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Sumee Park

Thermal Comfort, Energy Efficiency and User Behaviour in High-Rise Residential Buildings in Korea

FORSCHUNGSERGEBNISSE AUS DER BAUPHYSIK BAND 16

Herausgeber:
Prof. Dr.-Ing. Klaus Sedlbauer
Prof. Dr.-Ing. Gerd Hauser

Universität Stuttgart
Lehrstuhl für Bauphysik

Technische Universität München
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Kontaktadresse:
Fraunhofer-Institut für Bauphysik IBP
Nobelstraße 12
70569 Stuttgart
Telefon 0711 970-00
Telefax 0711 970-3395
E-Mail info@ibp.fraunhofer.de
URL www.ibp.fraunhofer.de

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Fraunhofer-Informationszentrum Raum und Bau IRB
Postfach 800469, 70504 Stuttgart
Nobelstraße 12, 70569 Stuttgart
Telefon 0711 970-2500
Telefax 0711 970-2508
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Abstract

Recently, the political and social interest in energy-efficient residential buildings in South Korea, as well as the required technical measures for such practice has grown rapidly. However, experience in the field of energy-efficient buildings in Germany has indicated that not all proven measures for energy efficiency have achieved the expected energy savings in practice. "Incorrect" user behaviour has been repeatedly mentioned as a cause of such failure. Sometimes certain measures caused a thermally uncomfortable indoor environment or even mould growth, which results in user complaints. Therefore, a holistic approach taking the indoor climate, energy efficiency and user behaviour into consideration becomes more and more important.

The objective of this thesis is to analyse the current situation of representative South Korean high-rise residential buildings and to offer recommendations based on the holistic, multi-faceted approach.

For this purpose, the indoor climate in 24 dwellings in four high-rise housing complexes in Seoul was measured for one-year duration and their energy consumption data was analysed. About 85 dwellings in these buildings were visited three times over the course of the data collection phase and the indoor climate was measured each time for a 20-minute interval. During the visit, the residents answered questions about their heating, ventilation and cooling behaviour, as well as their satisfaction with the indoor environment. The Blower Door measurement was carried out in 10 dwellings.

In addition to these field investigations, the energy-efficiency of each building was evaluated using national calculation methods and a building energy simulation tool. The effect of thermal bridges for a given dwelling was calculated and used as input data in the German calculation and building energy simulation. Although the measurement of CO_2 concentration and the information about CO_2 production may not be accurate enough for the determination of ventilation rate in the dwellings, they clearly showed the ventilation behaviour of individual users.

The hourly building energy simulation proves to be more useful for the investigation of indoor climate and energy consumption than the Korean calculation tool based on the annual heat balance, or the German assessment tool based on the monthly heat balance. The adjustment possibility of boundary conditions, such as the ventilation rate using the validation of measured indoor temperature and energy consumption in this study enables to recognize user ventilation behaviour.

The two established thermal comfort approaches, Fanger Model and Adaptive Model, are evaluated using the data from spot measurements and questionnaires in this study. However, both of the models could not adequately explain the thermal comfort of Korean residents in high-rise buildings. Therefore, the scientific interest in further statistical studies is to determine why the models did not work and which parameters are most influential on thermal comfort in this study. Afterwards, a new comfort model is developed using the most significant parameters and a logistic regression model.

According to the thermal comfort analysis, a neutral environment and a comfortable one are not identical, and the temperature has a dominant influence on thermal comfort in winter; while the temperature and absolute humidity similarly determine the perception of thermal comfort in the summer season. Koreans are comfortable in slightly cooler environment in winter. Nevertheless, some people heat their dwellings above 26 °C, although they are able to separately control the temperatures in each individual room. It is not a recommended practice from energy efficiency and thermal comfort points of view.

In summer, the indoor air temperature is on average 2K higher than outdoor temperature. In this situation, intensive ventilation would be a good measure for passive cooling, especially at night. However, this measure was not used. 35 % of residents complained about a warm environment, even though their apartments were equipped with air conditioning, but most people avoided to use it.

In winter, the dwellings are rarely ventilated using windows or a mechanical system. This user behaviour could be advantageous to energy conservation, however, it caused a high CO_2 concentration in the apartment and frequent mould growth in the glazed balcony area. The high air change between indoor and unheated balcony and an increased tightness of balcony windows to the outside environment aggravate not only the mould problem but also noticeably reduce energy efficiency in the future, due to an inadequate thermal envelope layer.

Such "incorrect" user behaviour was analysed in detail and the causes were investigated. Based on this analysis, different measures were suggested for practice in the form of decision trees, because the choice of the most appropriate measure in a particular project depends on the target energy efficiency and the cost of available technology on the market at that time. The decision trees introduce potential problems associated with a particular choice of measure and the appropriate remedial action.

This study shows that "incorrect" user behaviour can be physically explained and could be avoided. In practice, the success of an energy efficient measure strongly depends on the user, thus the user and the environment should be considered carefully prior to the implementation of a specific measure.
In the future, a thermal comfort field study should serve not only as a basis for

the definition of comfort areas but also for the identification of parameters determining user behaviour and the degree of resident satisfaction. Such parameters can be examined in detail from a controlled laboratory testing and can be systematically controlled in practice for high indoor climate quality and energy efficiency.

Zusammenfassung

In letzter Zeit hat das politische und gesellschaftliche Interesse an energieeffizienten Wohngebäuden in Korea rasant zugenommen und dementsprechend sind technische Maßnahmen für die Praxis gesucht. Aber die Erfahrungen in Deutschland zeigen, dass nicht alle Maßnahmen für energieeffizientes Bauen in der Praxis die vorhergesagte Energieeinsparung erzielen und nicht selten wird das falsche Nutzerverhalten als Ursache des Misserfolgs genannt. Zudem verursachten manche Maßnahmen ein thermisch unbehagliches Raumklima oder Schimmelpilze, welche wiederum Nutzerbeschwerden verursachten. Deshalb hat jüngst eine ganzheitliche Betrachtung des Raumklimas, der Nutzer, und der Energieeffizienz an Bedeutung gewonnen.

Das Ziel dieser Dissertation ist es, die Ist-Situation der Koreanischen Wohnhochhäuser zu analysieren und aus obengenannter ganzheitlicher Betrachtung praktische Empfehlungen für ein energieeffizientes und komfortables Wohnhochhaus in Korea abzugeben.

Für das Ziel wurde das Raumklima in 24 Wohnungen in vier Wohnhochhaussiedlungen in Seoul für ein Jahr gemessen und die Energieverbrauchdaten analysiert. Dazu wurden etwa 85 Wohnungen in den Siedlungen dreimal im Jahr besucht und das Raumklima für 20 Minuten untersucht, während die Einwohner nach ihrem Heizungs-, Lüftungs- und Kühlungsverhalten, sowie der Zufriedenheit mit dem Raumklima befragt wurden. In 10 Wohnungen wurden im Winter Blower-Door-Messungen durchgeführt.

Neben diesen Felduntersuchungen wurde die energetische Qualität des Gebäudes anhand der Gebäudesimulation und nationalen Berechungsmethoden bewertet. Die Auswirkung von Wärmebrücken wurde berechnet und die Ergebnisse werden als Eingabedaten für die DIN V18599 Berechnung, sowie für die Gebäudesimulation verwendet. Obwohl die CO_2-Messung und die Information über die CO_2-Produktion in dieser Untersuchung nicht die Genauigkeit für eine Bestimmung der Luftwechselzahl einzelner Wohnungen besitzen, zeigte die Messung das individuelle Lüftungsverhalten deutlich.

Bei der Bewertung der Energieeffizienz zeigte die Gebäudesimulation mehr Möglichkeiten für die Untersuchung des Raumklimas und der Energieeffizienz als das auf einer Jahresbilanz basierende koreanische Bewertungstool, oder das auf Monatsbilanzen basierende deutsche nationale Bewertungstool. Die Anpassungsmöglichkeit der Randbedingungen, z.B. Luftwechselrate, anhand einer Validierung mit dem gemessenen Raumklima und der Energieverbrauchsdaten aus dieser Untersuchung, ermöglichten das Lüftungsverhalten von Nutzern zu erkennen.

Anhand von Spot Messungen und Fragebögen wurden zuerst vorhandene Ansätze für die Bewertung der thermischen Behaglichkeit - Fanger Modell und Adaptives Modell- evaluiert. Dabei zeigte sich, dass diese beiden Ansätze in diesem Fall keine adäquaten Vorhersagen lieferten. In weiteren statistischen Untersuchungen lag das wissenschaftliche Interesse darin, herauszufinden warum die Modelle in koreanischen Wohnhochhäusern nicht funktionierten und welche Parameter den thermischen Komfort beeinflussen. Danach wurde mit diesen Einflussparametern ein neues Komfortmodell für koreanische Wohnhäuser entwickelt.

Nach dieser thermischen Komfort Analyse sind die neutralen und komfortablen Umgebungen nicht identisch und im Winter beeinflusst die Temperatur die thermische Behaglichkeit dominant, während im Sommer die Temperatur und die absolute Feuchte der Umgebung in gleichem Maße die Komfortbewertung beeinflussen. Die Koreaner fühlen sich im Winter in etwas kühlerer Umgebung wohl. Trotzdem heizen manche Einwohner über 26 °C, obwohl sie selbst die Temperatur in jedem Raum separat regeln können, was energetisch und raumklimatisch nicht empfehlenswert ist.

Im Sommer ist die Innenraum Lufttemperatur durchschnittlich 2K höher als die Außentemperatur. In solch einer Situation wäre eine intensive Lüftung, besonders in der Nacht, eine gute Maßnahme für passive Kühlung, die aber nicht genutzt wird. 35 % der Einwohner beschweren sich im Sommer über das warme Raumklima, aber die meisten Einwohner verzichten auf die Nutzung einer Klimaanlage, obwohl sie eine besitzen.

Im Winter sind die Wohnungen selten gezielt gelüftet, was energetisch vorteilhaft sein kann, aber zu höherer CO_2 Konzentration in der Wohnung und zu Schimmelproblemen im verglasten Balkonbereich führt. Der hohe Luftaustausch zwischen Wohnung und Balkon und immer dichter werdende Balkonfenster nach außen, verschärfen nicht nur das Schimmelproblem sondern reduzieren auch die Energieeffizienz, wegen der unklar definierten thermischen Trennschicht.

Solch ein raumklimatisch und energetisch "falsches" Nutzerverhalten wurde in dieser Untersuchung näher analysiert und die Gründe dafür erforscht.

Basierend auf diesen Analysen wurden nicht bestimmte Maßnahmen vorgestellt, sondern verschiedene Entscheidungsbäume erstellt. Das dient künftig dazu, die am besten geeignete Maßnahme im jeweiligen Projekt, in Abhängigkeit von den Sparzielen und den Kosten der auf dem Markt verfügbaren Technik, zu wählen. Die Entscheidungsbäume zeigen die möglichen Probleme bei der Wahl einer bestimmten energieeffizienten Maßnahme, sowie die entsprechenden Gegenmaßnahmen zur Vorbeugung weiterer Probleme.

Diese Untersuchung zeigt, dass das "falsche" Nutzerverhalten physikalisch erklärt und vermieden werden kann. Da der Erfolg einer energieeffizienten Maßnahme in der Praxis stark vom Nutzer abhängt, sollten die Nutzer und die Umgebung vor dem Einsatz einer bestimmten Maßnahme genau betrachtet werden.

In Zukunft sollte eine Felduntersuchung über thermischen Komfort eine Grundlage nicht nur für die Definition des Komfortbereichs, sondern auch für die Identifizierung von Parameter schaffen, die ein bestimmtes Nutzerverhalten und die Nutzerzufriedenheit beeinflussen. Solche ursächlichen Faktoren können mittels Laboruntersuchung genau analysiert und später in der Praxis für ein besseres Raumklima oder eine erhöhte Energieeffizienz gezielt gesteuert werden.

Contents

1. Introduction

1.1 Objectives

As a result of the rapid urbanisation since the 1970s, a high-rise residential building is now a popular residential building type in South Korea. The number of floors always has been constantly increasing from the typical 15 floors in the 1990s to more than 30 floors in the 2000s. More than half of the Koreans presently live in such high-rise buildings. The building sector is responsible for approximately 25 % of total energy consumption in Korea and half of the energy is consumed in residential buildings. Therefore, the national and political interest on energy efficiency of such high-rise residential buildings is enormous, as evidenced in the recently tightened Korean regulations. At the same time, the desire of residents for comfortable indoor environment grows stronger with the improved prosperity in Korea. On the other side, a space in a metropolitan city like Seoul is so prohibitively expensive that more and more residents had to abandon an old standard of Korean high-rise residential buildings: a full glazed and unheated balcony. This balcony in the past had worked as a buffer-zone. It increases the thermal insulation in winter in a closed situation and works as horizontal solar protection in summer in an opened situation. In addition, it could provide a high air exchange rate in summer due to its protective function against any driving rain. Until now, the compactness of a high-rise building and this glazed balcony have allowed a low thermal performance and a low tightness of a building envelope of Korean high-rise residential buildings. However, residents in the recent years prefer a larger living area rather than an unheated balcony as a buffer-zone. As a result, the building envelopes now face the outdoor climate directly. This new situation, the increased interest in the energy efficiency and simultaneously the residents' desire for a higher IEQ (Indoor Environment Quality) create a demand for a new concept in residential buildings.

This thesis study aims to assess thermal comfort and energy efficiency of existing high-rise residential buildings in Korea and to develop practical alternatives for the maximal thermal comfort and minimal energy consumption with the consideration of user behaviour.

Many studies concerning energy efficiency or thermal comfort have been carried out in Germany as well as in Korea. The difference between the two countries regarding energy efficiency research is that the Korean studies are rarely based on field measurements, whereas the German studies generally include field measurements for the evaluation of studies. The fundamental researches for the determination of boundary conditions (for example, indoor temperature, or energy loss due to thermal bridges) could scarcely be found in Korea in comparison to Germany, where such example parameters are discussed and evaluated in great detail. However, in both countries, few studies consider the relationship between thermal comfort, energy efficiency and user behaviour. A proposed alternative, even if it promises to improve the energy efficiency of a given building tremendously, cannot achieve the theoretical gain in practice without the acceptance or sustainable support of the users. In addition, it could cause a thermal discomfort or even structural damage if subjected to "incorrect" user behaviour.

Therefore, the results of measurement studies performed in this thesis could lead to fundamental discussion of energy efficiency assessment in Korea and the comprehensive approach in this study could shed light on the relationship of these three factors - energy, comfort and user behaviour.

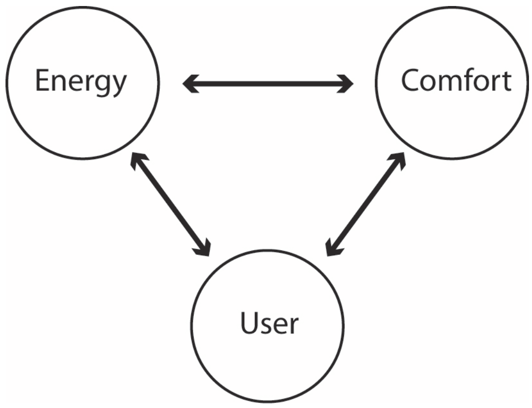


Figure 1:
Relation between Energy Efficiency, Thermal Comfort and User Behaviour

The scientific focuses of this thesis for the achievement of objectives are the following:

- Understanding the relationship between user behaviour, thermal comfort and energy efficiency.
- Providing accurate boundary conditions by means of measurements and calculations for the assessment of energy efficiency.
- Comparison and evaluation of existing methodologies for the assessment of energy efficiency and thermal comfort.
- Determination of comfort criteria for Korean residential buildings.

1.2 Procedure

At first the state of the art about assessment methodologies and actual technologies is identified. Then the existing indoor climate, dissatisfaction factors of indoor climate as well as user behaviour are analysed. For this step, a long-term monitoring of the indoor climate in 24 dwellings was carried out for one year. In addition, questionnaires with spot measurement were conducted in 85 dwellings for three times.

The result of measurements and questionnaires are used not only for the analysis of the indoor climate quality and user behaviour but also for the determination of boundary conditions in energy efficiency analysis. In the following phase, the energy efficiency and thermal comfort of existing buildings are assessed by the use of existing international or national methodologies. The results of assessments are compared and evaluated using the measurements and questionnaires in this study.

The comfort ranges for Korean high-rise residential buildings are determined by means of a statistical model. In addition, requirements for the improvement of indoor environment and energy efficiency are determined with regard to the new comfort range and the real occupant behaviour.

Finally, the possible different practical alternatives are shown as decision trees for high thermal comfort, energy efficiency regarding the user behaviour and existing technologies. The procedure in this thesis can be found in Figure 2.

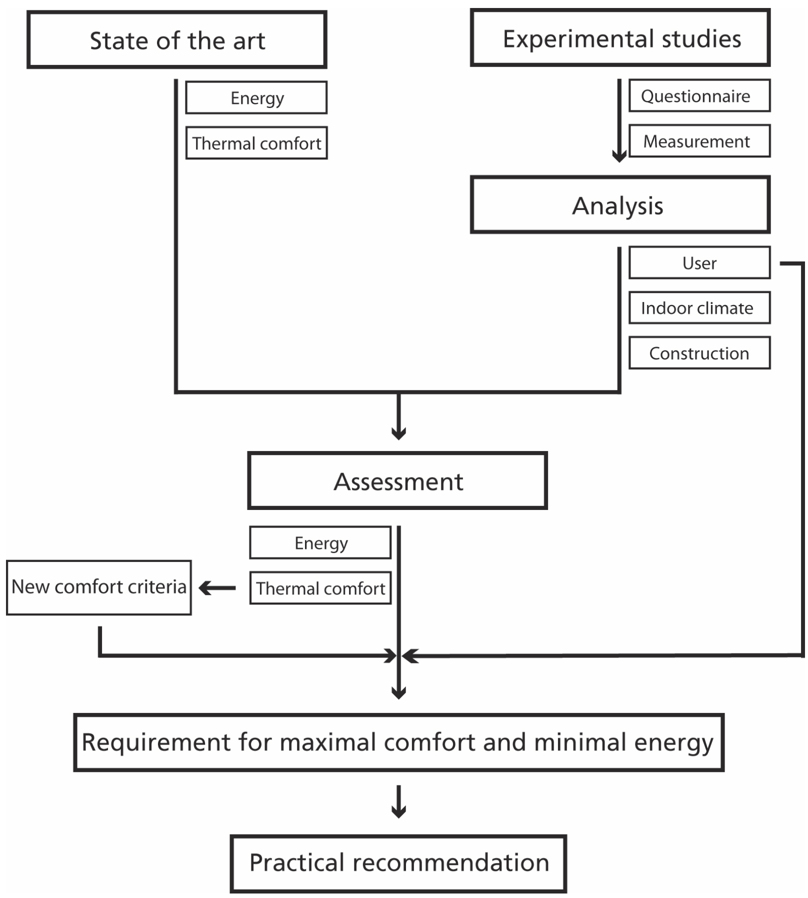


Figure 2:
Procedure in this Thesis

2. State of the Art

In this Chapter, the analyses of international and national standards and regulations concerning energy and thermal comfort in Germany, USA and Korea are carried out. Due to the different political and organizational handling of standards and regulations in these countries and the methodological complexity, a comprehensive comparison of standards and regulations was almost impossible. However, an overview of the existing standards may show a future trend of regulations and standards in spite of neglecting the details. Afterwards, the innovative technologies and the current researches in the field of energy efficient buildings and thermal comfort will be introduced.

2.1 Review of Standards: Energy

2.1.1 International Directive

Kyoto Protocol

In order to stabilize and reduce the greenhouse gas concentrations in the atmosphere, industrialized countries agreed to reduce their collective greenhouse gas (GHG) emissions by 5.2 % from the level in 1990 by 2008 and 2012. Under this committed treaty to the United Nations Framework Convention on Climate Change, commonly referred to as the Kyoto Protocol, national limitations vary from the reduction of 8 % for the European Union to increases of 8 % for Australia. Germany committed itself to reducing emissions by 21 %. In 2008, the EU achieved a reduction of approximately 6.2 %, whereas Germany succeeded in reducing 19 % [1] [2]. As of now, the United States (USA) has not ratified the Protocol. South Korea (Korea) ratified the Protocol in 2002, but it does not have any binding targets to reduce greenhouse gas emissions. Experts suppose that this will change in the second commitment period (after 2012) of the Kyoto Protocol. Korea will not be categorized at a “developing country” if it continues to be the world’s ninth largest emitter of CO_2, based on 2006 fossil-fuel consumption [2].

The trends of carbon dioxide emissions of Germany and Korea since 1950 can be found in Figure 3. Since 2004 the per capita carbon dioxide emission of Korea exceeded the Germans' emission rate.

