures in Fig. 8 indicate that the model was good enough to be used in further studies. Given that there are many local phenomena not included in the model, including, for instance, the thermal behavior of the temperature sensors, the results were surprisingly good. It might be possible, but not really worthwhile, to try to get a better fit by making a detailed model of the mounting of the sensors together with the solar shading of the aluminum foil. However, as stated above, it was not the goal of this study to make a perfect parameter fit for this particular house. The goal was to create a reasonable model that managed to capture the qualitative behavior of the house.

### 3.3.3. Simulation studies

After the validation, 63 calculation cases using the whole-year weather file (2014) were conducted, and the impact of different glazing and ventilation modes on the building's energy demand and summertime indoor temperatures were analyzed (the simulation model is shown in Fig. 9). The purpose of these investigations was to evaluate how effective the chosen renovation method was regarding energy use and thermal comfort, as well as to

investigate other possible renovation choices with the IDA-ICE model. The heating energy-saving studies (winter mode) included different amounts of glazing, i.e. glazing one, two or three of the façades, various facade solutions (single, double and triple glazing) and two air inlet modes (through the cavity space or directly from outside). The summer-conditions (cooling mode) studies included evaluations of the cavity window ventilation, the mechanical exhaust ventilation (FF2) and the ground duct system (TF1) as well as the internal and external blinds of the cavity glazing.

The cavity-cooling calculation cases were mainly chosen from alternatives that could feasibly be applied to real buildings. The controls of the systems also followed the actual designed set points set by the building owner. These were kept unchanged throughout the study to enable evaluation of the real building as well. The only exceptions to this principle were blinds placed in front or back of the added glazing to cover the whole glazed façade all the time (always down during 365 days a year) and variations in the depths of the ground ducts. The simulation analysis used standardized living habits of the tenants, this being the only difference between the calibration and simulation analyses.

## 4. Results and discussion

This section presents the results of this study, whose purpose was to identify the key factors affecting the ability of current energy-saving measures to reduce the energy demand of the studied building in Nordic climatic conditions. The results will help the readers to identify the possible variables in relation to possibilities to reduce the building energy demand with added glazing and to cool the cavity during summer.

### 4.1. Energy saving studies

#### 4.1.1. General

The table presents the cases from the simulation study. Cases

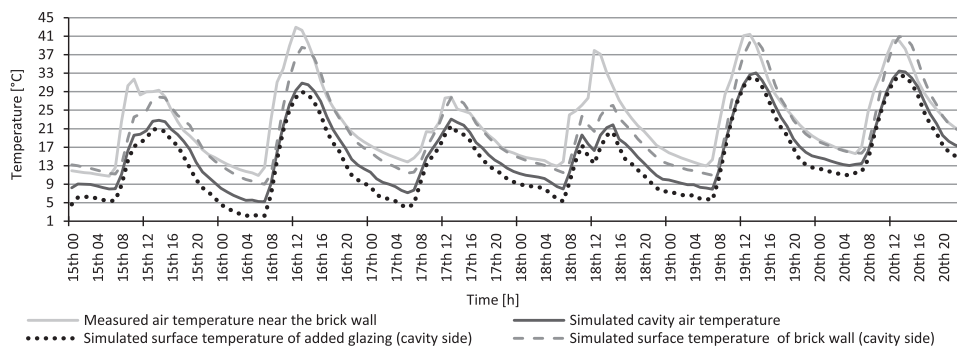


Fig. 8. Spring validation week between 15th and 20th of April 2014.

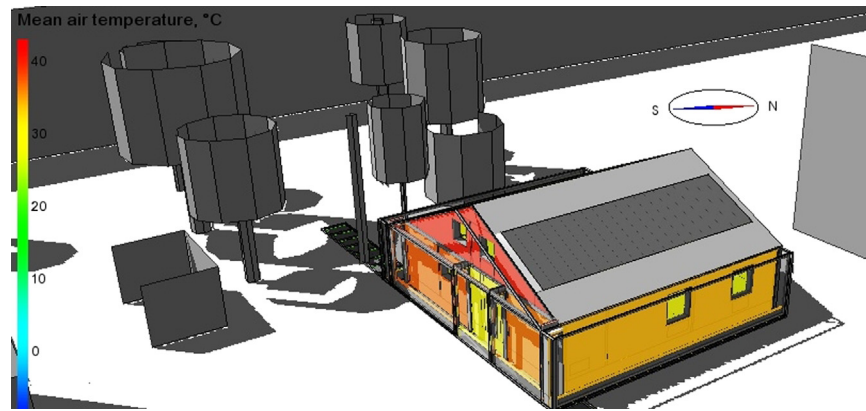


Fig. 9. This animated view of the simulation model on 3rd of August 2014 at 14 o'clock shows the very high temperatures inside the southern part of the cavity space.

1–16 were made with heat recovery and a heating coil while cases 17–23 were made without them. The descriptions of the studied cases are shown in columns two to seven. Columns 8–13 show the calculation results; the yearly energy demand for heating and ventilating the space and the percentage energy saving compared to the situation without any added glazing (Case 1) as well as the results of the temperature measurements for the flat and the cavity temperatures, in that order. The temperature information includes the operative and mean air temperatures of Flat 1, as well as the mean air temperatures of the cavity and the temperature difference between the cavity and the outside (the average outside temperature for 2014 was 9.6 °C). The installed summer cooling possibilities in the real building, i.e. the ground duct or exhaust fan, are not working in cases 1–23 in Table 3. The temperatures attained during July, therefore, represent a case where the real building would not been equipped with any cooling facilities.

#### 4.1.2. Evaluation of the different energy-saving measures

**4.1.2.1. The number of glazed façades.** With the help of calculation cases 2, 3 and 4, the effect of the number of glazed façades on the achievable energy savings is estimated. Case 2 represents the building with glazing added to the south façade, case 3 the building with glazing added to both the south and east façades, and case 4 the building with glazing added to the south, west and east façades. The results showed that the mean yearly temperatures of the cavity space were highest when only the south side was glazed (6.4 °C in case 2) and lowest when three of the building façades were glazed (5.7 °C in case 4). In its entirety, the cavity mean temperature was from 5.2 °C to 11.4 °C higher than outside on average in the cases 2–23 (Table 3). The number of glazed façades was directly associated with the achieved savings and increased directly as the number of glazed façades was increased. The reduced heat loss was directly proportional to the properties of the buffer zone. For example, the energy saving was 5.6% with one (south) glazed façade and 10.4% with the three (south, west and east) glazed façades. It seems also that the amount of glazing and the temperatures during the summer months were related. Adding glazing to the southern side of the building increased the indoor operative temperature in Flat 1 from 25.7 °C (case 1) to 26.7 °C (case 2). Then, the temperature rose by a further 0.1 °C when the eastern façade glazing was added (26.8 °C in case 3) and by a further 0.1 °C after the western façade glazing was added (26.9 °C in case 4).