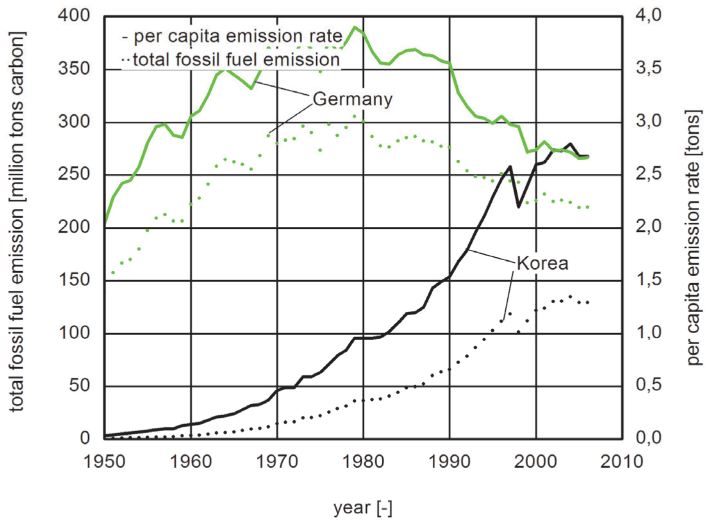


Figure 3:
CO_2 emissions of Germany and Korea since 1950 (according to the information of Oak Ridge National Laboratory [1])

Energy Performance of Buildings Directive [EPBD 2002]

In this global political framework, the "Directive on the energy performance of buildings of the European Parliament and of the Council"(EPBD) came into force on the European level in 2003. EPBD requires that the EU Member States implement the following four main measures until January 2006 [3]:

a) A common framework for the methodology of calculation of the integrated energy performances in buildings.
b) The application of minimum requirements for new buildings and for major renovations of large buildings. The minimum standards for buildings are calculated based on the above-mentioned methodology. The Member States are responsible for setting the minimum standards.
c) Mandatory energy certificate of buildings, carried out by recognised experts
d) Mandatory inspections of boilers and air-conditioners, carried out by accredited inspectors

Now some Member States of the EU including Germany already implemented these requirements in national regulations and some states are expected to do this in due time [4] [5].

2.1.2 National Regulation

Germany: Energy Saving Regulation (EnEV 2009)

Germany has a relatively clear structure of building energy performance regulations. The EU directive (EPBD), which is implemented in a national regulation as edict, determines the minimum performance, defines a certificate, and indicates the calculation methodology of standards, which contains detailed technical information.

- Minimum energy performance requirement

Germany started with requirements referring to the insulation of building elements, extended them to the net heating energy demand and delivered energy, at last to the primary energy demand (Figure 4). In the recent "Energy Saving Regulation 2009 (EnEV 2009: Energieeinsparverordnung: 2009)" minimum primary energy demand was 30 percentage lower than in the EnEV 2007 [5]. Another 12.5 % improvement is already planned for the next EnEV 2012. The minimum requirement of EnEV 2009 (reference building) can be found in Figure 6. Since the whole performance is compared between a certified building and reference building, performances of single measures may be below than the reference building, if other measures are better than the reference building. However, minimum requirement for the insulation of whole building envelop is determined in the regulation. In addition, there is another requirement based on DIN 4108-2 that determines the maximum solar gains of buildings in order to avoid overheating in summer [6].

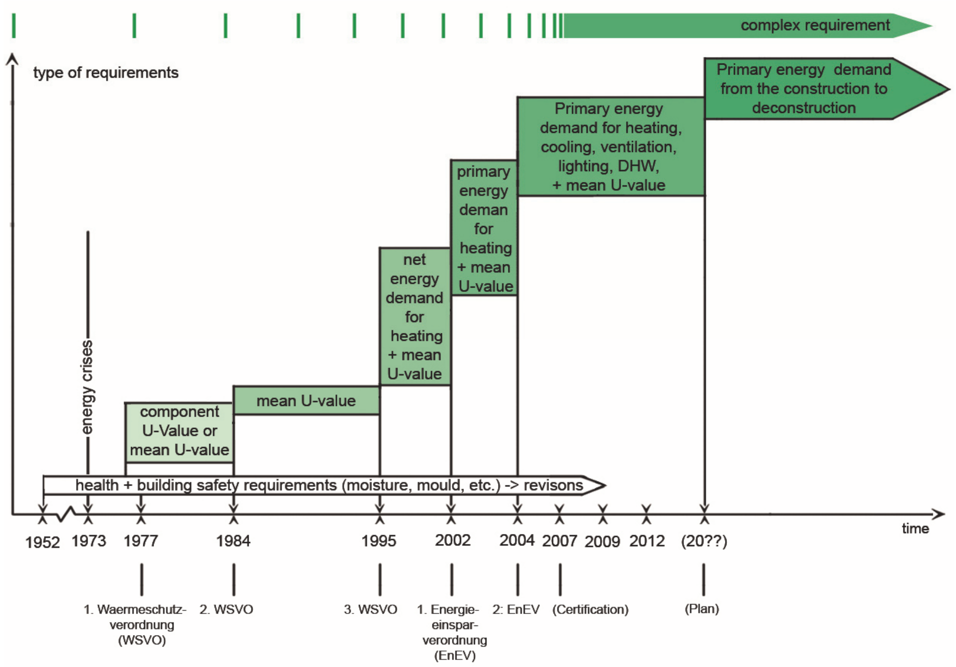


Figure 4:
Development of National Regulations for Energy Efficient Buildings in Germany (Modified from [8] and [9])

- Calculation methodology: DIN V 18599

The primary energy demand including heating, cooling, lighting, hot water and system energy is to be calculated according to the standard DIN V 18599 [7] and should be lower than that of the reference building defined in the EnEV 2009. For the residential building, also the DIN V 4108-6 in combination with DIN 4701-10 can be applied for the calculation [10][11]. Indoor environment parameters, occupancy times, as well as climate data for calculation are defined in DIN V 18599-10.

- Certificates: Energy Passport

The calculated primary energy demand must be issued in an "Energy Passport" for all new buildings. For existing residential buildings with an application before 1977 and with less than five dwellings, it can be issued based on energy consumption. An "Energy Passport" gives information on primary energy demand and CO_2 emission per square meter compared to reference buildings and the mean U-value of building envelopes as well as the heating energy demand. When buildings are constructed, sold, or rented, an energy certificate is made available to the owner, buyer, or tenant [5].

USA: Energy Codes

In contrast to Germany, the USA has a liberated building energy regulation system. There is first the "Energy Police Act"[12], which determines federal model codes. These model codes, in fact technical standards are implemented specific to local law in the federal states. However, the calculation methodology in the regulations does not serve for an energy certificate. The established energy certificate (Energy Star) is a separate system of the energy performance regulation (energy codes) and not mandatory.

- Minimum energy performance requirement
- Calculation methodology

Energy codes in the USA vary from state to state. Most state codes are modified versions of the national "model code" to reflect regional needs and practice. The last federal Energy Policy Act of 2005 specified as "Model Code" the International Energy Conservation Code 2004 (IECC 2004) for residential buildings and ASHRAE Standard 90.1–2004 (ASHRAE 90.1 2004) for commercial buildings [13][14].

The code of IECC 2004 for residential buildings defines only the performance of residential buildings with three stories or less in height. Therefore, the high-rise residential buildings should comply with the commercial energy code. The ASHRAE Standards determine the calculation methodology as well as the minimum requirements.

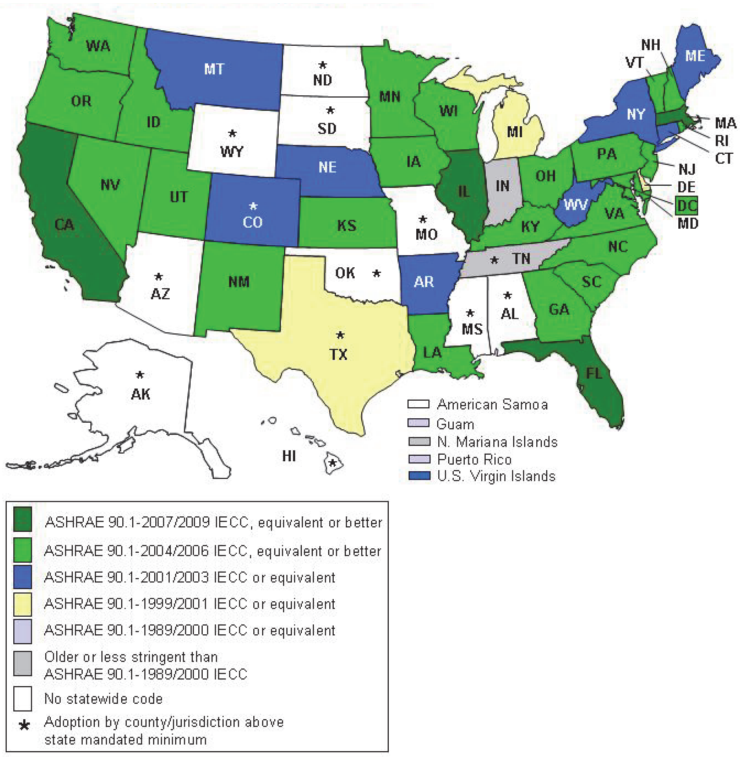


Figure 5:
Status of Commercial Energy Codes in the USA (Year 2009) from [13]

While a few states have no minimum requirements, some states like California and Florida have strong energy performance requirements (see Figure 5). Because these states already transcribed actual ASHRAE 90.1 2007 as state code, the minimum requirements of the new ASHRAE 90.1are compared with other regulations in Figure 6. For more information about the calculation methodology, ASHRAE 90.1.2007 [21], see Chapter 2.1.3.

- Energy performance certificates: Energy Star

As voluntary certification, "Energy Star" is backed by the U.S. Environmental Protection Agency (EPA) and more widely used for office equipment or home electronics than for buildings in USA.

Residential buildings including multi-family houses with three-stories or less can qualify for the Energy Star, if they are at least 15 % more energy efficient than homes built according to the 2004 International Residential Code (IRC), which is similar to the IECC Code, and includes additional energy-saving features that typically make them 20–30 % more efficient than standard homes.

For commercial buildings, energy consumption is compared to that of the peer group of similar buildings in the national population. For the certification, it must score in the top 25 per cent. This rating system accounts for different operating conditions and regional weather data. This peer group is identified through the survey (CBECS) by the government. Only 13 types of facilities are eligible in 2009 for the Energy Star. For example, high-rise residential buildings with more than five stories cannot qualify until as of now. Furthermore, the Energy Star certificates give no detailed information on building energy performance, but pass or fail. Due to the certification based on measured energy consumption a new commercial building cannot be qualified [14]. In June 2009, ASHRAE provides a new energy performance certificate "Building Energy Quotient" based on energy demand or energy consumption, which is very similar to the EU certificate recommendations in EN 15217 [15] [16].

Another established building rating system is LEED from U.S. Green Building Council (USGBC) that takes a broader approach than the energy performance of a building. LEED for New Construction (NC) Version 2.2 requires that buildings shall be designed to comply with ASHRAE 90.1-2004 or comparable local codes [17].

All three certificates in USA are voluntary.

Korea: Building Energy Saving Plan Standard 2008 (BESPS 2008)

- Minimum Energy Performance Requirement

Korean regulation for building energy efficiency "(BESPS 2008), 건축물의 에너지 절약설계 기준, 국토해양부 고시 제 2008-652)" determines the prescriptive design requirement of components in three parts: architectural, mechanical and electrical. These parts contain mandatory and encouraged requirements. As mandatory requirements, the insulation of building elements is pre-defined depending on climate regions in Korea. If a high-energy consumption is expected, a building, , e.g. a residential buildings with over 50 households, must offer a "Building Energy Conservation Plan", in which all requirements in BESPS 2008 are fulfilled as points depending on Pass / Fail [18].

- Calculation Methodology

As of now, BESPS 2008 has not offered or even suggested any standard as a calculation methodology for a building energy performance. In another regulation for the energy performance certificate, "Building Energy Efficiency Rating Operating Regulation 2007" [20] the net energy demand for heating is to be calculated based on the "seasonal method" with defined annual heating days.

- Energy Performance Certificates: E

Building Energy Efficiency Rating Regulation 2008 (2008 /14)
Building Energy Efficiency Rating Operating Regulation 2007 (2007)

Just like the U.S. certificate "Energy Star", the Korean energy certificate "E" can be assessed as a voluntary certification system. As of 2009, high-rise residential buildings are eligible for "E" (From 2010, commercial buildings can be also certificated). A comparison between the calculated annual heating energy demand and the corresponding demand of the reference building revealed the downgrading of the applied building from the first to the third plan.

This reference building has a required minimum U-value from BESPS 2008, a defined ventilation rate (0.7 ACH), heat gain, and room temperature (20 °C). After the completion of an applied building, experts inspect the building and then calculate the heating energy demand once again. According to this result, the final certificate is issued. For buildings built by public affairs, this certificate is mandatory. Otherwise, it is voluntary for all the others [19] [20] .

It is difficult to compare the minimum energy performance requirements between Germany, Korea, and the USA. In Germany, the minimum requirements for building envelopes can be changed according to the building system and energy generation. For example, if a renewable energy source or very efficient building technology is used, a building envelope with a U-value worse than presented in Figure 4 is permitted, if the mean U-value is better than 0.65 $W/(m^2 \cdot K)$ [5]. In the USA, the minimum single U-value can also be changed, if the "trade-off" method despite the "prescriptive method" is chosen for compliance with ASHRAE 90.1 [21]. The minimum energy performance requirements or rather reference buildings in Germany, the USA, and Korea can be found in Figure 6.

The abstracts of national regulations and certificates can be found in Table 1.

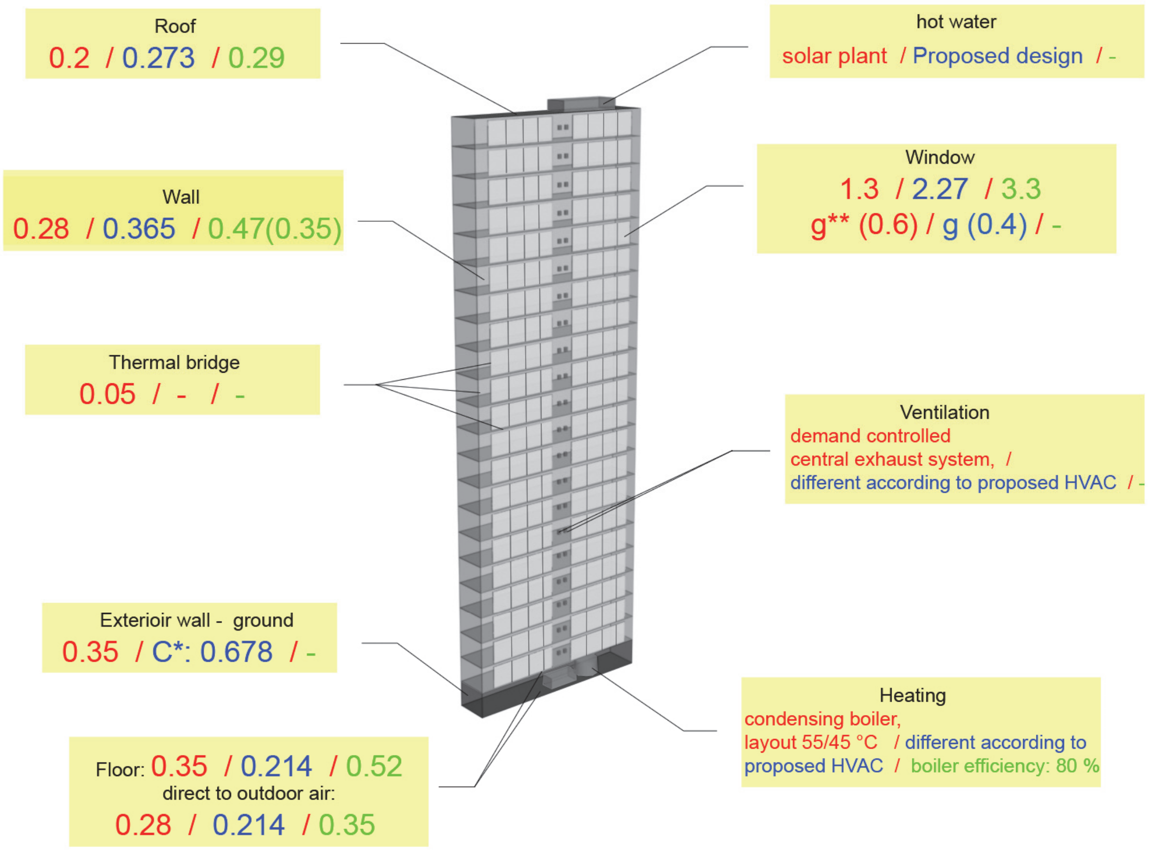


Figure 6:
Reference Building or Minimum energy performance requirement in Germany (EnEV 2009), the USA (ASHRAE 90.1.2007, Climate Zone 4), and Seoul in Korea (BESPS 2008). (Red: Germany, Blue: USA, Green: Korea; C*: thermal conductance (W/m²K), g**: Total Solar Energy Transmission = SHGC, otherwise: U-value (m²·K))

Table 1:
Comparison of Building Energy Performance Regulations (Year: 2009)

	Germany	USA	Korea
Regulation	Energy Saving Regulation 2009 (EnEV 2009)	Different state specific codes. Federal Model Code: For commercial (also for high-rise residential building): ASHRAE 90.1 For residential buildings: IECC	Building Energy Saving Plan Standard 2008 (BE-SPS 2008) Building Energy Efficiency Rating Operating Regulation (BEERO 2007)
Calculation Methodology	Residential building: DIN V 18599 or DIN 4108-6 with DIN 4701-10 Non-residential building: DIN V 18599	Contained in Model Code: ASHRAE 90.1 IECC	No calculation methodology for minimum energy performance requirement. Seasonal balance method for energy performance certificates (BEERO 2007)
Minimum Energy Performance Requirements	Reference building energy performance.	Different requirements depending on local codes. According to ASHRAE 90.1: Components performance or Reference building energy performance: Voluntary.	Components performance.
	Primary Energy U-value of whole building	Prescriptive requirement for components or annual energy cost.	Prescriptive requirement for components.
Energy Performance Certificates	Energy Passport	Energy Star	E
	Mandatory	Voluntary	Voluntary
	Mainly based on calculated primary energy demand.	Mainly based on delivered energy consumption. For new residential buildings: based on calculated energy demand.	Only based on calculated heat energy demand.

2.1.3 Standards: Building Energy Performance

There are international and national standards from the following organizations;

ISO: ISO (International Organization for Standardization)

EN: CEN (European Committee for Standardization)

DIN: DIN (Deutsches Institut für Normung: German Institute for Standardization)

ASHRAE: ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers)

KS: KSA (Korean Standard Association)

International Standards (ISO and CEN)

A comprehensive overview of international standards (ISO and CEN) concerning building energy performance is offered by prCEN/TR 15615:2006, "Explanation of the General Relationship between Various CEN Standards and the Energy Performance of Buildings Directive (EPBD)". This document can be summarized as follows [22]:

Building energy performance can be evaluated based on three different levels:

a) Evaluation of the building energy demand for heating and cooling
b) Evaluation of the delivered energy for heating and cooling, ventilation, domestic hot water and lighting
c) Evaluation of the overall energy performance indicators (primary energy, CO_2 emissions, etc.).

The existing standards offer methodologies for the different approaches. Until 2009, ISO only offered the first calculation approach using ISO 13790: 2008, which (also EN Standard) allows a calculation methodology for the heating and cooling energy demand of different levels of complexity as a) simplified monthly or seasonal calculation; b) simplified hourly calculation; c) detailed calculation. The simplified calculation methods are completely specified in EN ISO 13790 and two further calculations are based on specified boundary conditions of indoor climate (EN 15251) [23] and external climate.

EN standards offer second and third approaches not in one singular standard but in several standards. The delivered energy (second approach) for space heating and cooling, energy requirements for ventilation, domestic hot water, and lighting are calculated separately and are contained in the following standards:

1. Space heating – EN 15316-1, parts of EN 15316-4 (depending on the type of heating system) including losses and control aspects and EN 15377 for embedded systems. The input to calculation is the result from EN ISO 13790.
2. Space cooling – EN 15243, including losses and control aspects, and energy for humidification and dehumidification if applicable. The input to calculation is the result from EN ISO 13790.
3. Domestic hot water –parts of EN 15316-3, which include the specification of domestic hot water requirements for different types of building, and the calculation of the energy needed to provide it.
4. Ventilation – EN 15241, energy needed to supply and extract air, based on installed fan power and controls, including energy for humidification if applicable.
5. Lighting – EN 15193, based on installed lighting power and annualized usage according to building type, occupancy, and lighting controls.
6. Integrated building automation and controls – EN 15232, takes into account additional energy optimization based on interdisciplinary control functions and applications for space heating, ventilation, cooling, domestic hot water, and lighting.

For the third approach, calculation of overall energy performance indicator, a link between the delivered energy and the energy performance indicators for buildings is provided in the following two standards.

a) EN 15603 provides several methods to assess energy performance ratings for both new and existing buildings.
b) EN 15217 guidelines different ways of expressing the energy performance and the requirements in a certificate.

The relation between the EN standards can be found in Figure 7.