**4.1.2.2. Effect of the glazing U-value.** Because of their effect on the temperature in the buffer zone, the U-value of the glazing and the depth of the cavity space were also important factors to study in

relation to the achieved energy-savings. Of these, the U-value of the glazing had a clear impact on the building's energy demand. For example, by equipping the facade wall and roof structures with low energy solar protection glass ( $U=0.7 \text{ W/m}^2 \text{ K}$  and  $g=0.24$ ) an 18.7% energy-saving was achieved, while with argon-filled triple glazing ( $U=1.7 \text{ W/m}^2 \text{ K}$  and  $g=0.63$ ) a 22.1% energy-saving could be achieved. The results also showed that the difference between double glazing ( $U=2.6 \text{ W/m}^2 \text{ K}$ ) and low energy solar protection glass ( $U=0.7 \text{ W/m}^2 \text{ K}$ ) was not great because the solar energy transmission of double glazing and triple glazing with solar protection glass were  $g=0.73$  and  $g=0.24$ , respectively. This implies that there is a point after which it is no longer worthwhile reducing the heat losses from conduction, since the solar heat gain will also be reduced.

The thermal insulation level and the g-value of the glazing structures was also directly linked with the cavity space temperatures, and furthermore, the temperature of the flats. The temperatures varied between 15.3 °C (case 4) and 21 °C (case 15) in the cavity, and between 27.1 °C and 29.6 °C in Flat 1, respectively. It was also notable that the highest temperatures for the cavity space and Flat 1 in summertime were achieved with a solution that produced the highest energy-saving effects of all the calculation cases. The best solutions for façade glazing seem to be ones with a low U-value and high g-value, such as argon-filled triple glazing ( $U=1.7 \text{ W/m}^2 \text{ K}$  and  $g=0.63$ ), which was the most energy-saving option among the studied cases (energy-savings 22.1%). This design criterion was also found to be beneficial in another study about glassed-in balconies [50].

**4.1.2.3. Effect of the cavity depth.** The benefit of increasing the depth of the cavity space was not very clear. For example, the achieved energy savings with single vertical glazing and double horizontal glazing is lower with the 0.38 m cavity depth (8.5% in case 5) than it is with a cavity depth of 0.75 m (10.4% in case 4) or 1.5 m (11.4% in case 6). The net heat gains for the cavity space and, in turn, the amount of energy saved increased in direct proportion to the depth of the cavity. This meant that the solar heat gain grew faster than the space's thermal losses when the depth of the cavity, and thus the glazing area towards the sky, increased. However, the effect was different with low energy solar protection glazing ( $U=0.7 \text{ W/m}^2 \text{ K}$  and  $g=0.24$ ). Added glazing with 0.38 m cavity depth meant 13,444 kWh energy demand, 0.75 m cavity depth meant a 13,313 kWh energy demand, and the 1.5 m cavity depth meant a 13,400 kWh energy demand. So, the highest energy demand was with 0.38 m cavity depth and the lowest was with the 0.75 m cavity depth, which indicates that the optimum cavity depth with this type of façade glazing is between 0.38 m and 1.5 m, rather than at either of the extreme values.

**Table 3**  
Results of the energy saving studies calculated with heat recovery and heating coil (cases 1–16) and without (cases 17–23).

Case Number of glazed sides	Glazing structures, single vertical glazing $U=5.7 \text{ m}^2 \text{ K}$ and horizontal double glazing $U=2.6 \text{ m}^2 \text{ K}$	Glazing structures, argon-filled double glazing, $U=2.6 \text{ W/m}^2 \text{ K}$ , $g=0.73$	Glazing structures, argon-filled triple glazing (without low-E), $U=1.7 \text{ W/m}^2 \text{ K}$ , $g=0.63$	Glazing structures, argon-filled triple glazing (low-E), $U=0.7 \text{ W/m}^2 \text{ K}$ , $g=0.24$	Outdoor air passing through the cavity when space temperature $< 20 \text{ }^\circ\text{C}$	Yearly energy demand for zone and ventilation heating [kWh]	Energy saving [%]	Flat one mean air temperature, July [ $^\circ\text{C}$ ]	Flat one mean operative temperature, July [ $^\circ\text{C}$ ]	Annual cavity air temperature (South facade, top gable) [ $^\circ\text{C}$ ]	Annual temperature difference between cavity and outside (South facade, top gable) [ $^\circ\text{C}$ ]
1	0	-	-	-	-	16,384	-	25.8	25.7	-	-
2	1	x	-	-	-	15,466	5.6%	26.9	26.7	16.0	6.4
3	2	x	-	-	-	15,013	8.4%	27.0	26.8	15.7	6.1
4	3	x	-	-	-	14,672	10.4%	27.1	26.9	15.3	5.7
5	3 (****)	x	-	-	-	14,985	8.5%	26.5	26.3	14.8	5.2
6	3 (*****)	x	-	-	-	14,520	11.4%	27.7	27.6	15.3	5.7
7	3	x	-	-	x	14,686	10.4%	27.1	26.9	15.2	5.6
8	3	x	-	-	x (*****)	14,672	10.4%	27.1	26.9	15.2	5.6
9	3	-	-	-	-	13,367	18.4%	28.8	28.7	18.5	8.9
10	3	-	-	-	x	13,376	18.4%	28.8	28.7	18.4	8.8
11	3	-	-	-	x	13,313	18.7%	26.4	26.2	19.4	9.8
12	3 (****)	-	-	x	-	13,444	17.9%	25.8	25.6	18.8	9.2
13	3 (*****)	-	-	x	-	13,400	18.2%	26.9	26.7	19.5	9.9
14	3	-	-	x	x	13,429	18.0%	26.4	26.2	19.1	9.5
15	3	-	-	x	-	12,766	22.1%	29.6	29.5	21.0	11.4
16	3	-	-	x	x	12,728	22.3%	29.6	29.5	20.8	11.2
Calculation without heat recovery and heating coil											
17	0	-	-	-	-	20,558	-	25.5	25.4	-	-
18	3	x	-	-	-	18,709	9.0%	26.7	26.6	15.3	5.7
19	3	x	-	-	x	17,850	13.2%	26.8	26.6	15.2	5.6
20	3	-	-	-	-	17,310	15.8%	28.4	28.3	18.5	8.9
21	3	-	-	-	x	16,125	21.6%	28.4	28.3	18.4	8.8
22	3	-	-	-	x	16,642	19.1%	29.1	29.1	21.0	11.4
23	3	-	-	-	x	15,364	25.3%	29.1	29.1	20.8	11.2

(\*\*\*\*) Cavity depth halved.  
 (\*\*\*\*\*) Cavity depth doubled.  
 (\*\*\*\*\*x) Half of the inlet air comes through the cavity during heating periods.



#### 4.1.2.4. Ventilation air supply through the cavity

**4.1.2.4.1. First: heat recovery and heating coil in use.** The results showed that the air-supply intake from the cavity space was not always clearly beneficial from an energy point of view. For example, the difference between the energy demand in case 4 (14,672 kWh) and case 7 (14,686 kWh) was 14 kWh with three single-glazed facade. The difference is slightly smaller in the case with double glazing (9 kWh difference between cases 9 and 10) but higher with low energy solar protection glass (116 kWh between cases 11 and 14). It seems that the heat recovery efficiency of 82% was so high that there were only short periods during midwinter when the cavity space's "extra pre-heating capacity" was needed. In contrast, the clear triple-glazing with a somewhat higher g-value ( $g=0.63$ ) gave opposite results ( $-38$  kWh between cases 15 and 16), which meant increased energy savings. Because no clear pattern can be identified on how to operate the ventilation system in the most optimal way, it suggests a topic for further research. The results do, however, indicate that the combination of the U-value, the g-value and the ventilation solution should be carefully examined by simulations during the design stage.

**4.1.2.4.2. Second: heat recovery and heating coil out of use.** After the analysis with the heat recovery in operation, simulations (Cases 17–23) were made without the heat recovery and heating coil in use (Table 3). Case 17 represents the new starting point, in which added single-glazing (cases 18 and 19), double-glazing (cases 20 and 21) and triple-glazing (cases 22 and 23) were compared. Low energy solar protection glazing was excluded from the study because its results were so similar to those of the double glazing in previous calculations (of the Case 9 and 11 results).

The Case 17 simulation results showed that if the heat recovery and heating coil were shut down the energy demand was increased by 4171 kWh, from 16,384 kWh (Case 1) to 20,558 kWh (Case 17), which accounted for a 20% change in the building's energy demand. After that, it was possible to achieve a 3916 kWh decrease in energy use (from 20,558 kWh to 16,642 kWh) with added glazing on three façades of the building, and a further reduction of 1278 kWh in demand was achieved (from 16,642 kWh to 15,364 kWh) by passing the outdoor air through the cavity. The energy demand reduction with single ( $-859$  kWh), double ( $-1185$  kWh) and triple ( $-1278$  kWh) glazing clearly shows the benefit of letting the outdoor air pass through the cavity in a building with mechanical exhaust ventilation. The results also show that the benefit is greater, the larger the temperature difference between the cavity space and the outside air.

**4.1.2.4.3. Third: the effect of varying the air intake volumes of cavity air.** The results showed that with the current set points for the ventilation unit operation and with clear single-glazing, the supply through the cavity is not very beneficial with regard to the building's energy demand. In contrast to the expected energy saving, the energy demand actually increased slightly, in, as previous mentioned, for example, Cases 4 and 7 (14 kWh). However, such a difference in energy demand is so small that it is not possible to make more generalized conclusion of it. Secondly, the analysis showed that if 50% of the outdoor air is passed through the cavity when the temperature is below 20 °C, the impact on the supply air in the cavity was neutral (in Cases 4 and 8 the energy demand is the same). This shows that in order to optimize the use of the cavity in the case of heat recovery, a more detailed analysis with various air volumes and control set points would have to be conducted.

## 4.2. Cavity cooling studies

### 4.2.1. General

The results of the energy saving studies showed that the mean and operative temperatures risen indoors during July in the

majority of cases (Table 3). For example, the single glazing added to the buildings three façades (case 4) raised the monthly mean operative temperature 1.2 °C, double glazing (case 9) 3.0 °C, and triple clear glazing (case 15) 3.8 °C in relation to the case without added glazing (case 1). Furthermore, the Table 3 shows that if none of the cooling measures applied in the real building are used (case 7 which is case 24 in Table 4) an operative temperature of 26.9 °C in July (1.2 °C warmer than case 1) are produced. Different cavity cooling solutions established in the real building are therefore studied in detail together with other added sun-protection options in this section.

Cases 24–46 represent the options that can be implemented in the real building without additional construction (e.g. increased air change rate) or with only minor changes (increasing the number of openable windows). Cases 47–63 represent additional options that improve the indoor climatic conditions but are not installed in the real building, i.e. venetian blinds integrated to the inside or outside of the added glazing. As a whole, the efficiency of the cavity space cooling is studied with two openable windows, a mechanical exhaust ventilation system (FF2) and the ground duct system (TF1). The starting point of the study was the existing building with real window sizes and air flows, but then three times as high openable window areas and air change volumes (450 l/s) were examined. From the calculations, the mean temperature for July and the yearly maximum temperatures for the cavity spaces respectively for Flat 1, together with the mean operative temperature for July and the yearly maximum operative temperature for the flat are shown in Table 4. The cavity space air temperature shown is the temperature in the middle of the south façade's top gable.

Fig. 10 shows that the overall situation has changed after renovation (changes from Case 1). The minimum and mean temperatures of Cases 24–46 are somewhat higher and the maximum temperature is mostly higher (17/23) than in Case 1. Also the temperature fluctuation has increased somewhat. In Case 1, the temperature fluctuated mostly between 21 °C and 23 °C and the temperature largely remained between 21 °C and 24 °C in most of the cases between 24 and 46. The analysis also showed that the use of integrated blinds (cases 47–54 and cases 57–60) considerably decreased the indoor temperatures inside the flat. This is reflected in a significant change in both the maximum temperatures and the temperature fluctuation (the grey area is small). It is also shown that the minimum temperatures were lowered, but this is caused by the continuous use of blinds throughout the year. It would be possible to eliminate this effect by using suitably adjustable venetian blinds.

The excess heat in summer was also studied and expressed in terms of degree hours (Fig. 11). These were obtained by summing up the positive temperature difference between the calculated temperatures and a reference temperature of 23 °C during the hours of the year. The temperature limit of 23 °C was selected as the reference value as this most clearly illustrates the difference between the worst (Case 24) and the best (Case 54) cases. Fig. 11 clearly shows the cases, which slightly (e.g. Case 33) or dramatically improve the indoor thermal comfort in contrast to the situation before renovation (Case 1). Fig. 11 also show that the thermal comfort was worse in the actual solution in Malmö (Case 46) than in the pre-renovation situation (Case 1), i.e. if the air change rate of the ground duct system and/or cavity exhaust unit is not increased from the design values.