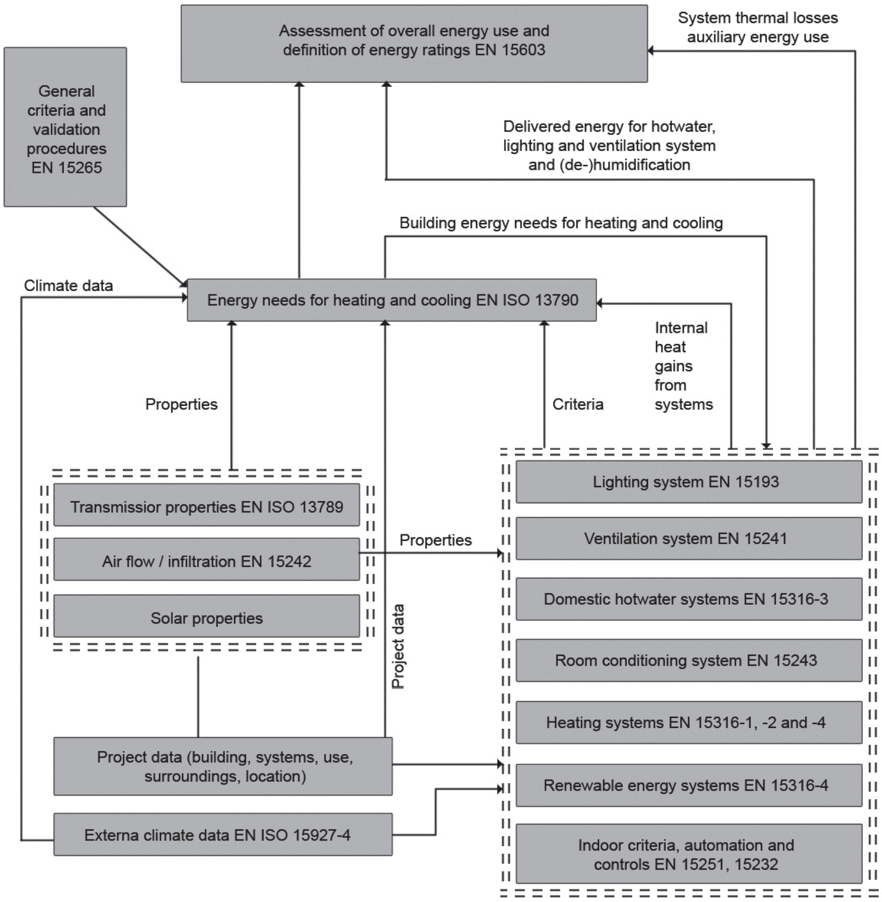


Figure 7:
Explanation of the General Relationship between Various CEN Standards and the Energy Performance of Buildings Directive (EPBD) from [22].

National Standards (DIN, ASHRAE, KS)

Germany (DIN V 18599: Energy efficiency of buildings- Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting)

DIN V 18599 takes the third approach of the previous international approach, calculation of overall energy performance indicator, where the primary energy demand for a whole building is estimated. In contrast to EN standards, DIN V 18599 offers all different aspects in one standard. It is holistically designed in energy balancing approach, taking into account the interaction between the building system and the building [24].

It is based on a monthly calculation and comprised in eleven parts:

- Part 1: General information
- Part 2: Net energy demand for space heating and cooling
- Part 3: Net energy demand for air conditioning
- Part 4: Final energy for lighting
- Part 5: Final energy for heating
- Part 6: Final energy for ventilation systems of dwellings
- Part 7: Final energy for air conditioning + cooling in non-residential building
- Part 8: Final energy for domestic hot water
- Part 9: Final energy for multi-functional generators
- Part 10: Boundary conditions
- Part 11: Building automation

It is almost impossible to calculate the primary energy based on DIN V 18599 without a professional computer program.
The outline and calculation scheme of DIN V 18599 can be found in Figure 8.

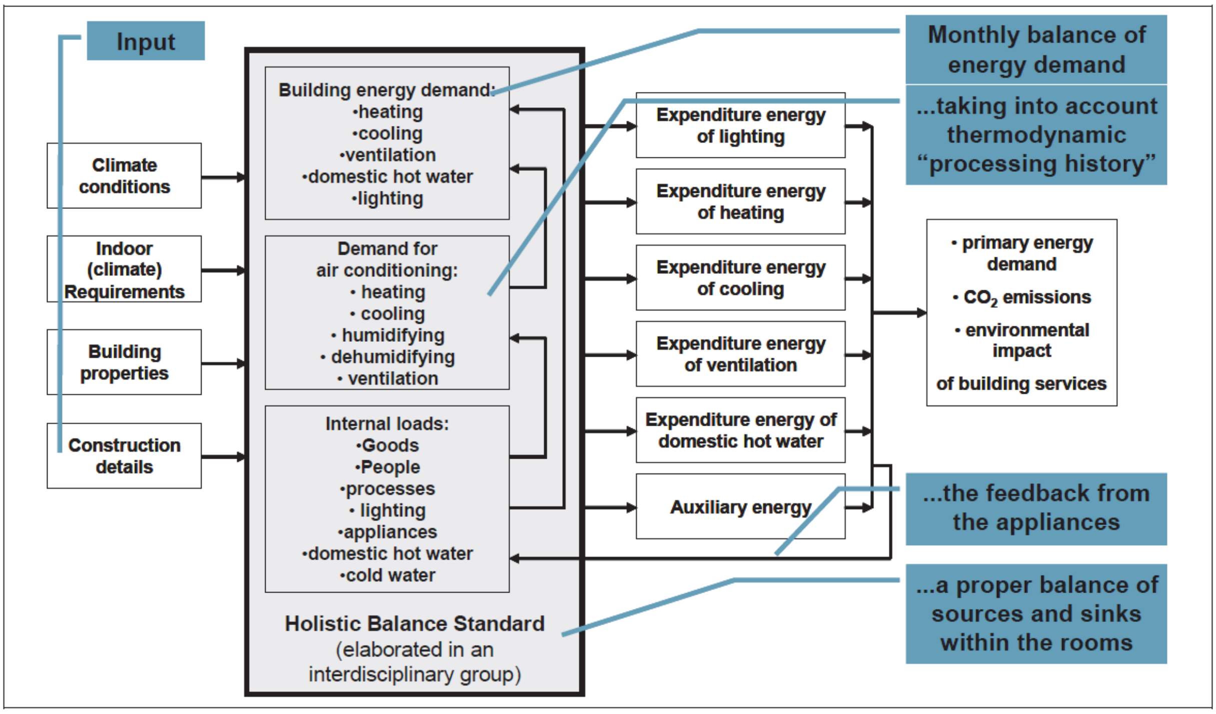


Figure 8:
Outline and Calculation Scheme of DIN V 18599 from [25]

USA (ASHRAE 90.1.2007: Energy standard for building except low-rise residential buildings)

While DIN V 18599 aims at offering an objective calculation method for energy performance with standardized boundary conditions, ASHRAE 90.1. offers minimum requirements for the energy efficient design of buildings and building systems.

The compliance with Standard 90.1 has two approaches (see Figure 9):

a) Prescriptive provision

b) Energy cost budget method.

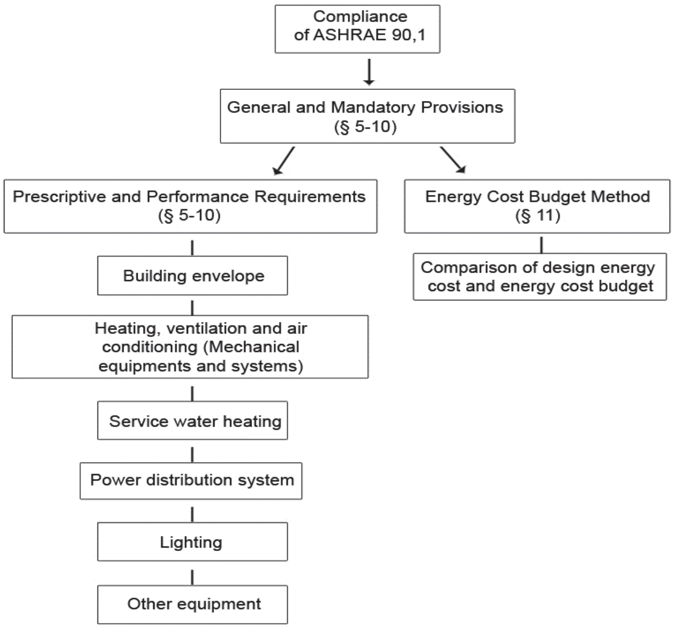


Figure 9:
Two Compliance Paths of ASHRAE 90 .1. 2007

For the compliance of Chapter 5, building envelope can be performed by means of either prescriptive path for the single building envelope or trade-off option based on the mean U-value. The alternative approach, energy cost budget method, shall be calculated using energy simulation programs defined in the same standard. The energy costs of a planned building are then compared to those of the reference building in the standard.

Korea (KS)

Korea does not have any special standard for building energy performance, except mechanical systems and products.

2.2 Review of Standards: Thermal Comfort

2.2.1 ISO 7730: 2007

ISO 7730 [26] provides the methods (PMV, PPD) for evaluating and analysing thermal environments. PMV (Predicted Mean Vote) assumes the mean vote, which will be assessed by the occupancy in an environment using a scale from -3 (cold) to +3 (hot). PPD (Predicted Percentage Dissatisfied) derives from PMV, and estimates how many people may be satisfied with the thermal environment. For example, in an environment where PMV equals zero (neutral), 95 % of the occupants would be satisfied with the thermal environment.

Environmental parameters determining thermal comfort are air temperature, radiant temperature, humidity, air velocity, and personal parameters like clothing and metabolism. PMV can be calculated from these six parameters and PPD is determined from this calculated PMV.

PMV and PPD are based on subject studies in climate chambers under light sedentary activities and steady-state conditions. The PMV- PPD model will be discussed in more detail in Chapter 2.4.3. In addition, ISO 7730 serves evaluation methods to PMV and PPD for local discomforts, such as draft, asymmetric radiant temperature, vertical temperature difference, and warm/cold floor. Furthermore, the Annex H in ISO 7730 provides some thermal comfort assessment alternatives for long-time periods by means of PMV.

ISO 7730 is accepted in Germany as a national standard (DIN EN ISO 7730) as well as by CEN as European Standard (EN ISO 7730).

2.2.2 ASHRAE 55-2004

ASHRAE 55- 2004 [42] provides two methods for determining acceptable thermal general conditions:

a) Graphical method for typical indoor environment
b) Computer model method for general indoor application

Graphical methods determine the 80 % acceptable comfort ranges based on the 10 % dissatisfaction of general thermal comfort plus an additional 10 % dissatisfaction of local discomfort. These ranges are defined using PMV calculation with typical indoor conditions: 1.1 met, 0.1 (m/s) air velocity, clo=1.0 for winter and clo=0.5 for summer. The defined acceptable range is - 0.5 < PMV < 0.5, which belongs to the second category of ISO 7730 as well as EN 15251 [23]. The difference of the ASHRAE comfort range to the other two standards is the upper limit of the absolute humidity of 12 (g/kg) (see Figure 10) .Though

EN 15251 recommends 12 (g/kg) as the upper limit in case of dehumidification, no upper or lower limit of humidity is determined for a thermal comfort range in both standards. Next to the limitation of absolute humidity, the difference between ISO 7730 and ASHRAE 55-2004 is to be found in Chapter 5.3. in ASHRAE 55-2004 "Optional Method for Determining Acceptable Thermal Conditions in Naturally Conditioned Spaces" as so-called adaptive model.

In order to apply this method, a space must be primarily controlled by the occupants through opening and closing of windows. There must be no mechanical cooling system in the space, and the method itself is not applicable, if a heating system is in operation. The occupants can freely adjust to their clothing according to the different thermal environments. The thermal environment in this kind of spaces can be evaluated by using an "adaptive model" that determines an acceptable operative temperature range, depending on the monthly average of the outside air temperature (see Figure 11). This figure indicates temperature limits for 80 % and 90 % acceptability. This new model is based on the field studies, which have shown that occupants in naturally conditioned spaces can accept higher indoor temperatures than estimated by the PMV model [27] .

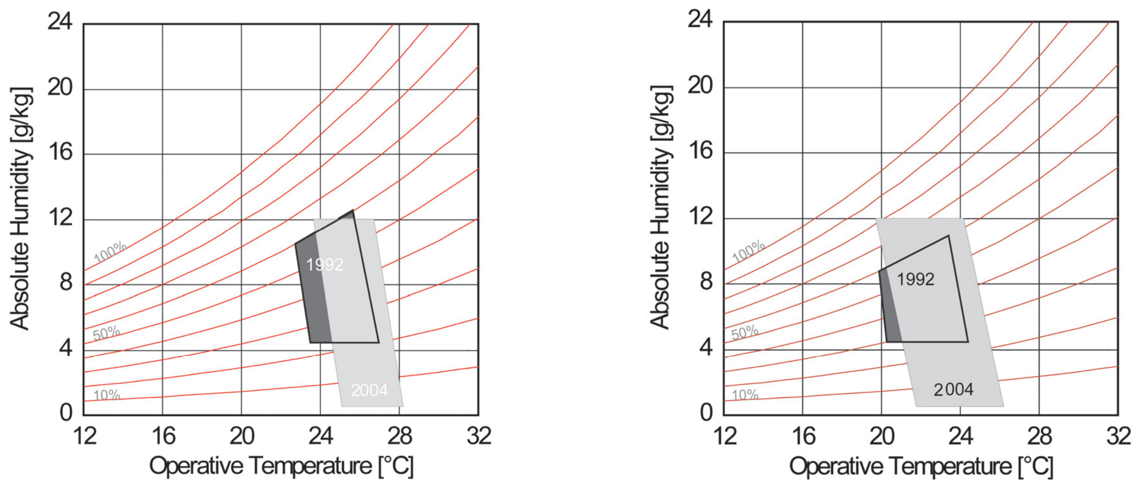


Figure 10:
Comfort Range by Means of Graphical Methods in ASHRAE 55 -1992 [41] and in ASHRAE 55- 2004 [42]. Left: Summer Comfort Range, Right: Winter Comfort Range.

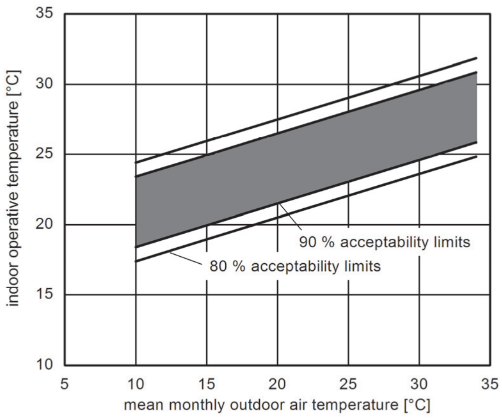


Figure 11:
Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces [42]

Korea (KS)

Korea does not specify any standard for thermal comfort. Instead, ASHRAE 55 was usually applied by thermal comfort research in Korea.

2.2.3 EN 15251:2007

Another standard to assess the thermal environment and energy performance is EN 15251[23].This European standard determines "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics".

The building energy performance depends highly on the indoor environment, e.g. room temperature or ventilation rate that specifies thermal comfort or indoor air quality. Therefore, according to Olesen [28], the energy certificate must include information on the indoor environment. This approach can be accomplished by means of EN 15251, although the standard does not offer any methodology for the integrated evaluation of indoor environment parameters. This standard provides the defined indoor parameters for energy calculation and categories of IEQ (Indoor Environmental Quality) separately for indoor air quality, thermal environment, lighting, and acoustics.

The Category I, "High Level of Expectation" is recommended for spaces occupied by very sensitive and fragile persons and Category 4, "Outside the Criteria" is only acceptable for a limited part of the year. Category II should be used for new buildings and renovations as "normal level of expectation" [28]. For thermal environment assessment in buildings, the standard offers two approaches: for mechanically conditioned buildings based on PMV and PPD (see Table 2) and for buildings under free-running mode based on the adaptive model (see Figure 12).

Table 2:
Thermal Comfort Category for Mechanically Heated and Cooled Buildings According to EN 15251:2007

Category	PPD (%)	PMV
I	< 6	-0.2 < PMV < +0.2
II	< 10	-0.5 < PMV < +0.5
III	< 15	-0.7 < PMV < +0.7
IV	> 15	-0.7 > PMV or PMV > +0.7

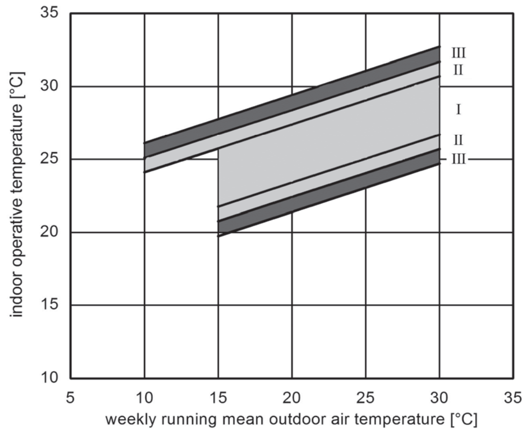


Figure 12:
Thermal Comfort Category for Buildings without Cooling According to EN 15251:2007

While the adaptive model of ASHRAE 55 determines the acceptable indoor temperature according to the mean monthly outdoor temperature, the EN 15251 model specifies the acceptable range in dependence of the mean running outdoor temperature. This model is based on European field studies of office buildings within the SCATS project [54]. The difference between two adaptive models as well as the methodology of adaptive model will be further discussed in Chapter 2.4.3.

2.3 Review of New Energy Efficient Technologies for Buildings

In recent years, a large number of technologies have been developed to improve the energy efficiency in buildings. In this Chapter some technologies are reviewed, which are interesting for the energy efficiency of high-rise residential buildings in Korea.

2.3.1 Building Envelope

New insulation material

Neopor (brand name) is a new high performance insulation of expanded polystyrene (EPS) with 0.032 -0.030 W/(m·K) thermal conductivity instead of 0.037 W/(m·K) of conventional EPS. The silver-gray granules of Neopor contain infrared absorbers and reflectors to reduce thermal conductivity. Mineral Foam Panel is developed especially for external insulation systems. According to the manufacturer's information this non-combustible insulation contains of a mixture of calcium silicate, can be applied for up to 100 m high-rise buildings and can easily be cut by using a saw. Both properties, non-combustibility and high resistance properties, allow a wide range of applications in spite of its relatively high thermal conductivity of 0.045 W/(m·K) [29].

The total heat transfer of conventional insulation materials is dominated by the contribution of gas in the hollow spaces or pores. Thus, the large potential to improve insulation properties can be realized by reducing or even completely eliminating the gas conductivity [30]. This elimination allows an improvement of the thermal insulation property of VIP (Vacuum insulation panels) which is almost ten times better than that of conventional insulation materials. Such relatively expensive technology has been used for freezers or cold shipping boxes. However, a passive house calls for an U-value of 0.15 W/(m²·K) for the building envelope [32], i.e. approx. 25 cm thick insulation layers. A thick insulation in return requires an expensive space. Therefore, the research of "vacuum insulation panels" as a high performance insulation was carried out in Europe in the last years and a few products are now available on the market. VIP is generally dwelling elements consisting of an open evacuation-capable porous core material, which must resist external load as well as a sufficiently gas-tight envelope to maintain the required quality of the vacuum. Silica is used as core material [30]. Besides the high costs, the main disadvantage of VIP is the vulnerability to a gas-tight envelope's damage. Therefore, VIP is realized often together with EPS used as a protection layer or developed for a pre-cast construction elements.

Window

Glazing: In last years, the technology in glazing production increased so rapidly that the thermal insulation of glazing could be improved from 5.8 W/(m²·K) in the 1970s to 0.7 W/(m²·K) in the 1990s. Nowadays, double-glazing with argon filling and low-e coating (Ug =1.1 W/(m²·K)) is usually applied in Germany.

For summer, the required property of glazing is not insulation but solar control ability. The solar gain through glazing should be reduced, but if possible without the decreasing a visual transparency, i.e. high light transmission (VT factor) and low solar energy transmission (g-value). In general, glazing with an extreme low solar energy transmission, the so-called "solar protection glazing" available on the market also has low light transmission. As with the "vacuum insulation glazing", the Ug-value is reduced to 0.5 W/(m²·K) through evacuation between the panes.

Frame: Since the 1990s insulated frames with up to U_f = 0.6 W/(m²·K) capacity are available on the market. The usual thermal bridge in a frame, the composite material of panes, is recently made of PVC instead of conventional aluminium. Using this kind of frame the total U-value of the window (U_w) < 0.8 W/(m²·K) can be realized in combination of glazing with Ug = 0.7 W/(m²·K) [31] [33].

2.3.2 Advanced Ventilation Systems

Natural Ventilation

Windows with an Automatic Control on the Opening: Window ventilation is generally performed manually by the users. However, the interest for controlled natural ventilation is increasing in order to ensure a good air quality without abandoning window ventilation. Recently components are available to control the opening of windows in wide as well as other positions. These elements can be operated central or individual according to the control system. In addition, they are equipped with a weather sensor, so that windows can be closed under rain or strong wind [34] [35].

Air Inlets on the Façade: The small inlets installed on the walls or window frames can be closed or opened according to the required CO_2 concentration, relative humidity or based on presence detectors in a room [35]. The humidity-controlled inlets are primarily based on the change in length of a tape due to a change in relative humidity [Figure 13]. In contrast to previous systems or de-centralized mechanical ventilation systems, these systems are applied mainly in residential buildings frequently in combination with mechanical exhaust systems.These systems provide the possibility of sound attenuation and air filtering function, which are most important factors for the ventilation in buildings near busy roads [35]. There are many manufactures in Europe nowadays.

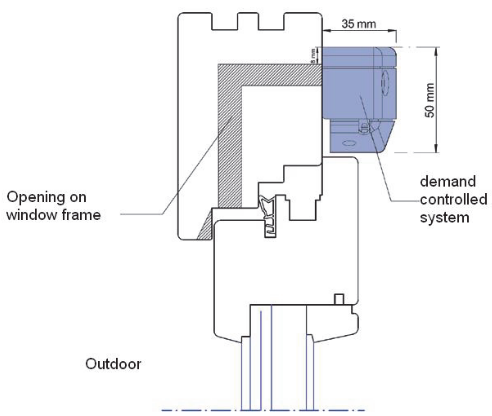
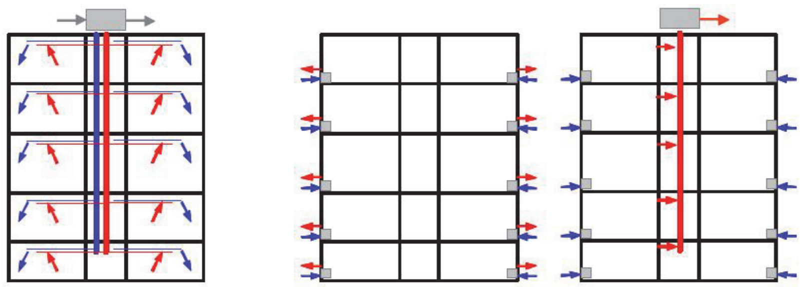


Figure 13:
Demand-controlled Air Inlets System (Example: humidity-controlled air inlets on window frame by Aereco)

Mechanical Ventilation

Decentralized ventilation system: Previously the most advanced and fast-expanded mechanical ventilation system was the decentralized ventilation system that directly draws air into each room through openings in the outer wall (Figure 14). Air is locally conditioned (heated or cooled) in each individual device either with or without heat recovery. This ductless system was applied in office buildings especially in combination with thermo-active systems (concrete core heating and cooling).



Central Ventilation System Decentralized Ventilation System

Figure 14:
Central Mechanical Ventilation System vs. Decentralized Ventilation System from [36]

In an investigation [36] funded by the German government, 16 buildings with decentralized façade-integrated ventilation systems are evaluated based on indoor environment monitoring and user questionnaires. The benefits and disadvantages of the new system compared to the conventional system are emphasized in this study [36]. On the German market, there are a few manufactures, whose products can be integrated on the floor or on the façade.

Table 3:
Benefits and Disadvantages of Decentralized Façade Integrated Ventilation Systems [36]

Benefits	Disadvantages
Reduced floor heights, thus no ventilation shafts necessary	Slightly higher maintenance costs due to a large number of devices
Smaller control centres	Maintenance must be carried out in the room
Reduced energy costs	More difficult to control humidity levels
Flexible use of space	
Only needs to be activated, if someone is in the room	
People can directly control their environment	

2.4 Review of Thermal Comfort Research

There are three approaches for the assessment of thermal comfort in an environment: Physical Indicators, Physiological Models, and Comfort Models. The Physical Indicators combine a part of the four physical indoor environment parameters such as air temperature, radiation temperature, relative humidity, and air velocity into a single index, while the Physiological Models estimate the thermal comfort using calculation of the thermoregulation of the human body in an environment. In contrast, the Psychological (Comfort) Models use the statistical analysis based on the questionnaires of subjects in climate chambers or in the field study.

2.4.1 Physical indicators

The Operative temperature (To), Effective Temperature (ET*) and Equivalent Temperature (Teq) belong to the first approach. Operative temperature is defined as "the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment"[42]. It is the average of the air temperature and the mean radiant temperature weighted by the heat transfer coefficients. The mean radiant temperature can be detected with a globe thermometer or can be calculated using the view factor and the measurement of a surface temperature [37].

Effective Temperature (ET*) is "the operative temperature of an enclosure at 50 % relative humidity"[41], while the Equivalent temperature (Teq) is "the operative temperature of an enclosure at 0 m/s air velocity"[46].

The ET* is an index combining the air temperature, radiation temperature and humidity and applied widespread in USA and in Asia. It can be calculated using the two-node model of Gagge [49].

In contrast, the Teq is a recognised measure of the effects of non-evaporative heat loss considering the air velocity instead of partial vapour pressure. It has a wide range of application in Europe, especially in Scandinavia [38]. By the local thermal comfort investigation, the equivalent temperature is often used due to the possibility of measurements on the local body segments using multi-segmented thermal manikins or heating sensors [46]. Teq does not consider the evaporative heat loss of the body that is influenced by the partial vapour pressure of the surrounding.

2.4.2 Physiological Models

The physiological (thermoregulatory) models estimate the skin, core temperature and skin wettedness of a typical human body based on its heat balance with the surrounding and thermoregulation of the body.

Heat balance of the body can be described by the following equation [48]:

$$M - W = C_{res} + E_{res} + C + R + E + K + S \quad (1)$$

Where:

$M - W$	Heat production of body from the metabolic rate (M) and external work (W)
C_{res}	Sensible heat loss due to respiration
E_{res}	Evaporative heat loss due to the respiration
C	Heat loss due to convection from skin
R	Heat loss due to radiation from skin
E	Evaporative heat loss from skin
K	Heat loss due to conduction from skin
S	Heat storage

If the heat loss due to convection and radiation is bigger than the heat production generated from the metabolism, the body preserves the heat by vasoconstriction and start shivering in order to increase the heat generation. In another case, the heat loss of the body is less than its production, it increases it's heat dissipation by vasodilatation and sweating.

The core sensor and the thermal sensors (cold and warm receptors) distributed across the body send a signal (too warm or too cold) to the hypothalamus, which controls the aforementioned thermoregulation mechanisms (vasoconstriction, vasodilatation, shivering, sweating) [48] [44]. Such signal systems based on the heat balance between human body and surrounding and human thermoregulation systems are simulated by a virtual physiological model. In recent years a few multi-segment models have been developed, especially in combination with computational fluid dynamics (CFD) [40]. Since the detailed knowledge about thermo physical properties and the thermoregulation system of human body is not available up until now, many factors of new multi-segment models are based on the physiological assumption led from previous investigations or models [39].

The main challenge of models is, besides the control of the signal, the assessment of thermal comfort using the outputs (skin temperature, core temperature, and sweating rate) of models. These physiological models are considered as a thermal assessment tool due to the strong relation of thermal comfort and the skin/core temperature. In a neutral environment, no thermal regulation system is active so that the skin and core temperature are close to the "set point" and thermo receptors should not send any signals to the corresponding control centre. However, the knowledge about the relation of "set point" and thermal sensation as well as the effect of deviation from it is so far inadequate. The reason for it would be the complexity of the physiological subject study.

The two node model, which is a one segment (whole body) model from Gagge [44], Stolwijk model (6 segments) [39] , Tanabe model (16 segments) [40] and Fiala model (10 segments for transient environments) [47] belong to these physiological models.

2.4.3 Comfort Models

For the assessment of thermal comfort, a comfort (psychological) model is always required. The physical indicator or physiological models would not be applicable for the comfort assessment, if the relation between physical indicator or skin/core temperature (how the environment is) to the thermal sensation or comfort assessment of human being (how the people feel) is not known. The comfort models provide this very important relation. This knowledge is achieved generally by means of questionnaire asking subjects about their thermal perception. Physical parameters or the physiological responses of bodies of subjects are investigated at the same time. The outputs of a model will be the mean thermal sensation or the thermal comfort assessment as the percentage of (dis)satisfied or as the rate of thermal satisfaction. It depends on the scale used in the questionnaires. Five typical questionnaires (sensation, comfort, preference, acceptance, and tolerance) and scales regarding to thermal comfort research are explained in ISO 10551 [59]. However, the definition of thermal comfort using one scale is in disagreement until now.

a) Comfort Assessment Using Physical Indicators

The previous ASHRAE 55-1992 [41] provided thermal comfort ranges for winter and summer according to the operative temperature and humidity ratio. These operative temperature ranges are derived from effective temperature. The new ASHRAE 55- 2004 [42] provides also the comfort ranges according to operative temperature and humidity ratio, but the areas are determined from the PMV for a sedentary activity and typical clothing. EN 15251[23] provides a comfort operative temperature range derived also from the PMV. ISO 14505-2 [46] provides different comfort ranges for vehicle cabins, considering 16 local body segments and using the equivalent temperature approach.

b) Theoretical Comprehensive Comfort Assessment

TSENS, DISC Model

There are few models indicating thermal perception and physiological responses of human body. Most of the published physiological experiments had taken place before 1970, from which Hardy [cited in [47]] summarized in 1970 the physiological conditions for the thermal comfort.

Gagge provided in 1967 the relationship of skin temperature and skin wettedness to the thermal sensation and comfort for the whole body [43]. According to Gagge, skin temperature is a good indicator of thermal comfort in cold environments, whereas skin wetness is more adequate when sweating occurs. Therefore, "DISC" (thermal comfort model) is related to skin wetness when body temperature is regulated by sweating, while the skin temperature determines the comfort rate in cold or neutral environment. His model "TSENS" (thermal sensation model) is defined in terms of deviations of mean body temperature from cold and warm set point representing the lower and upper limits for the zone of evaporative regulation [44]. TSENS and DISC have not been widely used by thermal comfort investigation [48]. Also the suggestion of PMV*, to use the ET* instead of To in PMV calculation have not found a widespread agreement [49].

There have been few physiological experiments investigating this relation on the local body segments [50][51]. However, no experiment is published in the detail and any result of such investigations could have not been established internationally up to now.

PMV-PPD Model

Fanger model (PMV) is not based on a computational physiological model but on physiological considerations. Fanger defines at first three conditions of physiological situation for the thermal comfort based on subject studies in climate chambers [52]:

- Body is in heat balance
- Sweat rate is within comfort limits (Equation (2))
- Mean skin temperature is within comfort limits (Equation (3))

$$E_{rsw} = 0.42\ (M - W - 58.15) \qquad (2)$$

Where:

E_{rsw}	Rate of evaporative heat loss from the skin through sweating	$[W/m^2]$

$$t_{sk} = 35.7 - 0.0275(M - W) \qquad (3)$$

Where:

t_{sk}	Skin temperature	$[°C]$

According to this precondition the heat balance of Equation (1) can be described to the following equation (comfort heat balance), if the minor heat loss due to conduction from skin is neglected.

$$M - W - C_{res} - E_{res} - C - R - E = 0 = Comfort \quad (4)$$

Where:

C_{res}	Sensible heat loss due to respiration
E_{res}	Evaporative heat loss due to the respiration
C	Heat loss due to convection from skin
R	Heat loss due to radiation from skin
E	Evaporative heat loss from skin

Since the skin temperature and evaporative heat loss are already determined depending on the metabolic rate, the comfort equation can be solved steady using the four-environment parameters (air temperature, radiation temperature, air velocity, humidity) and two personal parameters (clothing insulation value, metabolic rate).

If a calculated Equation (4) does not yield zero, the discrepancy from the comfort equation is regarded as thermal load (L), where a positive number indicates surplus of produced metabolic heat, thus a warm sensation. His PMV model explains the relation of this deviation (Load) and thermal sensation (Mean Vote) of the people determined empirically from the subject investigations in climate chambers.

$$M - W - C_{res} - E_{res} - C - R - E \neq 0 = L \quad (5)$$

3) Empirical Comfort Models

While the both theoretical models (Gagge model, Fanger model) are based on the heat balance calculations and extensive subject experiments in climate chambers, empirical comfort models are derived from field studies. Such studies consist of a measurement of physical parameters and questionnaires administrated by occupants during the visit of an investigation team. Relations of physical parameter and thermal perception of occupants are provided as an empirical model. The physical parameter could be indoor temperature, outdoor temperature, PMV or ET*.

Humphreys reviewed in [57] such survey works performed in Africa, Americas, Asia, Australia, and Europe between 1938 and 1973 and published the summary including information of investigation place, mean temperature, neutral temperature, and percentage of satisfied. A neutral or comfort temperature is defined as "the operative temperature at which either the average person will be thermally neutral or at which the largest proportion of a group will be comfortable" [54]. According to his review, the neutral temperature or comfortable temperature varies from the 17.5 °C for the elderly at home in winter in the U.K. to 32 °C for the office workers in summer in Iraq. He found strong relations between neutral temperature and indoor air temperature as well as between neutral temperature and outdoor temperature. From these results, he concluded that there is human adaptation to ensure their thermal environment comfortable, in that they change their clothing or behaviour. This adaptation results in their achieving thermal comfort at widely diverse temperatures [57].

Furthermore, simple indices such as air temperature or globe temperature explain in field studies often more of the thermal response of occupants than complex indices like PMV or SET* [Busch 1990, Schiller 1990 cited in [53]] (see Table 4). The adaptive models provide the "Comfort (neutral)" temperature as function of simple measurement parameters like indoor temperature or/and outdoor temperature.

Table 4:
Pearson Correlation Coefficients for the Warmth Scale and the Principal Indices from [53]

	Ta	Top	ET*	SET	PMV
TSV (1)	0.514	0.515	0.507	0.430	0.462
TSV (2)	0.352	0.333	0.319	0.320	0.249

(1) De Dear database (n=20,468)

(2) SCATs database (n=4068)

There are many subjective models according to researches and climate conditions. International established models are the ASHRAE 55-2004 adaptive model based on the meta-analysis of de Dear et al.[27] and the EN 15251 adaptive model based on the SCATs (Smart Controls and Thermal Comfort) project performed by Nicol et al. in Europe [54]. Both models provide the comfort indoor temperature against outdoor temperature.

The differences between two models are the following [54]:

- different database (ASHRAE from the world database, SCATs from the Europe)
- different building classification (Application for building with natural ventilation in ASHRAE, free running mode (without cooling and heating) in EN 15251)
- different derivation of neutral temperature
- different definition of outdoor temperature (mean monthly outdoor temperature in ASHRAE, mean running weekly outdoor temperature in EN 15251)

2.4.4 Discussion about Comfort Models

PMV-PPD model is the standard analysis tool for a thermal comfort research as well as for engineering of HVAC since 40 years. The models can clearly provide the required parameters for thermal comfort and generally well predict the mean sensation vote in controlled spaces [27] [89]. Using PMV - PPD model engineers can constantly control the indoor parameters (air temperature, air velocity) as the most comfortable environment. However, some subject studies in climate chamber show relative higher dissatisfaction (15 %) than 5 % predicted in PPD in most comfortable environment [88]. In addition, the thermal satisfaction or acceptance is in practice often higher in natural ventilated or free running buildings than mechanically ventilated, heated or cooled buildings, although such buildings do not always provide the constant comfort environment [55] . It is likely that not only "heat balance" of people but also "other parameters" might affect the comfort assessments of people, as adaptive models assumed.

Questions Regarding to Adaptive Models

The observation of field studies like "People appear to be more tolerant if they have control over their own thermal environment. There is no objection to sophisticated (intelligent) control systems, so long as they are under the effective control of the user" [cited from [56]] would explain one of these other parameters. The contribution of the adaptive approach in recent years would be to strengthen a trend of building design with "passive methods" in combination with the user control. If a building without any active system (mechanical ventilation or cooling) can comply with the relatively wide comfort ranges in adaptive models, it may abandon costs and extensively active energy systems. Therefore, a high-cost passive system in a construction phase like night ventilation with thermal storage of a building construction could be rentable for an owner under a consideration of operation costs.

However, there are few evaluation investigations, in which 90 % or 80 % percentage of satisfaction comfort range in adaptive models is evaluated in field studies. Would 90 % of occupants feel comfortable in practice within the first category of the adaptive models?

According to database of [57], the average comfort temperature is 2.4 K below the indoor temperature in free-running buildings. It means the occupants assess average "slightly warm" independent of the actual indoor environment. They do not feel "neutral" under actual indoor environment. The neutral temperature in an adaptive model is based on the assumption that occupants will feel neutral or comfortable, if the temperature will be some 2.4 K lower than actual temperature. Would the occupants feel so?

- Interpretation of Scale by Occupants

According to the personal observation during questionnaire campaigns, it is likely that subjects avoid a strong expression like "cold", "hot", "very hot" or "very uncomfortable", unless they are very dissatisfied with the environment. Therefore, they tend to answer "slightly warm", if the environment is warm independent of the air temperature 28 °C or 30 °C, especially if they are not exposed to other comparable temperatures. The participants in the field studies cannot compare the indoor environment in a short period. In addition, their assessment could be affected not only from the thermal environment but also from the other elements such as the lighting and acoustics, while the subjects in climate chambers generally experience the concentrated thermal comfort as a single variable. As a result of it, subjects in climate chambers would be more sensitive to the thermal environments, not only because they often have a better understanding of a scale in a questionnaire based on the repeated experience as subject. It could be that although people assessed 30 °C temperature as "slightly warm ", they would not feel "neutral" at 27.6 °C against the assumption of adaptive models.

- Calculation of Comfort or Neutral Temperature

It is difficult to follow how the comfort or neutral temperature has been determined in an adaptive model in empirical studies. The comfort (neutral) temperature can be calculated using the comparison of actual comfort or sensation vote administered by occupants and the physical measured temperature, which could be an air temperature or globe temperature or operative temperature. The difficulty of generating comfort temperature is the determination of temperature discrepancy by "one rating scale" in a questionnaire. If a thermal judgement of an occupant or an average mean vote is "slight cool" according to ASHRAE scale at an actual temperature (for example, 21 °C), how high is the neutral temperature? How can it be defined? The adaptive researchers use the following two methodologies:

a) Calculation with Constant Temperature Discrepancy 2 K Per One Rating Scale

The neutral temperature can be calculated using so-called "Griffiths Constant" which is a single standard regression coefficient determined from the linear relationship between comfort vote and operative temperature.

$$T_{comf} = T_g - \frac{C}{G} \tag{6}$$

Where:

T_{comf}	Comfort temperature
T_g	Globe temperature (or operative temperature)
C	Comfort vote
G	Griffiths Constant

Humphreys suggests 0.5 as Griffiths constant, which means that one rating scale indicates the 2K temperature discrepancy as in our previous example; the neutral temperature is 23 °C. This constant is derived empirical from the regression analysis using the temperature as predictor variable and the sensation vote as dependent variable.

b) Temperature as Central Rating "Neutral" using Regression Analysis

According to [27], neutral temperature can be defined as "a specific value of the indoor thermal environmental index corresponding to a mean thermal sensation vote of zero". It is obtained by solving a regression equation for y (thermal sensation) = 0 = f (physical indicator) using the experimental results. The predictor variable could be different physical indicators like operative temperature or PMV (example see Table 5). This methodology requires amount of samples and cannot provide an individual comfort temperature.

Table 5:
Neutral To (operative temperature), preferred To and PMV at thermal sensation vote=0 in the ASHRAE RP-884 study [27]

	Centrally Heated Air Conditioned Buildings		Naturally ventilated buildings	
Season	Summer	Winter	Summer	winter
Neutral To	24.1 °C	22.5 °C	24.6 °C	22.4 °C
Preferred To	23.1 °C	22.9 °C	24.3 °C	23.1 °C
PMV	0.01	-0.55	-0.43	1.11

c) Possible Other Methodologies

A possible method for the determination of neutral (comfortable) temperature will be an average value of satisfied group in a field study, who indicated an actual environment as "neutral" or "comfortable" in the questionnaire. In addition, the "Comfort temperature" can be derived by means of the PMV calculation, in which the optimal operative temperature is solved as variable for the case of PMV = 0. If there is an uncertain parameter by measurements like clothing insulation value or metabolic rate, it could be calculated inverse for PMV = TSV (Thermal Sensation Vote). Then the comfort temperature can be defined using a calculation of PMV = 0.

- The Problem of Regression Analysis

According to a subjective experience in thermal comfort researches, the result of a statistical regression analysis is strong dependent on test designs. A wide test design (for example from 18 °C to 32 °C) in an investigation will show a high significant correlation between independent variable and dependent variable, while a limited test design (for example from 22 °C to 26 °C or from 26 °C to 30 °C) might not show often any significant correlation.

The observation of adaptive model "the comfort temperature is strong dependent upon outdoor temperature" could be diverse, if only limited temperature range would be analysed in an investigation.

Theoretical Limitation of PMV for Comfort Assessment in Warm Environment

The reason, why PMV cannot well explain the thermal comfort in warm environment will be the neglecting of the evaporative heat transfer process in the phase of sweating in PMV model.

In the neutral or cold environment the convective and radiative heat loss determine the thermal comfort in the similar part in typical indoor. In warm environment, however the evaporative heat loss dominates the heat loss respectively the thermal comfort. If an air temperature or radiation temperature is high, the heat loss due to the convection as well as radiation will be decreasing and the required evaporative heat loss for the heat balance will be increasing. In such warm condition, the bigger heat loss of the body, the less required sweat secretion followed, thus the more comfortable the people may feel in the environment. However, PMV neglects this different evaporative heat loss process in a warm environment. The heat balance model of Fanger is based on the "comfort" heat balance under steady state conditions, in which the skin temperature and the sweat secretion are within comfort limits. Therefore, the evaporative heat loss in his comfort heat balance is determined only by the metabolic rate. If people sweat and evaporate more than the defined comfort evaporation, they are not in a comfortable situation. Fanger`s PMV assesses the difference between this comfort situation and actual environment as load. However, in the same thermal load, say PMV=1 or operative temperature 29 °C, the perceived thermal comfort of occupants will vary depending on the success of evaporative heat transfer. In such situation they begin to sweat and how fast and slow this sweat evaporates will affect the further heat balance of body. Under high air velocity and low absolute humidity, the evaporative heat loss will increase and contribute to the thermal comfort. In PMV the effect of air velocity is considered only by convective heat loss and the effect of the water vapour pressure only by evaporation heat loss due to respiration and diffusion from skin, without sweat secretion. Therefore, PMV could not explain exactly thermal comfort assessment, if people are sweating.