By using the graphs in Figs. 10 and 11 it is possible to rank the cooling solutions from the most to the least effective with maximum temperatures, even though the magnitude of the overheating problems cannot be evaluated without further analysis with degree hours. Fig. 10 also shows that the changes in the mean temperatures are so slight that they cannot be used as a basis for

**Table 4**  
Efficiency of the different cooling options.

Case	Outdoor air through the cavity when cavity < 20 °C	Cavity cooling solution			Added blinds		Cavity, mean air temperature (July) [°C]	Cavity, max. air temperature [°C]	Flat one, mean air temperature (July) [°C]	Flat one, max. air temperature [°C]	Flat one, mean operative temperature (July) [°C]	Flat one, max. operative temperature [°C]
		Window airing	Mechanical exhaust	Ground duct system	Internal	External						
Without added glazing (case 1)												
24	–	–	–	–	–	–	28.7	47.4	27.1	30.3	26.9	30.0
25	x	–	–	–	–	–	28.7	47.4	27.1	30.3	26.9	30.0
26	–	X	–	–	–	–	28.3	45.6	27.0	30.1	26.8	29.8
27	–	x (**)	–	–	–	–	27.8	44.9	26.8	29.8	26.7	29.5
28	x	X	–	–	–	–	28.3	45.7	27.0	30.1	26.8	29.8
29	–	–	x	–	–	–	27.6	45.1	26.6	29.7	26.4	29.4
30	–	–	x (*)	–	–	–	26.0	41.8	25.9	28.9	25.7	28.6
31	x	–	x	–	–	–	27.5	45.1	26.6	29.7	26.4	29.4
32	–	–	–	x	–	–	27.6	46.0	26.5	29.5	26.3	29.2
33	–	–	–	x (*)	–	–	24.9	40.1	25.7	28.5	25.5	28.2
34	x	–	–	x	–	–	27.5	45.9	26.4	29.5	26.3	29.2
35	–	X	x	–	–	–	27.3	44.0	26.6	29.6	26.4	29.3
36	–	x (**)	x (*)	–	–	–	25.8	41.4	26.0	28.9	25.8	28.6
37	x	X	x	–	–	–	27.3	44.0	26.5	29.6	26.4	29.3
38	–	–	x	x	–	–	26.6	43.3	26.3	29.4	26.2	29.1
39	–	–	x (*)	x (*)	–	–	24.5	38.4	25.8	28.6	25.6	28.3
40	x	–	x	x	–	–	26.6	43.3	26.3	29.4	26.1	29.1
41	–	X	–	x	–	–	27.1	43.8	26.4	29.4	26.2	29.1
42	–	x (**)	–	x (*)	–	–	24.7	38.7	25.7	28.6	25.5	28.3
43	x	X	–	x	–	–	27.1	43.8	26.4	29.4	26.2	29.1
44	–	X	x	x	–	–	26.4	42.3	26.3	29.2	26.1	28.9
45	–	x (**)	x (*)	x (*)	–	–	24.4	37.6	25.7	28.5	25.5	28.2
46	x	X	x	x	–	–	26.4	42.3	26.3	29.2	26.1	28.9
47	–	–	–	–	x	–	28.5	51.0	24.9	27.6	24.7	27.3
48	–	–	–	–	–	x	22.7	32.6	23.2	25.2	22.9	24.9
49	x	–	–	–	x	–	28.5	51.0	24.9	27.9	24.7	27.3
50	x	–	–	–	–	x	22.7	32.6	23.1	25.2	22.9	24.9
51	x	X	x	x	x	–	27.0	42.8	24.2	26.7	23.9	26.3
52	x	X	x	x	–	x	21.1	28.8	22.2	24.0	22.1	23.7
53	x	x (**)	x (*)	x (*)	x	–	24.1	36.2	23.4	25.5	23.5	25.6
54	x	x (**)	x (*)	x (*)	–	x	20.3	26.8	22.2	23.9	21.9	23.6
55	–	–	–	x (***)	–	–	27.4	45.8	26.4	29.5	26.2	29.1
56	x	X	x	x (***)	–	–	26.2	42.1	26.2	29.2	26.0	28.9
57	–	–	x (*)	–	–	x	21.8	30.3	22.9	24.8	22.6	24.5
58	–	–	x (*)	–	x	–	25.2	40.7	24.0	26.4	23.8	26.1
59	–	–	–	x (*)	–	x	20.9	28.1	22.7	24.5	22.4	24.2
60	–	–	–	x (*)	x	–	24.3	39.6	23.9	26.1	23.7	25.9
61	–	–	–	x	–	–	24.5	39.6	25.6	28.3	25.4	28.0
				(*****)								
62	x	X	x	x	–	–	24.3	38.5	25.6	28.4	25.4	28.1
				(*****)								
63	x	x (**)	x (*)	x (*)	–	–	24.3	37.6	25.7	28.5	25.5	28.2

(\*) Air change rate tripled.

(\*\*) Openable window area tripled.

(\*\*\*) ground duct depth changed from 0,5 m to 3 m.

(\*\*\*\*\*) ground duct depth changed from 0,5 m to 3 m and air change rate tripled.

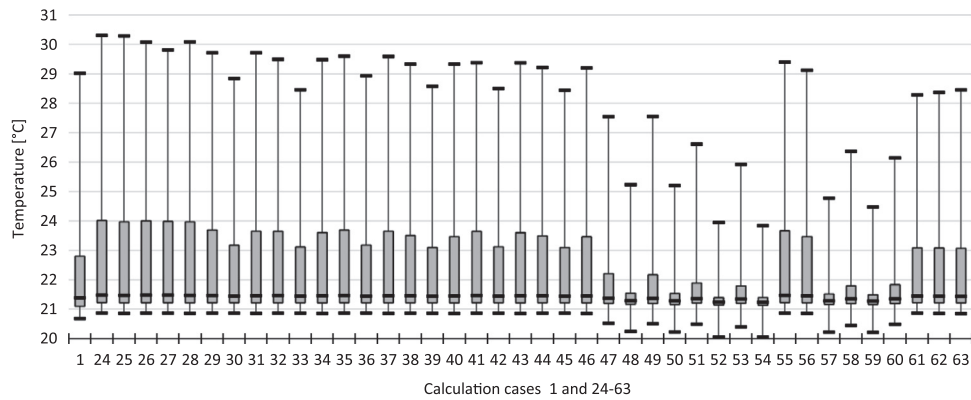
drawing any wider conclusions about the overheating problems. However, the boxplot graph (Fig. 10) and the degree hours graph (Fig. 11) give a clear illustration of the annual temperature behavior of Flat 1, and the duration of the excess temperatures (set-point 23 °C in Fig. 11), in that order. The temperature criterion of 23 °C in Fig. 11 is very tight, but at the same time it is still two degrees higher than the heating set point in Finnish building regulations [44].