The above-mentioned questions regarding to comfort models will be evaluated using the questionnaire and measurement data in this study.

3. Experimental Studies

3.1 Investigated Buildings

A partner construction company in Korea selected four building complexes for this study. Building A and C are the typical high-rise apartment complexes, which mostly have south or southeast orientation and make up over 10 buildings for a residential use only. Building B and Building D complexes have only two or three buildings, with a commercial use on the 1st and 2nd floors. The Buildings B and D also have a mechanical air supply system, whereas the Buildings A and C only have a mechanical exhaust system in the bathroom and kitchen.

Figure 15:
Four Investigated Buildings in this Thesis

Three dwellings each from the Building A and B were comprehensively investigated using a detailed monitoring system in every room and energy simulation , while 3 dwellings in the Buildings A and B, and 6 dwellings in the Buildings C and D were studied by means of measurements in the living rooms only. The apartment building (Buildings A, C) is the most common living form in Korea for over 20 years, while the super high-rise (Buildings B, D) is relatively new as a residential building.

3.1.1 Building A

Building A is from an apartment complex of 14 buildings with different heights, ranging from 16 to 25 stories. The complex includes 919 dwellings with different floor sizes from 86 m² to 142 m². This apartment complex was completed in November 2007.

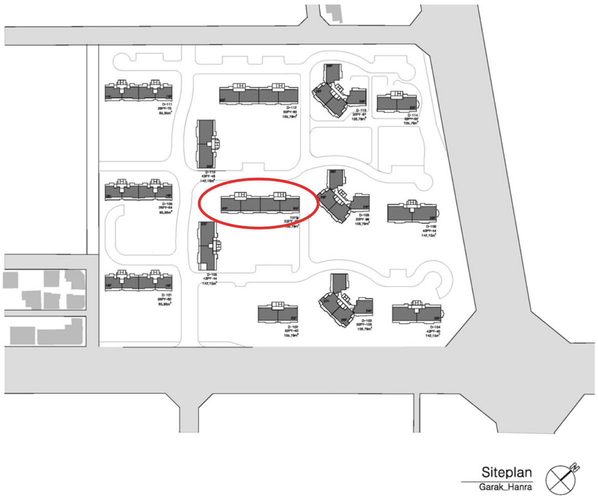


Figure 16:
Site Plan of Building A (Red Circle Building: Comprehensive Investigation)

The general information of Building A is based on the plan analysis and inspection shown in Table 6.

Table 6:
General Information on the Building A

	Building A: Comprehensive Investigated Building
Building No.	107
Story of the Building	20 F
Floor of Dwellings Measured	1F, 11 F and 20 F
Construction	Steel concrete
Size	105,79 m² (Net living space: 93.5 m² without balcony)
Room Height	2.4 m
Ventilation	Window ventilation, Mechanical exhaust only
Heating	District heating / Floor heating
Cooling	Split air conditioner

Envelope

In Korea, internal insulation has been generally used until now due to the complexity of an external insulation at high-rise buildings. The measurement building also has an internal insulation except for the ground floor. The exterior walls towards the balcony are insulated inside of the construction with a 6.5 cm Styrofoam. The exterior sidewalls facing the outdoor air have a 9 cm-thick insulation and the roof has an 11cm-thick insulation. The ground floor is constructed with a 5 cm insulation in the inside layer and a 5 cm in the outside layer of the concrete bottom. The windows consist of a 16 mm double-glazing (5 mm + 6 mm (air) + 5 mm) in plastic frames. The calculated U-values for the envelope can be found in Table 32 in Chapter 5.1.1. If the specification of a material is available, this value is used to calculate the U-values, otherwise the typical specific value of the Fraunhofer IBP (Fraunhofer Institute for Building Physics) database is used (Table 7).

Table 7:
Example of U-value Calculation of Exterior Wall to Balcony with the Property of Material [Source: Property of Insulation- Specification of Product, Property of Another Material from IBP Database]

Material	Thickness [m]	Thermal Conductivity [W/(m K)]	Thermal resistance [(m² K)/W]
External Thermal Resistance			0.04
Cement Brick	0.19	0.8	0.32
Insulation	0.065	0.035	1,86
Gypsum Plaster	0.019	0.2	0.14
Internal Thermal Resistance			0.13

Special Characteristic

The balconies in the dwellings are often expanded to the living room or to the bedrooms by the owners after the completion of construction work by the partner company (see Figure 17). These enlargements, generally carried out by small local companies, became a very popular trend in Korea in recent years. Hence, the construction companies plan to design without the balcony in front of the living room.

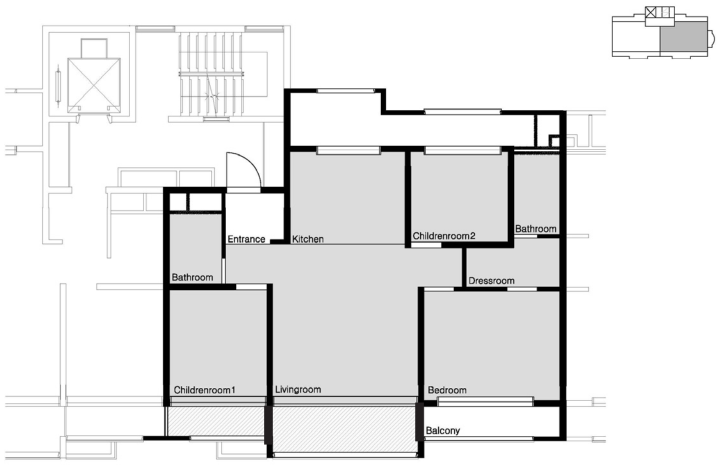


Figure 17:
The Floor Plan of Investigated Dwellings of Building A; Hatched Area Is the Balcony Enlarged to Living Area

The original slide windows (left in Figure 18) with U-Value of 3.3 W/ (m²·K) were replaced by double slide windows (right in Figure 18). According to [58], the U-value of double windows is generally smaller than 2 W/ (m²·K) and the calculated U-value in this study based on the heat flux measurement yields approximately 1.1 -1.4 W/ (m²·K).

Figure 18:
The Windows Before(Left) and After the Enlargement of the Balcony (Right) : Double Sliding Window with U value 1.1-1.4 W/(m²·K) (from outside to inside: mosquito net, 1 m high glass balustrade, double-glazed window, air layer (9 cm), double-glazed window)

3.1.2 Building B

In comparison to the Building A, the Building B, has only two buildings with 204 dwellings. These houses were completed in August 2006 and have different sizes from 106 m² to 212 m².

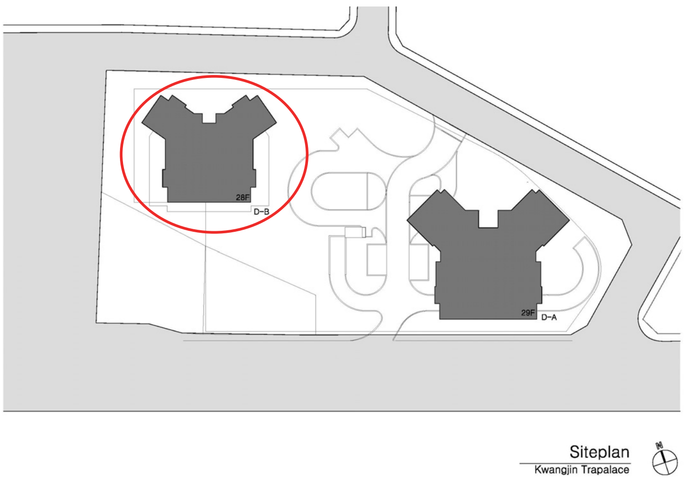


Figure 19:
Site Plan of Building B: (Red Circle Building: Comprehensive Investigation)

The general information of dwellings measured in Building B can be found in Table 8.

Table 8:
General Information on the Building B

	Building B: Comprehensive Investigated Building
Story of the Building	28 F
Floor of Dwellings measured	11F (B1), 17 F (B2) and 25 F (B3)
Construction	Steel concrete
Size	148,76 m² (Net living size: 129.6 m² without balcony)
Room Height	2.4 m
Ventilation	Mechanical air supply and general exhaust without heat recovery.
Heating	Local gas boiler / Floor heating
Cooling	Split air conditioner

Envelope

The envelope of the Building B has the same construction as the Building A.

Special Characteristic

The fresh air is supplied to the main bedroom and to the living room and exhausted in the bathroom. In the kitchen, the hood exhausts the warm air caused by the cooking and uses this heat to warm the fresh air supply in the kitchen. The three dwellings measured in the Building B were also enlarged by their owners (Figure 20).

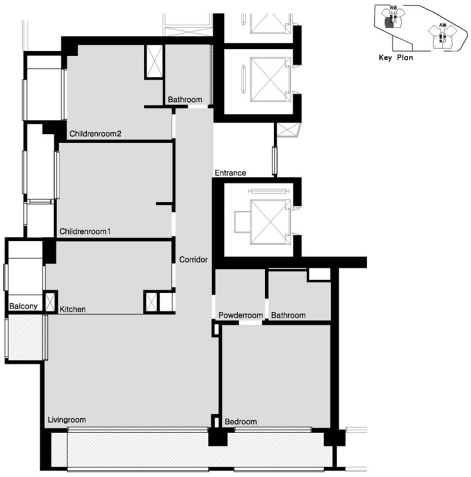


Figure 20:
Floor Plan of Investigated Dwellings of Building B. Hatched Area Is the Balcony Enlarged to Living Area

3.2 Measurement Systems

Comprehensive Measurement in the Six Dwellings

The first requirement of the partner company concerning the measurement system was the minimization of annoyance for the occupants in the dwellings. Generally, the measurement system for a long-term monitoring consists of four parts: sensors, measurement device, data recording, and database (Figure 21).

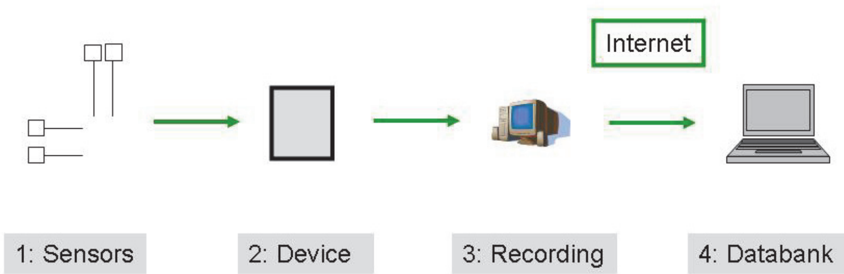


Figure 21:
General Measurement System

Up until now, only a few sensors are integrated or wirelessly connected to a device, with the exception of temperature and relative humidity sensors. So the sensors must be wired independently to the device system. At the time of a preparation for the measurement, there were three possibilities available on the market for the data transfer from the device to the recording system: a) conventionally wired communication, b) wireless system and c) Ethernet system.

The existing wireless system with a transmitter on the device and a receiver connected to the recording system should have worked freely without the walls or the ceilings, but they did not work in the dwellings. Furthermore, the system was too expensive. Fraunhofer IBP decided in favour of the Ethernet system for this study, since the network was already provided in all rooms of the dwellings measured. In the Ethernet system, all devices were connected to each other and to the recording system in a proper network. The data from these devices in one dwelling was collected by Ethernet in one measuring computer which was connected to the Fraunhofer IBP database using IMEDAS system (Internet-based Measurement Data Acquisition System). This data could be tracked via the internet by Fraunhofer IBP as well as by the partner company (see Figure 22).

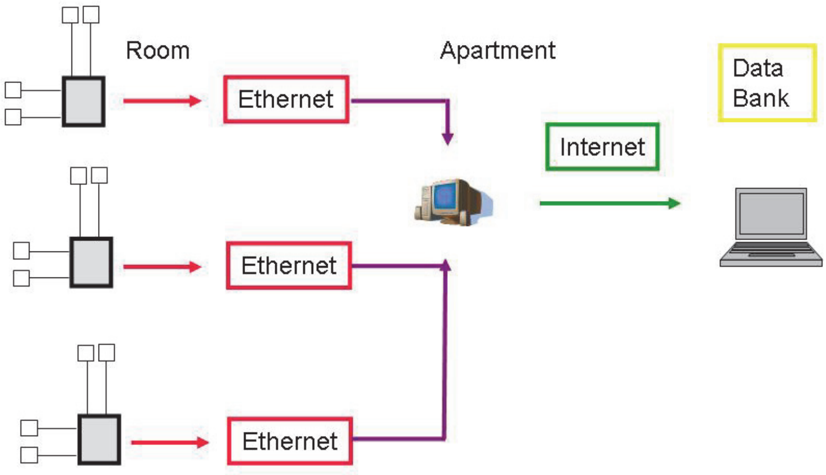


Figure 22:
Measurement System for This Study

Stand Alone System in the 18 Dwellings

For the measurement in the 18 dwellings, a stand-alone system was chosen due to its cost efficiency. The data recordings of every 10-minute intervals on data logger (ESCORT) were downloaded every three months.

3.3 Preparation of Questionnaire

Parallel to the investigation of the environmental conditions (measurement activities) the perceptions of the occupants to these conditions will be analyzed in this study to assess the indoor environment. Generally, these perceptions are studied psychologically in nearly all field studies using self-administered questionnaires.

The objectives of the questionnaires are:

a) Developing of a thermal comfort model with regards to the Korean climate and culture.
b) Study of the user behaviour.
c) Study of the dissatisfaction on the existing indoor environment.

First of all, the momentary thermal perceptions of the occupants will be studied and related to the measured environmental conditions. Then, the general user behaviour regarding ventilation, heating, cooling, and normal occupancy in the dwelling will be questioned. Finally, the general perception about the indoor environment regarding temperature, humidity, airflow, air quality, acoustics, and sunlight in relation to the season will be asked. In addition, a few indoor symptoms will be questioned in order to find out the relation between the physically measured indoor climate and perceived indoor climate in homes.

How Should It Be Questioned?

Since the questionnaire is a psychological investigation, the results often depend on the linguistic expression, scales, and sequence of questions. Being aware of this problem, the international standard organization offers a standard on subjective judgement scales for the assessment of thermal environment (EN ISO 10551(2002) [59]). However, the five judgement scales about thermal sensation, preference, comfort, acceptance, and tolerance of the thermal environment may be useful for the first purpose described above, but not for the second or third purpose. There are a few systematic studies on the psychology-based questionnaire developed for the indoor environment study in homes. One of the most comprehensive studies is the "Stockholm Indoor Environment Questionnaire"[60]. According to this work, the general structure of the questionnaire was constructed, by making a rational order of the questions. On the opinion of Engvall [60], this is more important than being short and compact. In Engvall Investigation, she began with initial questions about general satisfaction with different aspects in order to give the occupants the possibility to express the strong emotional feelings, which are not directly related to indoor climate. After this initial questions the environmental questions about thermal condition, ventilation and air quality, sound, and illumination follow. According to [60] , delicate questions such as on health should be asked in between the more emotionally neutral environmental questions. Finally, background questions can be asked.

Regarding these aspects and purpose of this thesis the questionnaire is developed based on the Stockholm Indoor Environment Questionnaire [61] and the previous investigations in Fraunhofer IBP.

Therefore, the questionnaires include the following:

a) General Information
Age, gender, size of dwelling, daily attendance duration of family.

b) General Satisfaction
Location, planning, standard of apartment, indoor environment, and as whole

c) User Behaviour

- Use of air conditioner in summer.
- Use of heating system in winter.
- Window opening behaviour.
- Use of mechanical exhaust.
- Use of mechanical air supply.
- Condensation and mould in a dwelling.

d) General Satisfaction on Indoor Environment
Thermal comfort, humidity, air quality, noise, sun light.

e) Thermal Comfort in Moment
Thermal sensation, thermal comfort, clothing insulation value.

The questionnaire form used in three seasons can be found in [62].

3.4 Measurement Campaign

3.4.1 Spot measurement and Questionnaire

A mobile cart modified from a trunk was developed for the spot measurement at Fraunhofer IBP especially for the aircraft transport. It provided every second measurement values of air temperature, globe temperature, relative humidity, and air velocity in 1.1 m height by a data logger. The spot measurement took 20 minutes for its operation in one dwelling while the resident was answering questions, using the self-administered questionnaire on the tablet PC. Fraunhofer IBP and Fraunhofer Korea recruited 90 residents in July 2009 to participate three times in the questionnaire campaign. The spot measurements and questionnaires were worked out at three times; in July 2009, October 2009, and January 2010. The number of participants in four building complexes can be found in Table 9. Approx. 75 % of the participants were women and 41 % were between 35 and 44 years old (Table_ A 1, Table_ A 2). Approximately half of the households had four residents and 30 % of the rest had three residents living in an apartment (Table_ A 3). The average size of an apartment is between 107 and 149 m² (Table_ A 4). The average daily occupancy duration of residents varied from 19 hours of an adult to 9 hours of a child (Table_ A 5).

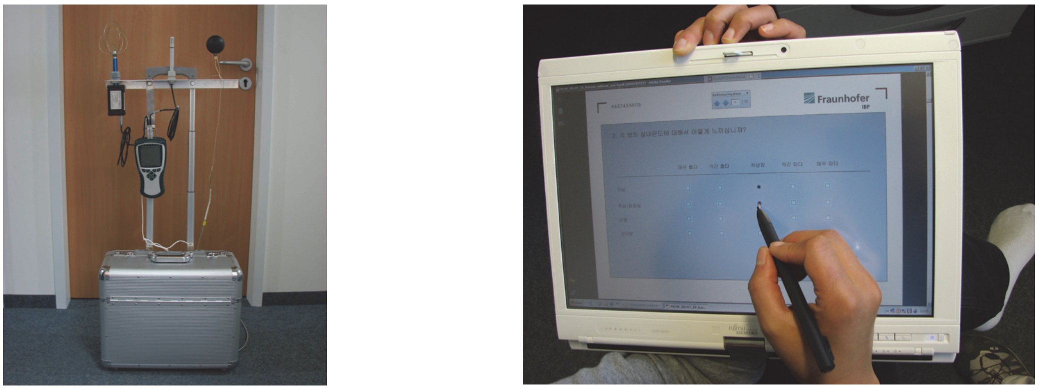


Figure 23:
Spot Measurement Equipment and Questionnaire Equipment

Table 9:
Number of Participants in Spot Measurements

	Date	All	Building A	Building B	Building C	Building D
Summer	July 2009	88	27	10	26	25
Autumn	October 2009	82	28	8	26	20
Winter	January 2010	85	27	10	25	23

3.4.2 Long-term Monitoring from May 2009 to July 2010

After the calibration of sensors, the equipment were transported from Germany to Korea and set up in 24-dwellings. This campaign was carried out by Fraunhofer IBP on behalf of the partner company between May 13, 2009 - May 24, 2009. The data acquisition began on May 25, 2009. All sensors and data loggers in 24 measurement dwellings were uninstalled in July 2010 and finished the measurement action.

Comprehensive measurements in the six dwellings

Monitored parameters were:

a) Air temperature
b) Relative humidity
c) Carbon dioxide concentration
d) Globe temperature
e) Electrical power for ventilation and cooling, if available

The air temperature and relative humidity were monitored in living rooms, bedrooms children's rooms, bathrooms, stairway as well as the balconies. The carbon dioxide concentrations were measured in living room, bedroom, and children's rooms. In addition, the globe temperature and the electrical power for air conditioners were monitored in a living room, if available.

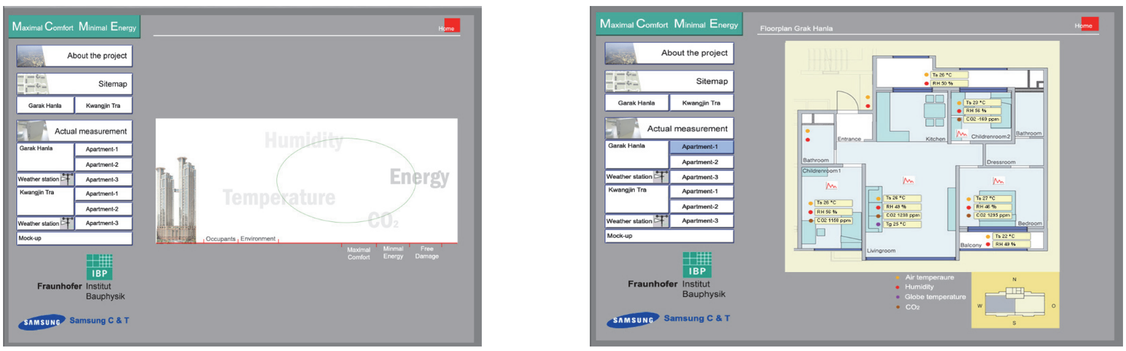


Figure 24:
Monitoring of Indoor Environment by Means of IMEDAS (Internet-based Measurement Data Acquisition System)

Simple measurements in the 18 dwellings

Monitored parameters were:

a) Air temperature
b) Relative humidity
c) Carbon dioxide concentration

A lamp without a light but sensors and data loggers were situated in the living rooms in the 18 dwellings.

4. Analyses of the Existing Buildings

4.1 Analyses of Questionnaire

4.1.1 General Satisfaction

Most residents, who participated in the questionnaire campaign, were satisfied with the location, planning, standard, and indoor environment of apartment as well as an apartment as a whole. Figure 25 shows the mean value of assessment of residents depending on the building. The question has a five scale rating from very satisfied to very dissatisfied with acceptable as a middle point. The mean values for five parameters can be found between satisfied and acceptable in all buildings.

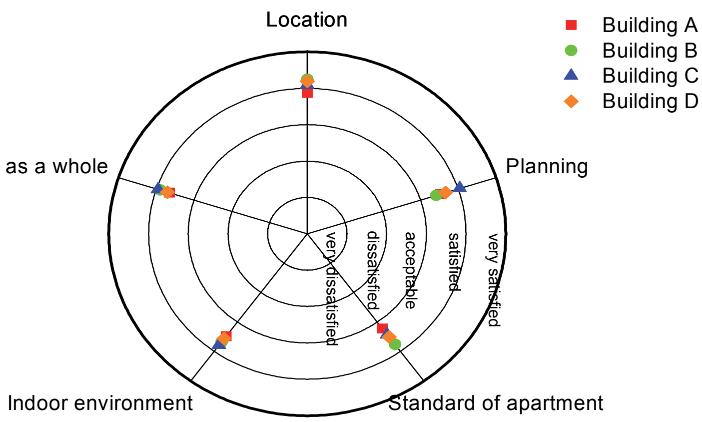


Figure 25:
General Satisfaction (mean value) in the Four Buildings

Figure 26 shows the general assessment of the temperature in the last four weeks in living room, bedroom, children's room, and bathroom in the three seasons. This question also has a five scale rating from "too cold" to "too warm" with "just right" as a middle point. The residents assessed the temperature in the rooms in summer with the tendency of "slightly too warm" and in winter "slightly too cold". The differences between summer and winter are greatest in Building D, especially in the bedroom and children's room.

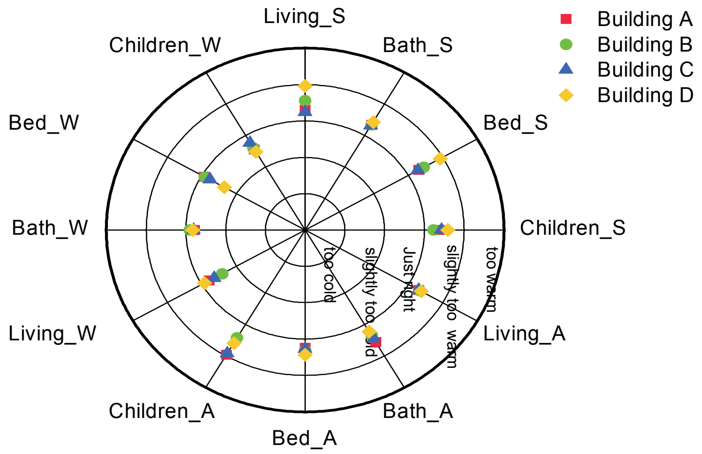


Figure 26:
General Thermal Judgement (mean value) of All rooms in Three Seasons (S: Summer. A: Autumn. W: Winter)

4.1.2 User Behaviour

Thermal Control in Summer

The residents in Buildings A, B and C controlled the thermal environment in summer by means of windows or ventilators rather than air conditioners, while the residents in Building B preferred the ventilator to the window, especially during the sleeping hours. The residents in Building D preferred to use the air conditioners during the day and the ventilators at night than to open windows (Figure 27,Figure 28). The question was a multi-choice question on the thermal control method, if they feel warm.

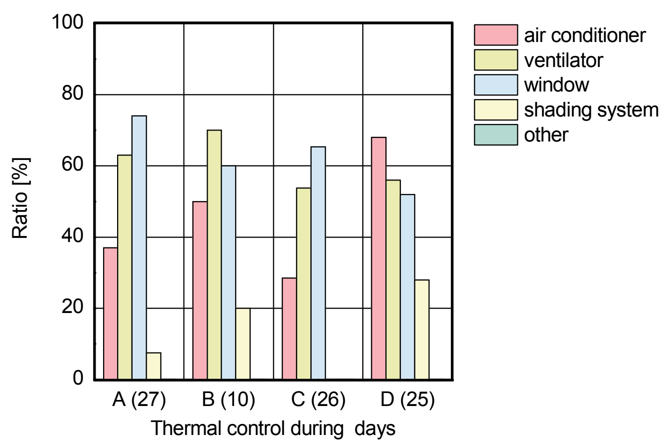


Figure 27:
Thermal Control in Summer during the Day in the Four Buildings (Figures in parenthesis are the number of participants)

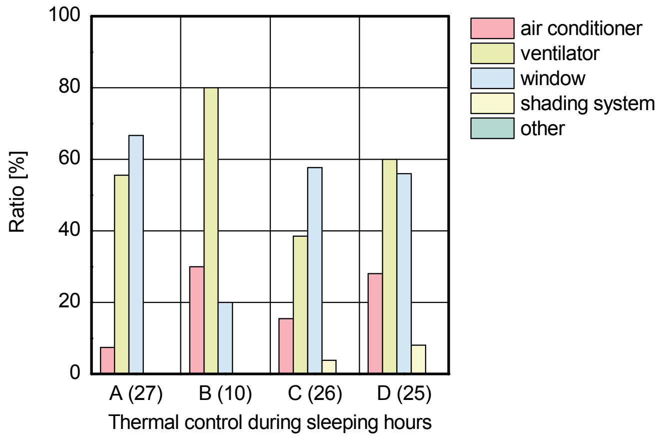


Figure 28:
Thermal Control in Summer during Sleeping Hours in the Four Buildings (Figures in parenthesis are the number of participants)

The same result can be found in the question on how often they use an air conditioner. Most residents seldom or sometimes turned the air conditioners on, except for Building D. It could also be observed during the visits, when the air conditioners were in use in the 42 % of Building D, while the most air conditioners in other buildings were not in operation (Figure 29).

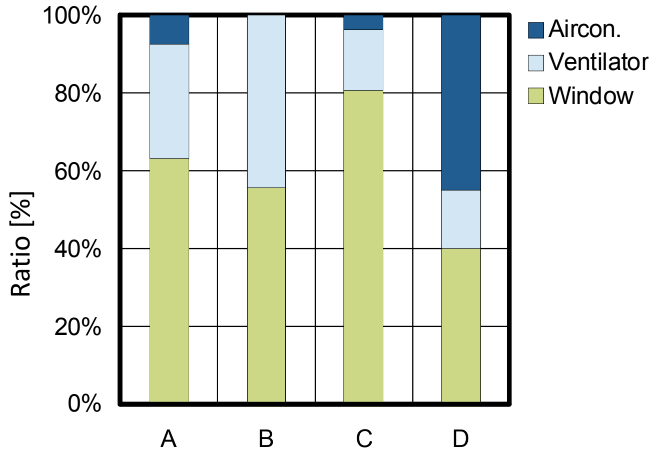


Figure 29:
Ratio of Air Conditioner and Ventilator Use during the Spot Measurement in Summer

The high-energy consumption, the bad air quality, and closed windows for the air conditioner operation stopped the occupants from regularly using an air conditioner (Figure 30).

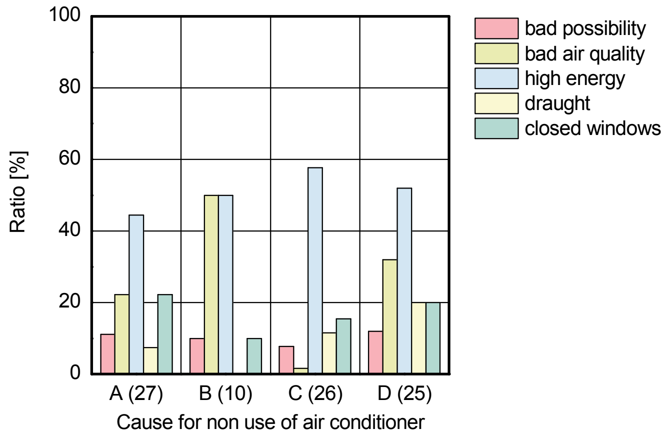


Figure 30:
Cause for Not Using the Air Conditioner

In the four dwellings, the time used and the energy consumed of the air conditioners were measured by means of energy consumption data loggers, which recorded the electric current and the energy consumption of air conditioner at every minute (Table 10). Dwelling A2 and C5 hardly used the air conditioner, while the other two dwellings in the Building B turned on the air conditioners for approx. 20 % of the three summer months (June, July, and August). In the questionnaire, the residents in A2 and C5 stated that they use the air conditioner "seldom" and the resident in B4 "regular, turn on and off". The resident in B5 did not take part in the questionnaire in summer. More than 50 % of the questioned residents except for the Building D used the air conditioner "seldom". Only 4 % of the residents in the Building A and C were regular users of the air conditioners, whereas the 22 % in the Building B and 42 % in the Building D were (Table 11).

Table 10:
Measured Operation Time of Air Conditioner in the Four Dwellings

	A2	B4	B5	C5
Energy Consumption (kWh)	6.7	560.7	373.6	17.7
Operation Time (h)	12.2	456.4	337.5	14.1
Ratio(operation time / 3 months)	1 %	21 %	16 %	1 %
Mean Air Temperature during Three Months [°C]	28.2	28.1	27.6	26.9

Table 11:
Frequency of the Air Conditioner Use in Summer in All Buildings (n=86) According to Questionnaire

	No air conditioner	Seldom. Only If Very Hot	Sometimes. Only for Short Time.	Regular. Only for Short Time.	Regular. Turn On and Off.	Regular. Defined Air Temperature
All	12 %	50 %	21 %	9 %	7 %	1 %
Building A	19 %	52 %	26 %	4 %	0 %	0 %
Building B	11 %	67 %	0 %	0 %	22 %	0 %
Building C	12 %	65 %	19 %	0 %	4 %	0 %
Building D	4 %	25 %	25 %	29 %	13 %	4 %

According to the analysis of air temperature in the dwellings in Chapter 4.3.1, the mean air temperature in the dwellings is rather depending on its building type than on the air conditioner user behaviour. Dwelling B4 shows the lowest average for the absolute humidity of 13.6 g/kg and 13.3 g/kg in July and August among the 24 dwellings (Table_ A 18). These values are below the outdoor absolute humidity of 14.3 g/kg in July and 14.6 g/kg in August and indicate that the dwelling B4 might use the most air conditioning out of the 24 dwellings.

Figure 31 shows a typical temperature pattern in a case of turning the air conditioner on. The air temperature decreases immediately within 5 min. or 10 min. Therefore, the frequency of turning on an air conditioner as well as the initial air temperature and the set air temperature of the air conditioner can be found by the temperature decrease. Using the long-time measurement data from the 24 dwellings, the frequency of air temperature decreased more than 1 °C within 10 minutes was analysed. The mean value of this analysis according to the building can be found in Table 12.

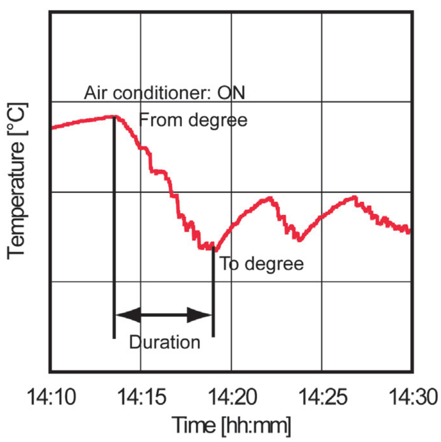


Figure 31:
Typical Temperature Course in a Case of Turning On the Air Conditioner

Table 12:
Cases of Temperature Decrease in 18 Dwellings during the Summer Months (June - August)

	Degree From[°C]	Degree To [°C]	Duration	Average Frequency Per Dwelling [-]
Building A (n=3)	28.4	25.6	22 min.	7
Building B (n=3)	28.9	26.7	30 min.	15
Building C (n=6)	27.5	25.4	21 min.	5
Building D (n=6)	30.6	27.7	32 min.	39
All (n=18)	30.0	27.2	30 min.	17

At the average temperature of 30 °C, the air conditioner would be turned on as a set temperature of 27.2 °C. This effect can also occur by opening the windows if the outdoor air is explicitly colder than the indoor air, but these cases are seldom in summer in Korea. This analysis is not able to evaluate the attended time of the air conditioners, but in which indoor environment the residents might need an air conditioner and in which air temperature they feel acceptable.

The mean air temperature in August by continuous monitoring in the Buildings A, B and C were respectively 28.8 °C, 29.1 °C, and 27.7 °C, which were lower than the Building D with its 30.1 °C (Table_ A 16). The mean outdoor air temperature of 25.5 °C during the whole day and 26.7 °C during the daytime (09:00 - 18:00) in August 2009 were considerably lower than in indoor air temperature. Therefore, the residents controlled the thermal environment by means of opening the window, if the air temperature is not very high and the window ventilation functions. Satisfaction with the window ventilation was lowest in the Building D, although according to questionnaire they opened the windows more frequently than the residents of the other buildings did. This may explain the high frequency use of the air conditioners in the Building D.

Thermal Control in Winter

In all buildings, the residents can control the air temperature by using a small control pad in the living room and separately in each other rooms. These set temperatures in the control pad were asked depending on the following four different occupancy situations: 1) while the family is at home. 2) when only an adult is alone at home. 3) while nobody is at home. 4) at night.

The question has seven scales from "no heating" to "over 29 °C". For the comparison of the data measured, the mean value of the set temperature in the question was calculated in that "no heating" is assumed as 18 °C and "over 29 °C" as 29 °C. The typical set temperature during the time of the occupancy varied between 23 °C and 26 °C, in which the Building C had the lowest of 23 °C, and the Building D had the highest set temperature of 26 °C. These questionnaire results generally corresponded with the continuous measurement data from the 24 dwellings in January 2010 and the 20 min. spot measurement in the 85 dwellings during the questionnaire campaign.

Table 13:
Set Air Temperature in Heating System in Winter According to Questionnaire and Measured Mean Air Temperature [°C]

	Questionnaire				Measurement	
Building	Family_ Living	Sleep_ Living	Sleep_ Bed	Absence_ Living	Monitoring Jan. 2010 (n=24)	Spot Measurement Jan.2010 (n=85)
Building A (27)	24.5	23.5	24.1	21.5	22.5	23.3
Building B (10)	23.2	21.8	23	20	23.2	24.3
Building C (25)	23.0	23.1	23.6	21.4	21.9	23.1
Building D (23)	25.7	26	26.2	22.6	25.1	25.4

The indoor air temperature in Korea is generally higher than in Germany. The cultural difference in between these two countries can be found especially at the set air temperatures in bedrooms. In Germany, the air temperature in a bedroom is generally the lowest in a dwelling during the day as well as during the sleeping hours, while the Koreans prefer to sleep at a similar or warmer temperature than the living room at a daytime. Approx. the 30 % of the residents turned off the heating system, if nobody was at home.

According to the questionnaire, the mean heating energy costs differ between the buildings. The mean heating cost per square meter of living area is the highest for the Building D, followed by the order of the Building B, A and C. This is the same order when the air temperature measured during the spot measurement and according to the assessment of the heating costs. The 43 % of the residents in the Building D found the heating cost "too expensive" in contrast to the 16 % of the Building C. According to this analysis, the high air temperature in the Building D cannot be explained with a failed interest on the heating cost.

Table 14:
Mean Size and Heating Costs of Dwellings and the Assessment of Residents of Heating Cost; All Information Based on the Questionnaire.

Building	Mean Size (m²)	Mean Heating cost (KRW)	Mean Heating Cost (KRW/m²)	Too expensive	Expensive. But OK	Not expensive
Building A (27)	119	94.000	790	27 %	42 %	31 %
Building B (10)	166	145.000	870	40 %	50 %	10 %
Building C (25)	129	78.000	600	16 %	52 %	32 %
Building D (23)	123	112.000	910	43 %	35 %	22 %

Ventilation

– Window (opening)

In summer, the residents in all buildings rather open the windows for the thermal control than for the air quality, which is the dominant cause for the window opening in autumn and in winter (Figure 32, Figure 33). The average for the window opening duration per opening and the frequency of the opening per day were asked in questionnaires and the average opening hours per day were calculated for summer and for winter (Table 15). In summer, the residents let the windows open all day except at night (16.5 hours in living room), while in winter they open only once or twice for a short time. The cold weather in winter forces the residents to close the windows, whereas in summer, the noise and dust from the opened windows induce the residents to close the windows (Figure 34). The Building B has relatively a shorter opening duration in summer, especially in bedrooms. The Building B lies directly on a busy street in Seoul.

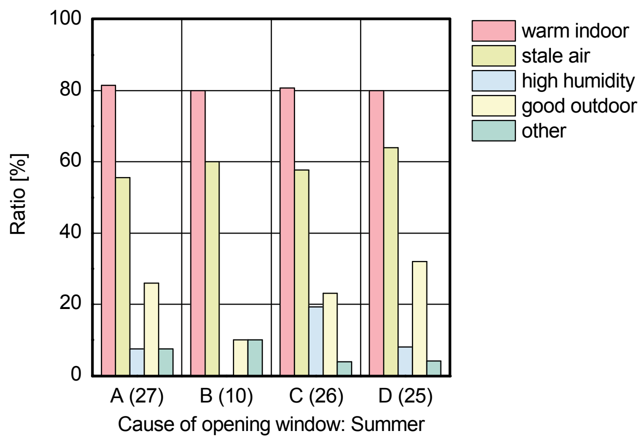


Figure 32:
Causes for Opening Windows in Summer

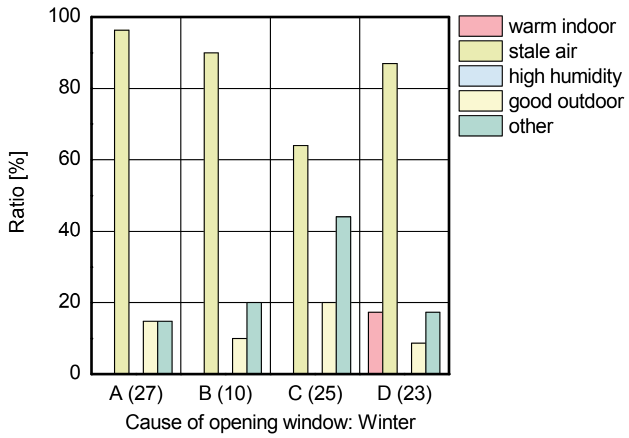


Figure 33:
Causes for Opening Windows in Winter

Table 15:
Average Window Opening Hours in Summer and in Winter According to the Questionnaire (hour/day)

	Summer			Winter		
Building	N	Living room (h)	Bedroom (h)	N	Living room (h)	Bedroom (h)
A	27	16.1	14.7	27	0.7	0.8
B	9	12.3	5.7	10	0.8	0.7
C	26	16.4	15.2	25	0.5	0.3
D	24	18.5	14.3	23	0.9	0.8
All	86	16.5	13.8	85	0.7	0.7

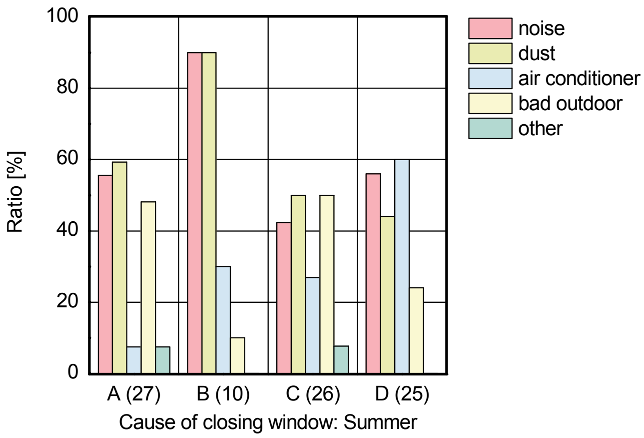


Figure 34:
Causes for Closing Windows in Summer

– Use of the Mechanical Ventilation System

The 75 % of residents in all buildings use the mechanical exhaust system in the bathroom regularly (Figure 35), and 10 % of residents never use the mechanical exhaust system. Noise is the main reason for not using the mechanical exhaust system. Some residents simply have no needs for an exhaust system and others fear the high-energy consumption of the system (Figure 36).

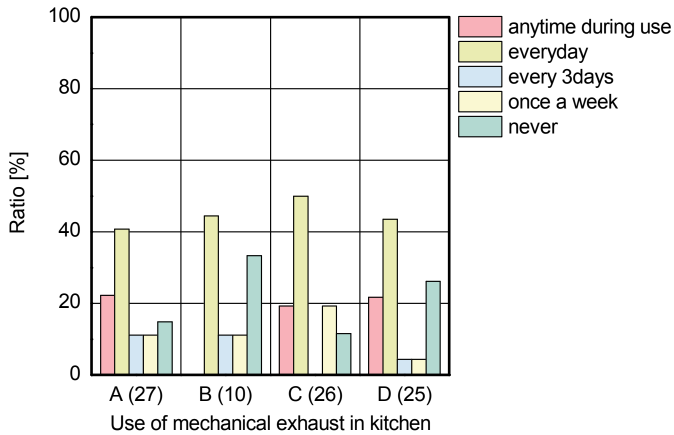


Figure 35:
Use of a Mechanical Exhaust in a Bathroom

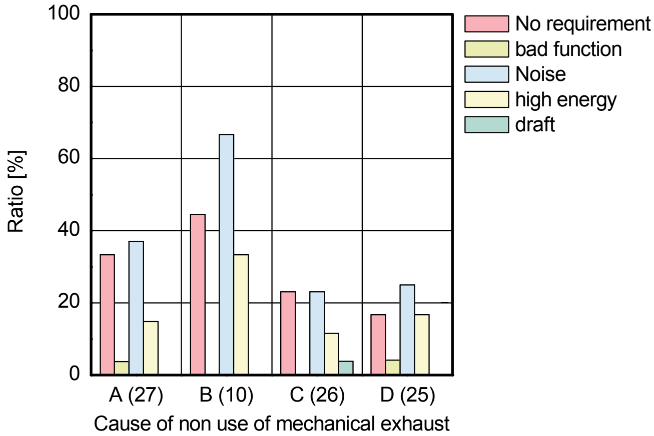


Figure 36:
Reasons for Non-use of a Mechanical Exhaust System

– Mechanical Air Supply System

Although a mechanical air supply system can be a good alternative for avoiding the dust and noise of window ventilation, the residents regularly refrained from using the mechanical air supply system. According to the questionnaire, more than 50 % of the residents never even turned on the air supply system (Figure 37). This user behaviour is confirmed also by the means of measurements. As is the case with the air conditioner, the energy consumption and used time of air supply system were measured by using an energy consumption data logger in 10 dwellings in the Buildings B and D. The results are shown in Table 16. Only one dwelling used the air supply system regularly (100 %) and two dwellings used it sometimes (14 % to 16 %) during the measured time. Another seven dwellings rarely or never used the system. The 100 % use of the mechanical air supply system in a dwelling is assessed as despairing in comparison to other dwellings, therefore the questionnaire of this dwelling is especially examined. The residents in this dwelling said that they never use the air supply system. In fact, the residents did not notice the air supply system although the mechanical system was operating at all times.