#### 4.2.2. Comparison of the current cavity space cooling methods

The current cavity-cooling methods were: mechanical cooling with air supply through the ground duct system, mechanical cooling with mechanical exhaust unit, and opening the vents, i.e. the windows, at the top of the south cavity. Although studied separately, it should be mentioned that the ground duct system and the exhaust fan are intended to work together in the real building,

supplying the same amount of air to the cavity and extracting it from the cavity.

The results showed that the single most efficient cooling measure was the ground duct system, even though the ground duct was placed just 0.5 m below the ground level. The air temperature difference between this case (Case 32) and the case without ground duct cooling (Case 24) was 1.1 °C in the cavity and 0.6 °C in Flat 1. It was possible to achieve a similar mean temperature as in Case 32 (27.9 °C) with the mechanical exhaust unit (Case 29), but this system was not as efficient for the building as was the ground duct system, because the operative temperature difference between Cases 29 and 32 for Flat 1 was 0.1 °C. Compared to the ground duct system and the mechanical exhaust fan, the effect of the window airing with two 0.5–0.7 m<sup>2</sup> windows at the top of the south cavity was quite modest, although the wind pressure was included in the IDA-ICE calculation and the building



**Fig. 10.** Boxplot graphs from Cases 24–63. The horizontal lines represent the minimum, median and maximum values (from bottom to top) of the current cases and the grey areas represent the area hit by 50% of the values during the period.

was classified as being “semi exposed” for wind pressure. Nevertheless, the cavity space temperature dropped by only 0.4 °C, and the temperature in Flat 1 by 0.1 °C with the help of window airing (Case 26), compared to the situation without cooling (case 24).

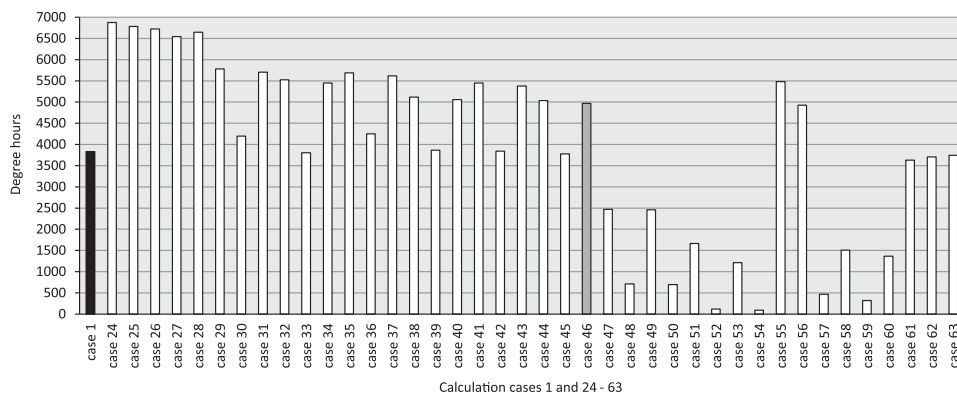
**4.2.2.1. Effect of increased window opening area and enhanced ventilation rates.** The effects of increasing the openable area of the two windows from 0.5 to 0.7 m<sup>2</sup> to 1.5–2.1 m<sup>2</sup> (Case 27), increasing the mechanical exhaust rate from 150 l/s to 450 l/s (Case 30), and increasing the mechanical air supply through the ground duct system ventilation from 150 l/s to 450 l/s (case 33) were slight (0.5 °C), good (1.6 °C) and excellent (2.7 °C), in that order. As seen in Table 4, the mean operative temperatures (Case 30) in Flat 1 were 25.7 °C (as in Case 1) and the number of degree hours was somewhat higher than in Case 1 when enhanced ventilation rate was used. It is worth noting that the mean air temperature level of the cavity space (26 °C) was very close to the temperature level of Flat 1 (difference 0.1 °C) in the current situation. The significance of the cavity temperature level becomes clearer after the simulation of the ground duct system case with enhanced ventilation rate (Case 33). The mean temperature of the cavity space changed from 27.6 °C (Case 32) to 24.9 °C (Case 33) after the ventilation rate was increased, which is 0.6 °C below the room temperature of the flat (25.5 °C) in the current case (case 33). As a result, the brick wall heat losses increased and the mean operative temperature in Flat 1 cooled down to below the baseline operative temperature (difference 0.2 °C) for the first time in this study. Case 33 is also the first case, in which the solution as a whole is better than Case 1 (Fig. 11) from the overheating point of view. The study reveals that the ventilation rates should be increased in the building if the intention is to improve the indoor climate situation.

**4.2.2.2. The effect of the use of combined cooling methods.** The most efficient combination of the above-mentioned cooling options was the ground duct system and mechanical exhaust ventilation with enhanced power of 450 l/s (Case 39). The cavity space temperature was 0.4 °C cooler and the temperature in Flat 1 was 0.1 °C warmer than using the ground duct system with enhanced ventilation rate alone (Case 33), i.e. the combination of mechanical exhaust and ground duct system slightly improved the situation inside the cavity. This confirms that it is possible to produce a similar or even better indoor climate for the flats than existed in Case 1 with the implemented solution, if the cavity supply and exhaust air volumes are tripled.

**4.2.2.3. Supply air solutions.** Table 4 showed that passing the outdoor air through the cavity during heating periods has no impact on mean or maximum air temperatures in the cavity, or on the indoor temperatures inside the building in the summer. This is due to the fact that the system is switched off when the temperature level of the cavity exceeds 20 °C and is started again when the temperature falls below 18 °C. With such set values, the system was off almost all the time during the hot summer days. When it was on, it cooled down the cavity space by 0.1 °C on average (Table 3) and 0.2 °C during the coolest time of year.