Although many residents never tested the mechanical air supply system, they stated the draft and noise as the causes for the non-regular use of the system (Figure 38). The above-mentioned case (100 % use of air supply system) shows that the air supply system used in dwellings produces neither a strong disruptive noise nor a draft. It indicates the negative association on a mechanical ventilation system of draft and noise based on a previous user experience or misinformation. On the other hand, the existing system may not convince the residents of the advantage on the air supply system.

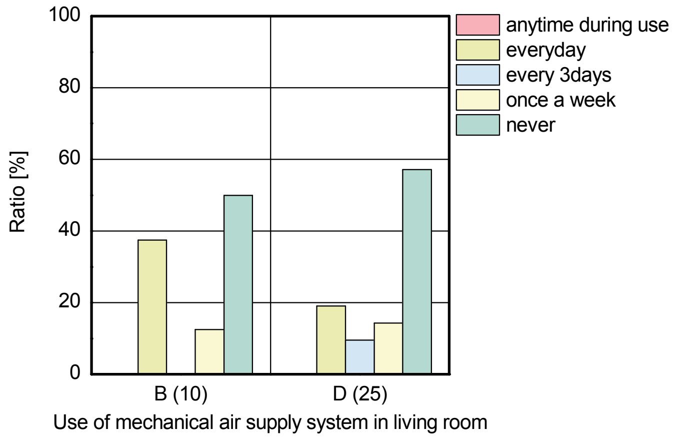


Figure 37:
Use of Mechanical Air Supply System in Living Rooms According to Questionnaire

Table 16:
Use of Mechanical Air Supply System According to Measurement Monitored

	B1	B3	B4	B5	B6	D1	D2	D3	D5	D6
Ratio (measured time / year)	55 %	46 %	63 %	16 %	92 %	34 %	62 %	38 %	56 %	61 %
Ratio (ON) by measured period	2 %	0 %	16 %	0 %	0 %	100 %	1 %	2 %	1 %	14 %
Energy Consumption (kWh) during Measurement	16.3	6.4	59.8	1.9	16.4	194.6	23.4	12.4	9.2	72.9
Assumed Energy Consumption for One Year (kWh/a)	29.5	14.1	94.9	12.1	17.9	579.2	37.7	32.7	16.5	119.2

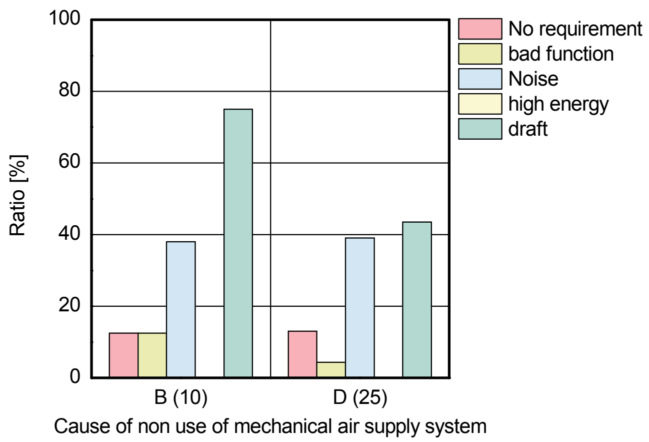


Figure 38:
Causes for Non-use of a Mechanical Air Supply System

4.1.3 Satisfaction with the Indoor Environment

In summer, the noise was among the most dissatisfying parameter of all five indoor environmental factors asked for: thermal conditions, humidity, air quality, noise, and sun light (Figure 39). This high ratio of dissatisfaction caused by noise was a little bit reduced in winter and the dissatisfaction with the humidity was considerably increased in winter (Figure 40).

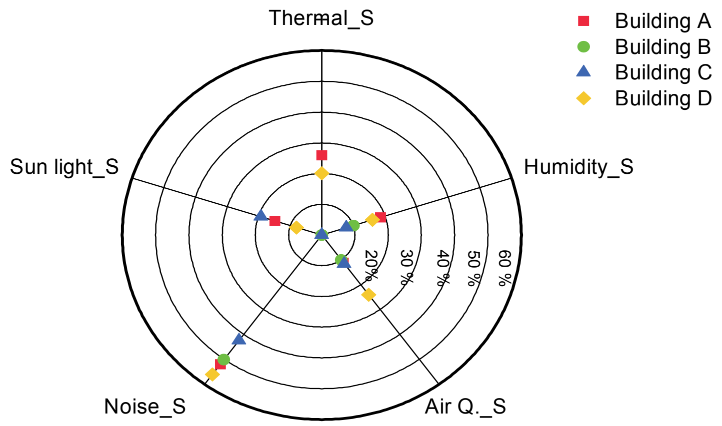


Figure 39:
The Ratios of Dissatisfied Residents on Five Indoor Environmental Factors in Summer

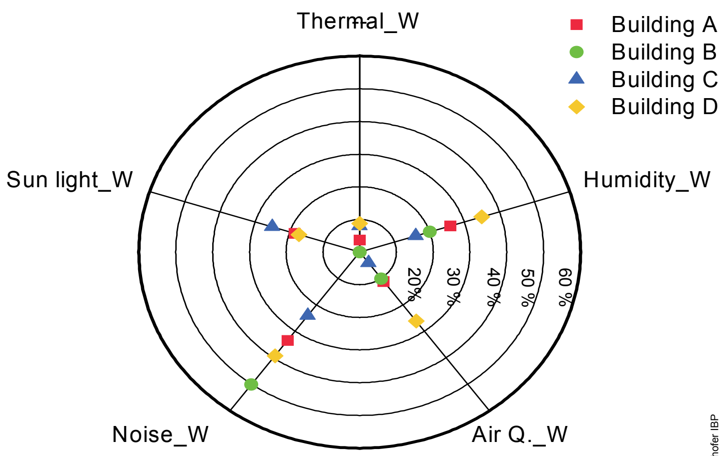


Figure 40:
Ratios of Dissatisfied Residents on Five Indoor Environmental Factors in Winter

The Figure 41 provides the source of noise in summer and Figure 42, for the winter. In summer, the questionnaire did not include the source of noise from the upper floor, however, some residents complained the interviewer about the disruption from the upper floor and this source was later included in the winter questionnaire. The annoyance from the upper floor was less in the Buildings B and D than in the Buildings A and C, as they were built as a solid construction. However, the dissatisfaction by noise was greater in the Buildings B and D than in both of the other buildings. Apparently, the noise from outside made the residents very dissatisfied especially in the Buildings A, B and D, depending on their locations. In order to determine the quality of noise protection of windows, the sound levels were measured under both closed and opened window conditions during the autumn questionnaire. It was difficult to qualitatively assess the sound level due to the individual noise source during the spot measurement, such as a noise from children or washing machine. The sound levels of a closed window condition without the extra indoor noise amounted to between 31 and 42 dB, which almost complied with the 40 dB of required level for living rooms in EN 15251. However, the sound levels with opened windows were higher than 50 dB, often even up to 60 dB, with the exception of several dwellings. Only one dwelling complied in accordance with EN 15251 with an opened window.

This result shows once more that the residents are disturbed very strongly by the outside noise produced by vehicles from the busy streets of Seoul, especially those of the residents living directly on the main streets.

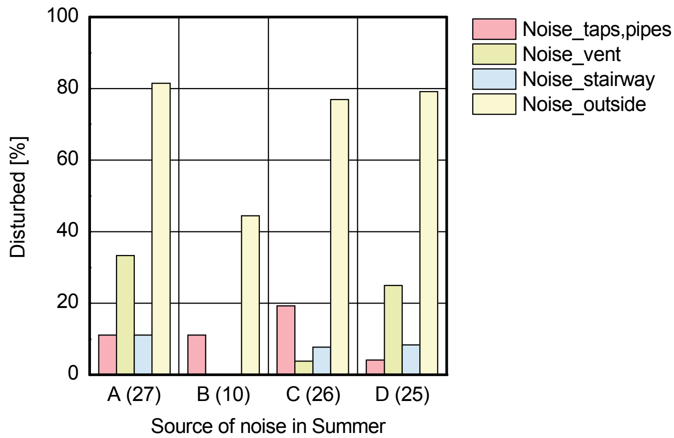


Figure 41:
Sources of Noise in Summer

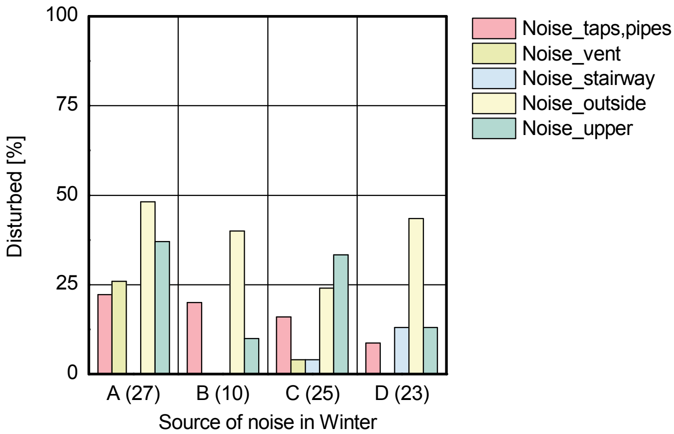


Figure 42:
Sources of Noise in Winter

Table 17 shows the measured relative humidity (RH) during the winter spot measurement. The RH in 28 % of all measured dwellings is lower than 30 %, which is generally recommended as a minimum value in order to avoid skin dryness.

Table 17:
Frequency of Relative Humidity During the Winter Spot Measurement

Relative humidity [%]	10 <=x< 20	20 <=x< 30	30 <=x< 40	40 <=x< 50	50 <=x< 60
Frequency (all=85)	1	23	32	24	5
Percentage	1 %	27 %	38 %	28 %	6 %

4.1.4 Mould and Condensation

On one hand, the generally low RH in winter constitutes as a problem for the occupancy satisfaction (see 4.1.3). On the other hand, many dwellings have problems with condensation and mould in winter.

Table 18 shows the ratio of the condensation problem in dwellings depending on the buildings and rooms. Most of the dwellings in the Building D do not have a balcony and the kitchen has no window. In Building C, the question about a condensation was left out on the self-administered questionnaire and was asked later from interviewers via telephone, but it did not include the balconies.

Table 18:
Ratios of Condensation on Windows According to Questionnaire

	A	B	C	D
Living room	22 %	10 %	27 %	61 %
Bedroom	0 %	10 %	10 %	57 %
Children's room	19 %	0 %	19 %	39 %
Kitchen	15 %	0 %	24 %	
Kitchen_Balcony	30 %	10 %		
Living_Balcony	15 %	10 %		

Although Building D has a high ratio of condensation on the windows, mould was hardly observed in comparison to Building A and Building C, where the mould problem was often noticed, especially in the balcony areas. The Building B had a low ratio of condensation and mould in winter. In one dwelling, the mould problem was noticed in summer (Table 19).

Table 19:
Ratios of Mould Problem in Winter According to Questionnaire

	A	B	C	D
Living room	11 %	0 %	16 %	4 %
Bedroom	0 %	0 %	4 %	4 %
Children's room	8 %	0 %	12 %	0 %
Kitchen	7 %	0 %	4 %	
Kitchen_Balcony	19 %	10 %	20 %	0 %
Living_Balcony	15 %	0 %	20 %	0 %

The high ratio of condensation in Building D could be explained by the low U-value of the windows (3.3 W/(m²·K) in comparison to other buildings with 1.1 - 1.4 W/(m²·K)). The low ratio of mould can occur due to the relatively high air temperature or high infiltration rate or user behaviour (high frequency of window opening) or thermal bridge-free construction. In addition, the high moisture buffer functions based on the gypsum board construction as inner wall in comparison to the concrete inner wall in Buildings A and C can result in a lower ratio of mould in Building D. If the low ratio of mould was based on the high ventilation or infiltration rate, then the absolute humidity in Building D should have been lower than in other buildings with similar humidity production. However, the measured humidity in the Building D was not lower compared to other buildings during the winter spot measurement as well as from the long time monitoring (Table_ A 18). If the humidity buffer functions in Building D was greater than in Building A and Building C, the standard deviation would have been smaller and the peak of the absolute humidity should have been lower in Building D than in Buildings A and C. However, the standard deviation as well as the difference between the minimum and maximum humidity was not diverse in winter between the Building C and Building D.

Table 20:
The Mean Value of Absolute Humidity and Relative Humidity during the Winter Spot Measurement

	Absolute Humidity (g/kg)	Relative Humidity
A (27)	6.2	34 %
B (9)	5.0	28 %
C (25)	6.8	39 %
D (23)	7.7	38 %

Therefore, the construction without the balconies and a high air temperature in winter might had resulted the low ratio of mould in Building D. Building B has also had low mould ratio due to the lower humidity load based on larger living areas per person and maybe to the higher air change rate than other buildings (see Table 20).

4.2 Analysis of Spot Measurement

4.2.1 Spot Measurement in Summer

The air temperature during the spot measurement in the 82 dwellings in summer varied from 25.2 °C up to 31.9 °C depending on the buildings, outdoor climate, and use of air conditioning systems. During the measurement, air conditioners in 12 dwellings were in operation. The average air temperature was 27.8 °C. The radiation temperature calculated according to ISO 7726 from the measurement of globe temperature was almost similar to the air temperature. The air velocity varied from 0.02 m/s up to 0.43 m/s. Most of the dwellings had the windows open and in addition, ventilators in 19 dwellings lead high air speed in the dwellings. The average air velocity was 0.14 m/s. The clothing insulation value was almost consistently with 0.5 clo in all dwellings. The relative humidity, as well as the absolute humidity were very high with an average value of 66 %, in respect to 15.2 (g/kg).

If the air temperatures and PMVs are compared in the four buildings, the PMV, as well as the air temperature in the Building B are the highest followed by the Buildings D, C and A. The low air temperature and PMV in the Building A can be explained by the outdoor climate during the spot measurement (Table 21). Although the outdoor air temperature during the spot measurement in the Building D was relatively lower than Building B and Building C, and also the air conditioners in 45 % of the dwellings were in use, the operative temperature in Building D was not lower than in Building C. The detailed descriptive analysis about the spot measurement can be found in Table_ A 9 to Table_ A 15 as well as in Figure_ A 7 to Figure_ A 12 in the annex.

Table 21:
The Average Outdoor Air Temperature and Indoor Operative Temperature in the Four Buildings during Summer Spot Measurement

Building	Date	n	Average Outdoor Air Temperature	Average Operative Temperature	Frequency of Air Conditioner [on]
Building A	13,14,15 July	27	22.8	26.7	2
Building B	16,17 July	9	25.1	28.8	0
Building C	20,21,22 July	26	25.2	27.7	1
Building D	23,24 July	20	23.7	28.3	9

4.2.2 Spot Measurement in Autumn

During the autumn spot measurement, most of the dwellings were neither heated nor cooled. Only in 5 dwellings out of 81 the heating was on. The air temperature varied from 21 °C to 29.5 °C and the average air temperature was 24.7 °C. The average air temperature and operative temperature in Building D was the highest and in Building C was the lowest. In contrast to the temperature, the average relative as well as absolute humidity were the lowest in Building D. The air velocity and clothing insulation values were similar in all buildings. Due to the high air temperature the PMV in Building D was approximately 0.5 higher than in other buildings. The detailed descriptive analysis of the spot measurement can be found in Table_ A 7 and from Figure_ A 13 to Figure_ A 17 in the annex.

Table 22:
The Average Outdoor Air Temperature and Indoor Operative Temperature in Four Buildings during the Autumn Spot Measurement

Building	Date	n	Average Outdoor Air Temperature	Average Operative Temperature
Building A	12,13,14 Oct	27	15.1	24.2
Building B	14,15 Oct	8	15.1	24.6
Building C	16, 19 Oct	26	14.4	23.8
Building D	21,22 Oct	20	13.9	26.1

4.2.3 Spot Measurement in Winter

The average operative temperature during the winter spot measurement was relatively high with 23.6 °C (Table 23).

Table 23:
The Average Outdoor Air Temperature and Indoor Operative Temperature in Four Buildings during Autumn Spot Measurement

Building	Date	n	Average Outdoor Air Temperature	Average Operative Temperature
Building A	22, 27 Jan	27	-3.0	23.1
Building B	26, 28 Jan	10	-0.1	24.0
Building C	18, 19 Jan	25	1.1	22.9
Building D	20,21 Jan	23	1.7	24.6

The air temperature varied from 20 °C to 29 °C and 19 % of all dwellings were heated more than 26 °C. Especially 47 % of the dwellings of Building D exceeded more than 25 °C, which was the upper limit of the recommended operative temperature for residential buildings according to EN 15251 (Table 24). While the air temperature and mean radiation temperature in summer and autumn do not show a difference in all buildings, the mean radiation temperature in Building D is 1.5 K lower on average than air temperature. It indicates the lower envelope insulation value of Building D in comparison to the other buildings (Table 25).The mean radiation temperature is calculated from the measured globe temperature according to ISO 7726.

Table 24:
The Percentage of Different Air Temperature in Four Buildings during Winter Spot Measurement

Building	N	20 - 21 °C	22 - 23 °C	24 - 25 °C	26 -27 °C	28 - 29 °C
Building A	27	11 %	48 %	33 %	7 %	0 %
Building B	10	0 %	40 %	50 %	0 %	10 %
Building C	25	16 %	44 %	32 %	8 %	0 %
Building D	23	4%	13 %	35 %	30 %	17 %
All	85	9 %	36 %	35 %	13 %	6 %

Table 25:
Comparison of Average Air Temperature and Average Mean Radiation Temperature During Winter Spot Measurement

Building	Air Temperature [°C]	Radiation Temperature [°C]	Difference [K]
Building A	23.3	22.9	0.3
Building B	24.3	23.8	0.5
Building C	23.1	22.7	0.4
Building D	25.4	23.9	1.5
All	23.9	23.2	0.7

The detailed descriptive analysis of the spot measurement can be found in Table_ A 8 and in Figure_ A 18 to Figure_ A 23 in the annex. The average clothing insulation value is relatively low with 0.8 (clo) in Buildings A.B and C, with 0.7 (clo) in Building D. Due to this lower clothing insulation value and lower radiation temperature in Building D, the average PMV in Building D is only 0.4 higher than in Buildings A and C, in spite of the high air temperature. The 0.1 (clo) difference of clothing insulation leads to 0.16 difference in PMV calculation at 24 °C operative temperature.

4.3 Analysis of Continuous Measurement

4.3.1 Indoor Environment in Living rooms in 24 Dwellings

The average air temperature in the living rooms in 24 dwellings greatly varied depending on the dwellings. The difference between the minimum and maximum average air temperature was greater in winter with 7.5 K than in summer with 4.5 K or 5.5 K in the change of two seasons (Figure_ A 24). The monthly mean air temperature in the four buildings is shown in Figure 43. The air temperature in Building D was always the highest independently of the month, while Building C always showed the lowest air temperature during one year. The difference between the two buildings was approximately 3 K. This result complies with the results of spot measurement (Chapter 4.2) as well as of the questionnaire (Chapter 4.1.2). The average air temperature in all dwellings was 23.5 °C in winter (Dec. - Feb.) and 28.3 °C in summer (Jun. - Aug.). The air temperature in September was similar to June with 27.6 °C, while in March it was similar (23.6 °C) to the winter months. A monthly average air temperature in all dwellings can be found in Table_ A 16.