#### 4.2.3. Effects of alternative cooling solutions and changed depth of the ground duct

The analysis showed that the use of integrated blinds placed on the front or back of the glazing to cover the whole glazed façade (Cases 47–54 and Cases 57–60) considerably decreased the indoor temperatures inside the flat. Table 4 and Fig. 11 showed that both the internal (Case 47) and external (Case 48) blinds could achieve



**Fig. 11.** Calculated degree-hours graphs from cases 24–63. Degree-hour values are calculated simply by summing up the differences between the real hourly temperatures and the reference temperature from the moments the temperature is over the 23 °C reference temperature.

better indoor temperature conditions than Cases 24–46. This is due to the fact that the blinds shaded the building's external wall and windows very effectively. In particular, the external blind seemed to have a decisive effect on the flat temperatures. With the help of the blinds, the cavity space mean temperature was lowered to 22.7 °C (–6.0 °C) and the mean operative temperature in the flat to 22.9 °C (–2.8 °C), which is in contrast to the cavity temperature of Case 25, and the operative temperature of Flat 1 in Case 24, respectively. It is worth noting that with interior blinds (Case 47), the cavity space temperature drop is small in contrast to the case without cooling (Case 24), i.e. internal blinds helps the situation only slightly (–0.2 °C) in the cavity space, but clearly improve the mean operative temperature situation inside the building (–1.0 °C as compared to the case without glazing). This means that it is desirable to use external sun protection, especially if the cavity space is intended to be used as a living area, such as a terrace space, which would be possible with cavity depths over 1.5 m.

The cooling effect can be further improved by adding blinds to the current system, and further enhanced with increased ventilation rates, as was done in Cases 53–60. However, the further enhancement does not have anywhere near as much influence on the air temperatures in the flat as the blinds themselves if applied as always down. For example, with the external blinds alone (Case 48) it is possible to achieve a mean operative temperature inside the flat of 22.9 °C (2.8 °C lower than in Case 1). By combining that with all the other cooling methods like enhanced ventilation rate and increased openable window area (case 54) it is possible to achieve mean operative temperature inside the flat of 21.9 °C, i.e. 1.0 °C lower than in Case 48. Interestingly, with the external blinds it is possible to achieve cavity mean temperatures of 20.3 °C (Case 54), 20.9 °C (Case 59) or 21.8 °C (Case 57) and to the overall temperature level in the flat, where the degree hours are 94, 323 and 467 with a 23 °C reference temperature, respectively (Fig. 11). This is a comfortable living temperature. The effects of other external shading cases (Cases 48, 50 and 52) also stand out clearly on the graph (Fig. 11).

Increasing the depth of the duct from 0.5 m (case 32) to 3.0 m (case 55) decreased the cavity space temperature by 0.2 °C and the mean operative temperature in Flat 1 by 0.1 °C. By increasing the air volume passing through the deeper-set duct (case 61), the cavity temperature fell by another 2.9 °C, which clearly indicates that the air-change rate is a much more important factor than the depth of the duct in this situation. However, it is important to remember that the ground duct system was modeled as an underground group of rectangular zones in a row. The different volumes were connected to each other and there was a constant coupling to the ground temperature. Changes in the depth of the pipe were only taken into account in the U-value calculation of the ground layer between the pipe and the earth's surface (the bottom and vertical sections' U-values were constant). This rather simple model treated the pipe as a number of volumes and did not model the two- (or actually three-) dimensional problem of heat transfer in the ground. As a result of this, the model development of the ground duct system in IDA-ICE appears to be an ideal area for follow-up research on this topic.

#### 4.3. Error analysis

The aim of this study was not to duplicate the measured results exactly, but to verify that the simulation model gave realistic results. It is nevertheless important to have an idea of the level of accuracy in the results. The model itself is obviously a simplification of reality. The zone model that was used was the default model, which only has a simplified long-wave exchange model. The window models were detailed and took into account the

reflectance, absorption and transmittance of individual glass panes. The actual air flow in the cavity is almost impossible to calculate with complete accuracy, even using a computationally fluid model, since it is sensitive to minute variations in the boundary conditions, and since the gravitational and pressure forces are of similar size. It is therefore arguable that it is enough to have a mixed air volume model, as in this study.

## 5. Conclusions and the needs for further research

This study focused on energy saving through an analysis of the indoor climate of an existing brick-walled building using different design solutions. The starting point of the study was an actual apartment building in Malmö, Southern Sweden, in which the ventilation unit was renewed and three facades of the building had been glassed in. Permanently installed measuring devices measured the air temperatures at different locations in the building, such as inside the cavity space, the ventilation units and the ducts. The primary aim was to evaluate the performance of the ventilation system. The data retrieved from the measurements was then analyzed. The study included a site inspection and the calibration of the IDA-ICE software in order to make a comparative analysis of the many possible different design options. The purpose of the simulation was to evaluate the energy and indoor climate effect of the proposed solution and further improve its efficiency. The heating energy-saving studies included the amount of added glazing and its U-value, and also whether the air supply passed directly from outside to inside or went through the cavity space first. The efficiency of cavity-space cooling systems during summertime was studied with a ground duct system, mechanical exhaust ventilation and airing the cavity space with windows. Additionally, the effect of placing the ground ducts deeper in the ground, and the use of internal and external shading were also evaluated.

Based on the results, the following conclusions can be made. The added glazing reduces the heating energy demands of the building by between 5.6% and 25.3% depending on the design solution. The annual temperature increase between the cavity space and the outside temperature varies between 5.2 °C and 11.4 °C in the moderately cold climatic conditions of Malmö. The factors that can be identified as having a significant influence on the heating energy demands of a building lie in the area of added glazing, the U-value and g-value of the added glazing, and any combination of these factors. If there is no heat recovery like a mechanical exhaust ventilation system, it is best to pass the outdoor air through the cavity before supplying it to the building. When heat recovery with a high efficiency (like > 80%) is applied, the effect is not clear. The U-value and the g-value of the glazing seemed to influence the outcome. The results indicate that any combination of the U-value, the g-value and the ventilation solution should be carefully examined by simulations in the design stage.

It can also be concluded that the factors that have a significant influence on the thermal indoor climate during summertime in terms of cooling the indoors are, in order of importance, external and internal shading of the cavity, a ground duct system with a fan which cools the outdoor air before supplying it to the cavity, an exhaust fan extracting the air from the cavity and the amount of air flow in these systems.

The added glazing inhibited the building's ability to achieve sufficiently cool indoor temperatures, despite the fact that the cavity space was cooled with two openable windows, and there was mechanical exhaust ventilation and a ground duct system. By increasing the ventilation rate above the designed values, it was possible to achieve clearly better indoor temperature conditions

than with the current ventilation rates in the real building if low indoor temperatures are aimed for. For example, the ground duct system with enhanced air volumes (case 33) alone could have given enough cooling capacity to allow better temperature conditions inside the building than existed before the glazing was installed (Case 1). If the indoor climate conditions need to be cooled in the summertime, perhaps because of renovation work, then another possible solution would have been to add internal or external blinds to the glazing. This would have been possible in another building, but not in the building studied here because the building was listed as being of historical importance, and so no significant changes could be made to the façade. With internal blinds, the flat's indoor temperature is clearly reduced and external blinds reduce it even more than in the cases without added glazing. The impact could have been further increased if venetian blinds had been implemented together with the cavity space's mechanical cooling system.

The results appear to show that a satisfying level of thermal comfort can be achieved with the installed cooling solutions in the real building. A lower indoor temperature during summertime than before the renovation can be achieved if the air flow is increased above its current design value, which fact illustrates that simulations during the design phase can be very worthwhile. The application of several technical measures and ventilation strategies at the same time creates a complex situation which is difficult to predict in the design phase, i.e. which air flows and ventilation strategies will be the most efficient, etc.? The results of this study clearly illustrate how complex a process this is. They also support the view that it's an important part of the design stage of a building project to be able to model such a complexly-controlled building with dynamic software, in order to optimize the installed systems.

In summary, it can be said that the addition of glazing in front of the brick wall reduced the heating energy demand of the building. As the temperature in the cavity was higher than the outdoor temperature, this implies that the old brick wall will now be in a warmer environment during the winter, which will have associated benefits, such as reducing the risk of freeze-thaw damage. Although the extra glazing may cause problems indoors during the summertime in terms of keeping the place cool and well-aired, it is possible to solve this by increasing the air-change rates of the cavity exhaust unit and ground duct air-supply unit. It should also be noted that all the cooling solutions, which will be able to create sufficiently low indoor temperature in summertime, are to a great extent sustainable solutions i.e. shading. The ground duct and exhaust system are not totally passive systems as mechanical fans are needed. But no active cooling energy is needed to be supplied to the system as opposed to air-conditioning units.

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### References

- [1] J. Zhou, Y. Chen, A review on applying ventilated double-skin façade to buildings in hot-summer and cold-winter zone in China, *Renew. Sustain. Energy Rev.* 14 (4) (2010) 1321–1328.
- [2] M.M.S. Ahmed, A.K. Abel-Rahman, A.H.H. Ali, M. Suzuki, Double skin façade: the state of art on building energy efficiency, *J. Clean Energy Technol.* 4 (1) (2016) 84–89.
- [3] H. Poirazis, Double Skin Facades for Office Buildings: a Literature Review, A Report of IEA SHC Task 34 ECBCS Annex 43, Lund University Lund, 2006, pp. 247.
- [4] L. Xu, T. Ojima, Field experiments on natural energy utilization in a residential house with a double skin façade system, *Build. Environ.* 42 (2007) 2014–2023.
- [5] G.-Y. Cho, M.-S. Yeo, K.-W. Kim, Design parameters of double-skin façade for improving the performance of natural ventilation in high-rise residential buildings, *J. Asian Arch. Build. Eng.* 12 (1) (2013) 125–132.
- [6] G. Kim, L. Schaefer, J.T. Kim, Development of a double-skin façade for sustainable renovation of old residential buildings, *Indoor Built Environ.* 22 (1) (2013) 180–190.
- [7] G. Ballestini, M. De Carli, N. Masiero, G. Tombola, Possibilities and limitations of natural ventilation in restored industrial archaeology buildings with a double-skin façade in Mediterranean climates, *Build. Environ.* 40 (2005) 983–995.
- [8] B. Nordquist, S. Elfborg, A. Vrbnjac, P. Wallén, J. Stein, Energy saving by adding a glass-façade to a brick building, in: *Proceedings of the 3rd International Conference Central Europe towards Sustainable Building (CESB13)*, Prague, 26–28 June 2013.
- [9] W. Oesterle, E. Lieb, R.-D. Lutz, M. Heusler, Double Skin Facades-Integrated Planning, Prestel Verlag Munich, Germany, 2001.
- [10] A.L.S. Chan, T.T. Chow, K.F. Fong, Z. Lin, Investigation on energy performance of double skin façade in Hong Kong, *Energy Build.* 41 (11) (2009) 1135–1142.
- [11] W. Ding, Y. Hasemi, T. Yamada, Natural ventilation performance of a double-skin façade with a solar chimney, *Energy Build.* 37 (4) (2005) 411–418.
- [12] A. Fallahi, F. Haghighat, H. Elsadi, Energy performance assessment of double-skin façades with thermal mass, *Energy Build.* 42 (2010) 1499–1509.
- [13] L.R. Arons, D.M.M. Glicksman, Double skin, airflow facades: will the popular European model work in the USA? In: *Proceedings of the International Conference on Building Envelopes Systems and Technologies (ICBEST)*, 27–29 June 2001, pp. 203–207.
- [14] R. Hoseggen, B.J. Wachenfeldt, S.O. Hanssen, Building simulation as an assisting tool in decision making: case study: with or without a double-skin façade? *Energy Build.* 40 (2008) 821–827.
- [15] W.N. Hien, W. Liping, A.N. Chandra, A.R. Pandley, W. Xiaolin, Effect of double glazed façade on energy consumption, thermal comfort and condensation for a typical office building in Singapore, *Energy Build.* 37 (2005) 563–572.
- [16] W.J. Stec, A.H.C. van Paassen, Symbiosis of the double-skin façade with HVAC system, *Energy Build.* 37 (2004) 461–469.
- [17] D. Saelens, J. Carmeliet, H. Hens, Energy performance assessment of multiple skin facades, *Int. J. HVAC&R Res.* 9 (2) (2003) 167–186.
- [18] J.H. Yoon, E.J. Lee, J. Hensen, Integrated thermal analysis of a three story experimental building with a double-skin and a ground-coupled heat exchanger, in: *Proceedings of International Solar Energy Conference (SOLAR 97)*, 27–30 April 1997, pp. 7–13.
- [19] S.Y. Kim, K.D. Song, Determining photosensor conditions of a daylight dimming control system using different double-skin envelope configurations, *Indoor Built Environ.* 16 (5) (2007) 411–425.
- [20] P. Wong, Natural Ventilation in Double-skin Façade Design for Office Building in Hot and Humid Climate, University of New South Wales, Australia, 2008.
- [21] H. Poirazis, Single and Double Skin Glazed Office Buildings: Analyses of Energy Use and Indoor Climate, Report EBD-T-08/8 (PhD Thesis), Lund University, Lund, 2008, pp. 405.
- [22] W. Lou, M. Huang, M. Zhang, N. Lin, Experimental and zonal modeling for wind pressures on double-skin facades of a tall building, *Energy Build.* 54 (2012) 179–191.
- [23] C.A. Heusler, Multiple-skin facades, *Fassade Façade* 1 (1998) 15–21.
- [24] S.F. Larsen, L. Rengifo, C. Filippin, Double skin glazed facades in sunny Mediterranean climates, *Energy Build.* 102 (2015) 18–31.
- [25] S.F. Corgati, M. Perino, V. Serra, Experimental assessment of the performance of an active transparent façade during actual operation conditions, *Sol. Energy* 81 (2007) 933–1013.
- [26] N. Hashemi, R. Fayaz, M. Sarshar, Thermal behavior of a ventilated double skin façade in hot arid climate, *Energy Built* 42 (2010) 1823–1832.
- [27] T. Pasquay, Natural ventilation in high-rise buildings with double facades, saving or waste of energy, *Energy Build.* 36 (2004) 381–389.
- [28] E. Sikander, S. Ruud, A. Blomsterberg, Underground supply ducts in passive stack ventilated school, moisture and microbiological growth, in: *Proceedings of the 5th Symposium on Building Physics in the Nordic countries*, Göteborg, 24–26 August 1999, pp. 145–152.
- [29] M. Wall, Climate and Energy Use in Glazed Spaces, Report No. TABK-96/1009 (PhD thesis), Lund University, Lund, 1996, pp. 404.
- [30] K. Hilliaho, J. Lahdensivu, J. Vinha, Glazed space thermal simulation with IDA-ICE 4.6.1 software – suitability analysis with case study, *Energy Build.* 89 (2015) 132–141.
- [31] P.G. Loutzenhiser, H. Manz, S. Moosberger, G.M. Maxwell, An empirical validation of window solar gain models and the associated interactions, *Int. J. Therm. Sci.* 48 (1) (2009) 85–95.
- [32] ISO/FDIS 15099: 2003(E), Thermal Performances of Windows, Doors and Shading Devices—Detailed Calculations, 2003.
- [33] A. Bring, P. Sahlin, M. Vuolle, Models for Building Indoor Climate and Energy Simulation, A Report of Task 22, Building Energy Analysis Tools Version 1.02,

[1] J. Zhou, Y. Chen, A review on applying ventilated double-skin façade to buildings in hot-summer and cold-winter zone in China, *Renew. Sustain.*

- Royal Institute of Technology in Stockholm, 1999.
- [34] J. Traversi, G. Maxwell, C. Klaassen, M. Holtz, Empirical Validation of IOWA Energy Resource Station Building Energy Analysis Simulation Models, IEA Task 22, Subtask A, 2001.
- [35] S. Kropf, G. Zweifel, Validation of the Building Simulation Program IDA-ICE According to CEN 13791 'Thermal performance of buildings – Calculation of Internal Temperatures of a Room in Summer Without Mechanical Cooling – General Criteria and Validation Procedures', Luzern, 2001.
- [36] M. Achermann, G. Zweifel, RADTEST – Radiant Heating and Cooling Test Cases, Subtask C, A Report of IEA Task 22, Building Energy Analysis Tools, 2003.
- [37] F. Karlsson, P. Rohdin, M.-L. Persson, Measured and predicted energy demand of a low energy building: important aspects when using building energy simulation, *Build. Serv. Eng. Res. Technol.* 28 (3) (2007) 223–235.
- [38] S. Moosberger, IDA-ICE CIBSE-validation, Test of IDA Indoor Climate and Energy version 4.0 according to CIBSE TM33, issue 3, Report 2007, HTA, Luzern.
- [39] P. Loutzenhiser, H. Manz, G. Maxwell, Empirical Validations of Shading/Daylighting/Load Interactions in Building Energy Simulation Tools, A Report for the International Energy Agency's SHC Task 34/ ECBCS Annex 43 Project C, 2007.
- [40] Equa Simulation Technical Group, Validation of IDA Indoor Climate and Energy 4.0 build 4 with respect to ANSI/ASHRAE Standard 140-2004, Technical report, Solna, Sweden, 2010.
- [41] M. Achermann, Validation of IDA ICE version 2.11.06, HTA (Hochschule Technik + Architektur) Luzern, Switzerland, 2000.
- [42] S. Elfborg, A. Vrbanjac, Inglasad tegelfasad – en energianalys, Report No. TVIT-5037 (in Swedish), Div. of Building Services, Lund Institute of Technology, Lund University, Lund, 2012, pp. 151.
- [43] J. Andersson, A. Bränd, Glasklar tilläggsisolering – möjligheter med förvärmning av tilluft, Report No. TVIT-5048 (in Swedish), Div. of Building Services, Lund Institute of Technology, Lund University, Lund, 2014, pp. 84.
- [44] RakMK D3, Rakennusten energiatehokkuus: määräykset ja ohjeet 2012, Ympäristöministeriö, Helsinki, 2011, 27s + liitt. 8s.
- [45] Meteorological data, Swedish Meteorological and Hydrological Institute (SMHI), 2015. Available from: (<http://opendata-download-metobs.smhi.se/expire/>) (accessed 19.05.15).
- [46] C.A. Gueymard, A Simple Model of the Atmospheric Radiative Transfer on Sunshine, Version 2 (SMARTS2): Algorithms and Performance Assessment, Report FSEC-PF-270-95, Florida Solar Energy Center, Florida, 1995, pp. 78. Available from: ([http://rredc.nrel.gov/solar/models/smarts/relatedrefs/smarts2\\_report.pdf](http://rredc.nrel.gov/solar/models/smarts/relatedrefs/smarts2_report.pdf)).
- [47] T. Landelius, W. Josefsson, T. Persson, A System for Modelling Solar Radiation Parameters with Mesoscale Spatial Resolution, Report RMK No. 96, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, 2001, pp. 51. Available from: (<http://www.smhi.se/publikationer/a-system-for-modelling-solar-radiation-parameters-with-mesoscale-spatial-resolution-1.2369>).
- [48] STRÅNG – a Mesoscale Model for Solar Radiation, Swedish Meteorological and Hydrological Institute (SMHI), 2015. Available from: (<http://strang.smhi.se/>) (accessed 19.05.15).
- [49] D. Koblick, Vectorized Solar Azimuth and Elevation Estimation, 2009. Available from: (<http://www.mathworks.com/matlabcentral/fileexchange/23051-vectorized-solar-azimuth-and-elevation-estimation>).
- [50] K. Hilliaho, E. Mäkitalo, J. Lahdensivu, Energy saving potential of glazed space: sensitivity analysis, *Energy Build.* 99 (2015) 87–97.

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