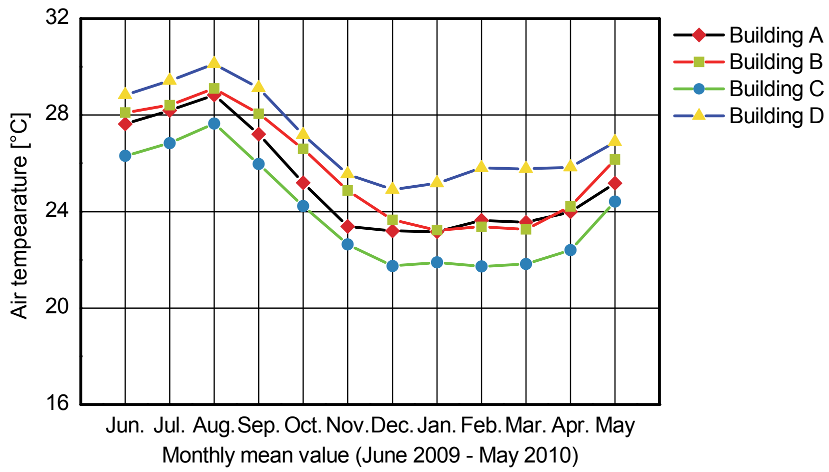


Figure 43:
Monthly Mean Air Temperature in 24 Dwellings (n=24 from Jun. 2009 to Jan. 2010 and n=21 from Feb. 2010 to May 2010)

The average relative humidity in all buildings was lower in winter with 37 % than in summer with 58 %. Especially the difference between the dwellings was great up to 52 % in winter. While the RH in all dwellings of Building B was below 30 % in January 2010, some dwellings in Buildings A and C exceed 50 % RH, and increased even up to 70 %. The absolute humidity was similar in all dwellings in summer, near to the outdoor humidity, which showed a very high humidity of approximately 14.5 (g/kg) in July and in Aug. The absolute humidity in Buildings B and D is slightly lower than outdoor humidity in August, which might be due to the air conditioner. In winter, the absolute and relative humidity in Building B were expectedly lower than in other buildings, that also with complied with the spot measurement (Table_ A 8). The relative humidity in Building D was lower than in Buildings A and C, but the absolute humidity was similar to both buildings. A monthly average relative humidity and absolute humidity in all dwellings can be found in (Table_ A 17, Table_ A 18) in the annex.

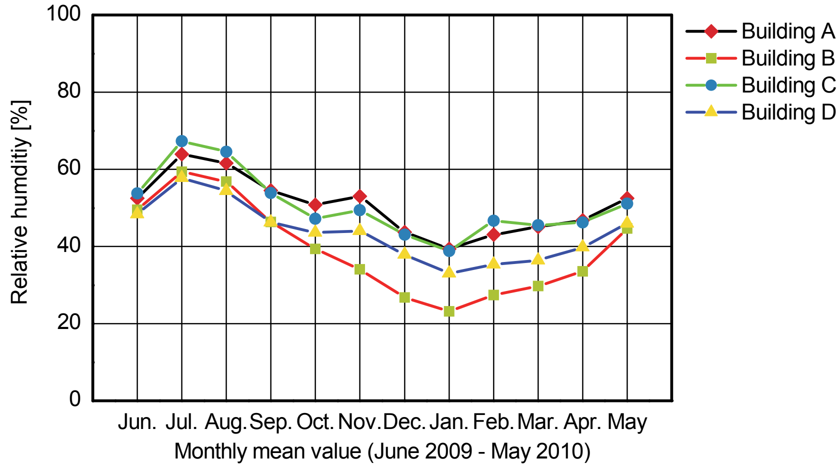


Figure 44:
Monthly Mean relative Humidity in 24 Dwellings

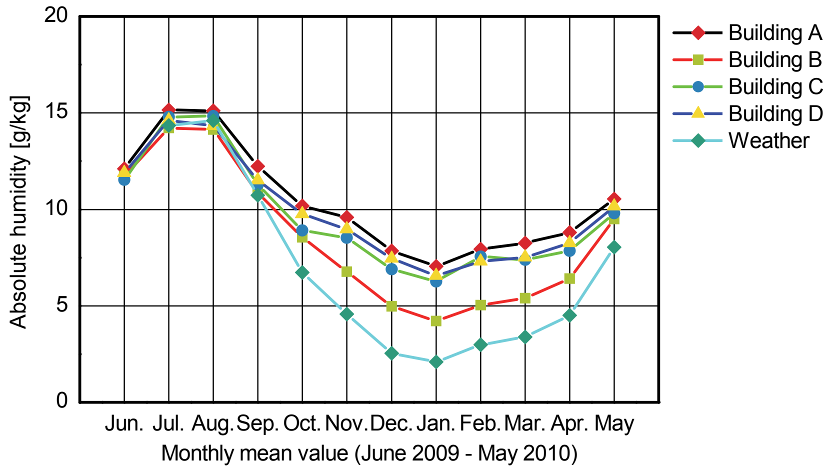


Figure 45:
Monthly Mean Absolute Humidity in 24 Dwellings

4.3.2 Difference of Indoor Environment between Rooms

In winter, the bedroom was warmer than the other rooms independent of the time. It confirmed the result of the questionnaire on the set temperature in rooms (Chapter 4.1.2). The air temperature in living rooms was warmer during the day than at night, while the air temperature in children's rooms was even higher at night than during the day. The weighted average air temperature based on the measurements of the four rooms in a dwelling does not differ from the average air temperature of a living room except A1, so that the average air temperature in a living room can be accepted and represented as the average temperature for a dwelling in a heating period. In A1, air temperature in the bedroom is considerably higher than in the living room, so that the weighted average temperature is 0.9 °C higher than in the living room.

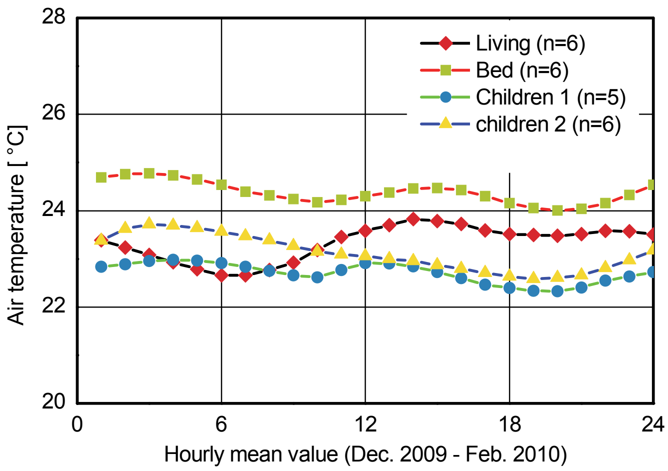


Figure 46:
Hourly Course of Average Air Temperature in Winter (Dec. 2009 - Feb. 2010)

Table 26:
Comparison of a Weighted Average Air Temperature in a Dwelling and Air Temperature in the Living Room in 6 Dwellings during the Heating Period (Dec.2009 - Feb.2010)

Average Air Temperature	A1	A2	A3	B1	B2	B3	Mean
Dwelling (weighted)*	22.4	25.3	21.2	23.2	23.3	26.0	23.6
Living room	21.5	25.2	21.1	23.4	23.3	25.5	23.3

*: Weighted according to area (living room with a factor of 0.4, all other rooms with a factor of 0.2).

In addition, in summer, the air temperature between rooms does not differ from each other. Only the children's room 1 is 0.4 K warmer than the other rooms, maybe based on the high solar heat gain (southeast orientation in the Building A and west in the Building B).

The difference of relative humidity, as well as the absolute humidity between rooms also can be neglected.

4.3.3 Indoor Environment in Balcony in 5 Dwellings

The air temperature on the balcony in 5 dwellings is rather similar to the indoor environment with the average temperature of 27.7 °C in the summer period (Jun. -Aug.) than the outdoor climate (Figure 47). In the winter period, it is warmer than outdoor climate with 13.2 °C ca.14 K. The fluctuation between balconies can be observed in the winter period due to the different air temperature in the dwellings.

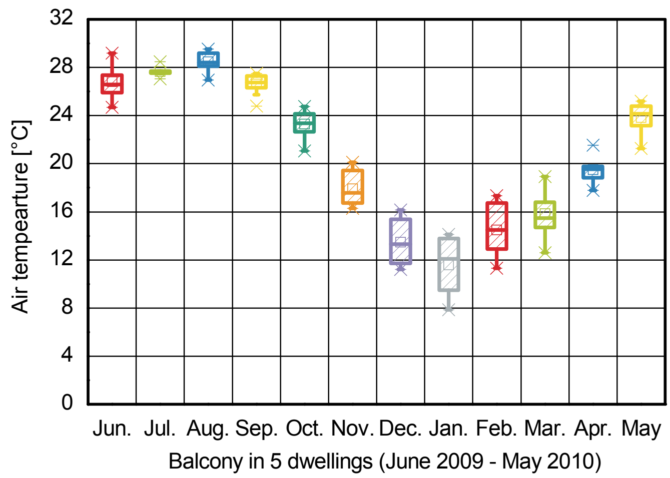


Figure 47:
Box-Plot of Air Temperature in Balcony (n=5): The explanation of Box-Plot can be found in Figure_ A 6 in Annex.

The relative, as well as the absolute humidity varied strongly between the dwellings from 26 % to 77 % respectively from 2.4 (g/kg) to 6.8 (g/kg) in the winter period, while they show hardly any difference in the summer period (Figure 48, Figure 49).

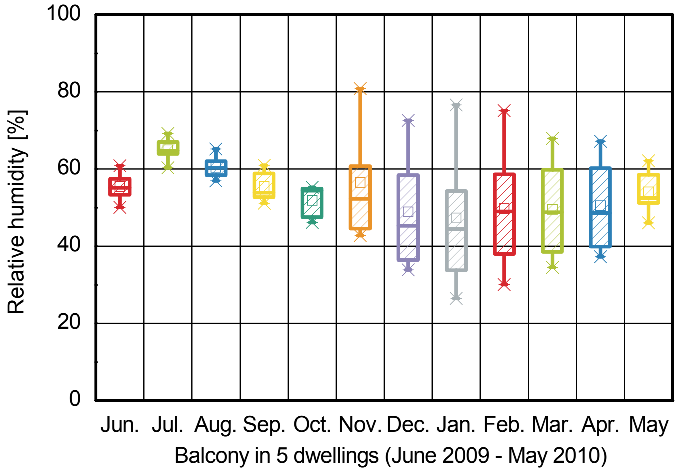


Figure 48:
Box-Plot of Relative Humidity in Balconies

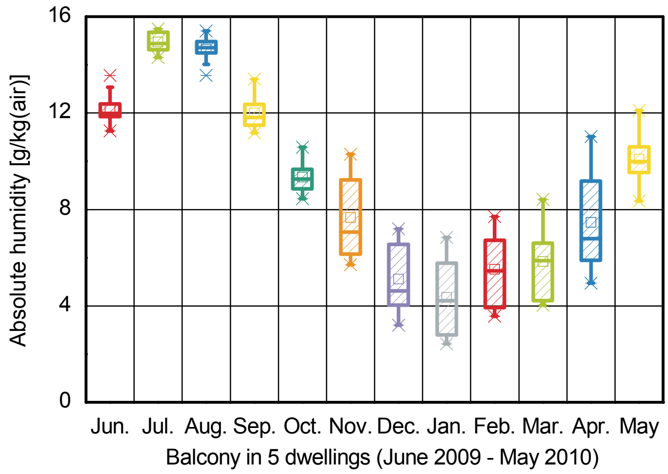


Figure 49:
Box-Plot of Absolute Humidity in Balconies

4.4 Analysis of Constructions and CO_2 Measurements

4.4.1 Thermal Bridge Calculation

Thermal bridges of a construction cause not only the mould growth or condensation problem on the surface of a building, but also influence the energy performance of a building. Especially in the buildings with a good insulation and airtight windows, the impact of a thermal bridge is considerable. The transmittance heat loss of a surface is reduced in a great deal by such buildings, thus the ratio of heat loss due to the thermal bridge is increased. On the other side, the high room humidity cause from a reduced infiltration rate increases the mould growth on the surface of thermal bridges. Therefore, generally two parameters, ψ (Linear Thermal Transmittance Heat Loss) for energy performance assessment and f (Temperature Factor) for mould growth risk assessment, are used for the evaluation of thermal bridges. Comprehensive investigations were carried out in1980s in Germany, which serve calculation methods as well as ψ and *f values* for different constructions with different dimension of internal and external insulation [63]. DIN 4108 -2; supplement 2 provides ψ value of typical construction details. Specific for the balcony construction

DIN V 18599 considers the impact of thermal bridges for the determination of the energy performance and specific transmittance coefficient, in which the effect of point thermal bridge can be neglected (Equation (7)).

$$H_{T,D} = \sum (U_j A_j) + \sum (l_j \psi_j) \tag{7}$$

Where:

$H_{T,D}$	Transmission Heat Loss Coefficient	$[W/K]$
U_j	Heat Transmittance	$[W/(m^2 \cdot K)]$
A_j	Area	$[m^2]$
l_j	Length of Linear Thermal Bridge	$[m]$
ψ_j	Linear Thermal Transmittance Heat Loss	$[W/(m \cdot K)]$

The ψ-value in Equation (7) can be estimated either from aforementioned literature or using software based on ISO 10211:2007 [66]. Such software calculate the overall heat flows, thermal coupling coefficient (L_{2D}) of a two dimensional geometrical model including a thermal bridge. The difference between this overall heat flows and heat flows calculated from the U-value is the ψ-value for the investigated two-dimensional construction (Equation (8)). The length in Equation (8) corresponds to the length by the calculation of energy performance. In Germany, the transmittance heat loss should be calculated using an external dimension of the building. In this case, also in this study, the external length of a geometrical model is used by ψ calculation.

$$\psi = L_{2D} - \sum U_i \cdot L_i \tag{8}$$

Where

ψ	Linear Thermal Transmittance	$[W/(m \cdot K)]$
L_{2D}	Thermal Coupling Coefficient for Two Dimensional Calculation	$[W/(m \cdot K)]$
L_i	Length, for it U-value is valid	$[m]$

All two-dimensional thermal bridges in Building A are determined in Figure 50 and these constructions are calculated using the thermal bridge software ARGOS of "Zentrum für Umweltbewusstes Bauen e.V".

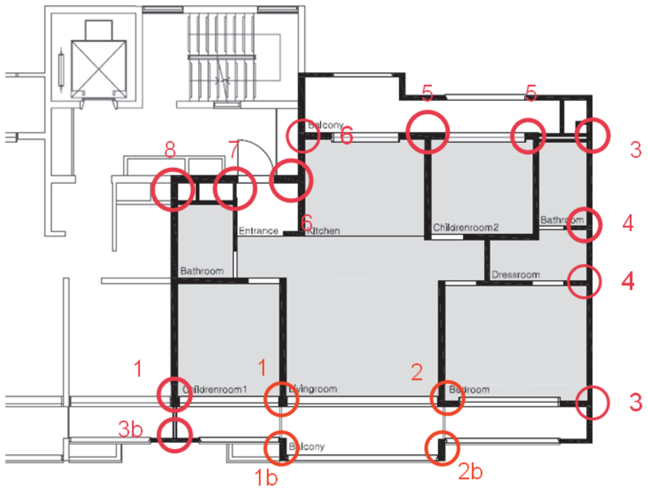


Figure 50:
Investigated Details of Building A

Thermal bridge calculation for current state variant (with expanded balcony area to living area) including details 1b, 2b and 3b can be found in the Table 27. A detailed result of the thermal bridge calculation can be found in Table_ A 20 in annex.

Table 27:
Thermal Bridge Calculation of Building A (current)

Section	ψ -value (W/(m·K))	l_j (m)	Heat loss (W/K)
Detail 1b	0.37	7.50	2.78
Detail 1	0.25	7.50	1.89
Detail 2	0.45	14.36	6.46
Sum			11.13
Horizontal			
Detail 1b	0.67	2.70	1.81
Detail 2b	-0.23	2.70	-0.62
Detail 3b	0.80	2.70	2.17
Detail 3	-0.13	5.40	-0.70
Detail 4	0.40	5.40	2.13
Detail 5	0.58	2.70	1.57
Detail 6	0.01	5.40	0.05
Detail 7	0.53	2.70	1.43
Detail 8	0.87	2.70	2.35
Sum			10.18
All			21.31

According to Hauser [67] the additional average U-value resulted from thermal bridges can be calculated using the following Equation (9). The temperature factors are assumed as 0.5 to stairway and as 0.7 to balcony according to Table 3 in DIN V18599 - 2. The additional U-value due to the thermal bridge yields 0.13 W/ (m²·K) for the plan situation with the external area of 92.8 m² and 0.17 W/ (m²·K) for the current state of 99 m². These results agree relatively well with cross-the-board value of 0.15 W/ (m²·K) for Building with internal insulation in DIN V 18599. All calculations were performed regarding to one dwelling as in Figure 50.

$$\Delta U = \frac{\sum F_{xj} \cdot \psi_j \cdot l_j}{A} \qquad (9)$$

Where:

ΔU	Additional U-value	$[W/(m^2 \cdot K)]$
F_{xi}	Temperature Correction Factor	$[-]$
A	Area of Building Envelop	$[m^2]$

4.4.2 Air Change Rate Calculation

Determination of Ventilation Heat Loss

While the transmission heat loss can be calculated relatively accurate in practice using the U-values of the building materials and ψ values, the determination of ventilation heat loss is often difficult due to the unavailable information of air change rate. The German energy code determines the air change rate depending on the ventilation type and air tightness of a building. The infiltration rate is determined from the result of the pressure test like blower door test (n50) and from the wind factor of the surrounding area. The air change rate affected user behaviour by means of window opening or operation of mechanical system is determined from air tightness, operation duration, the type of mechanical system and the required minimal air change rate for the utilization. The question is how high is the real Air Change rate per Hour (ACH) in the investigated buildings. The air change rate should be kept as low as possible in terms of energy conservation and on the other hand, should remain on an adequate level to assure good air quality and prevent mould growth. In order to assess an existing ACH compared to the recommendation, air change rates in 24 dwellings should be investigated by means of a measurement.

Measurement Methods

There are some methods to measure ACH in a building and an overview about the methodologies of ACH measurement can be found in [68]. The most accurate method is the well-known tracer gas technique using SF6, which is not applicable in this study for the long time monitoring requirement. The spot measurement can only show the ACH under the actual weather situation. It is difficult to study the real ACH affected from the user behaviour and weather. For the long time monitoring, either the PFT (perfluorocarbon tracer) technique, developed from the Brookhaven National Laboratory [69] or the measurement of CO_2 concentration is applied by the investigation of ACH in the occupied rooms [70] [71]. The first technique uses two small size devices, emitter with constant injection rate, and its receiver. The second method, CO_2 generated from the occupancy is used as a tracer gas and the ACH is calculated by means of a mass balance of CO_2 concentration in a building, if the outdoor CO_2 concentration and the CO_2 production in a building are known [74]. The both methods, PFT technique and CO_2 measurement are based on the assumption of a good mixed air in the investigated space, although the concentration of the gas is non-uniform, especially in the space with doors like dwellings. The main disadvantage of PFT technique is that only one average ACH in a whole measurement period can be estimated from the results. The main difficulty with the second method is the accurate estimation of the production of CO_2 variation depending on size, weight, and metabolic rate of a person [75]. The accurate estimation on the number or the duration of occupancy in a building is also difficult. In addition, the existing CO_2 sensors are either too complex for the field study or often not accurate enough. Another problem is that the mass balance is based on the steady state. The production and concentration varies in reality with time.

In spite of such inaccuracy, the CO_2 measurements were carried out in this study, since the concentration of CO_2 can be used also as the indicator of indoor air quality and provides the rudimental information for the air change rate calculation. Due to the aforementioned high inaccuracy of the method, an uncertainty analysis was performed in a student work. In this work [77], firstly CO_2 sensors in 24 dwellings were calibrated using CO_2 sensor of weather station. Then the infiltration rates in the four dwellings were calculated and compared with the results of the Blower Door Test. ACH in 24 dwellings were calculated and finally, the uncertainty analysis of the CO_2 method by ACH calculation was conducted. The aim of this work was to establish an analysis of uncertainty based on the previous mentioned inaccuracy of CO_2 method, especially the effect of time interval on the mass balance calculation. The following calculation results are based on this work. CO_2 AirCheck 2000 (Company: Steinel Solution in Swiss) was used for the measurement of CO_2 concentration. This sensor is based on the measurement principle of non-dispersive infrared spectrometry (NDIR).

CO_2 as an Indicator of Indoor Air Quality

It is generally accepted that CO_2 concentrations do not provide a comprehensive indication of indoor air quality, but they can be used as indicator of an acceptability of a space, where the biggest contaminant source is the human body [72].

According to the German hygienic guideline [73] the CO_2 concentration under 1000 ppm is evaluated as "good", between 1000 ppm and 2000 ppm as "noticeable" and over 2000 ppm is assessed as "unacceptable". Some dwellings showed high CO_2 concentrations in the three months from Dec. to Feb in winter. Especially, the two dwellings (A6 and C6) had "unacceptable" air quality over 70% during the three months of winter. Only Building B showed the adequate air change rate in winter.

Infiltration Rate

Air change rate consists of infiltration rate and air change resulted from window or mechanical ventilation. The Infiltration rate can be calculated based on tracer gas decay technique or using the pressure test like blower door test (n50) performed in this study during winter questionnaire. In the tracer gas decay technique, the tracer gas (CO_2 in this study) concentration is monitored over the time after the occupants leave a room. If any mechanical ventilation system is in operation, the infiltration rate through leakages or openings in the building envelope can be calculated and determined from the rate of concentration decay [74]. Since it could be assumed that the windows are remained closed for non-occupant periods in winter, the residents in 24 dwellings were asked about their absent period of the last month during winter questionnaire. The time of the beginning of decay was analysed in this period and the infiltration rate is calculated using Equation (10) under the assumption that a dwelling as a single zone exchanges air only with the outdoors.

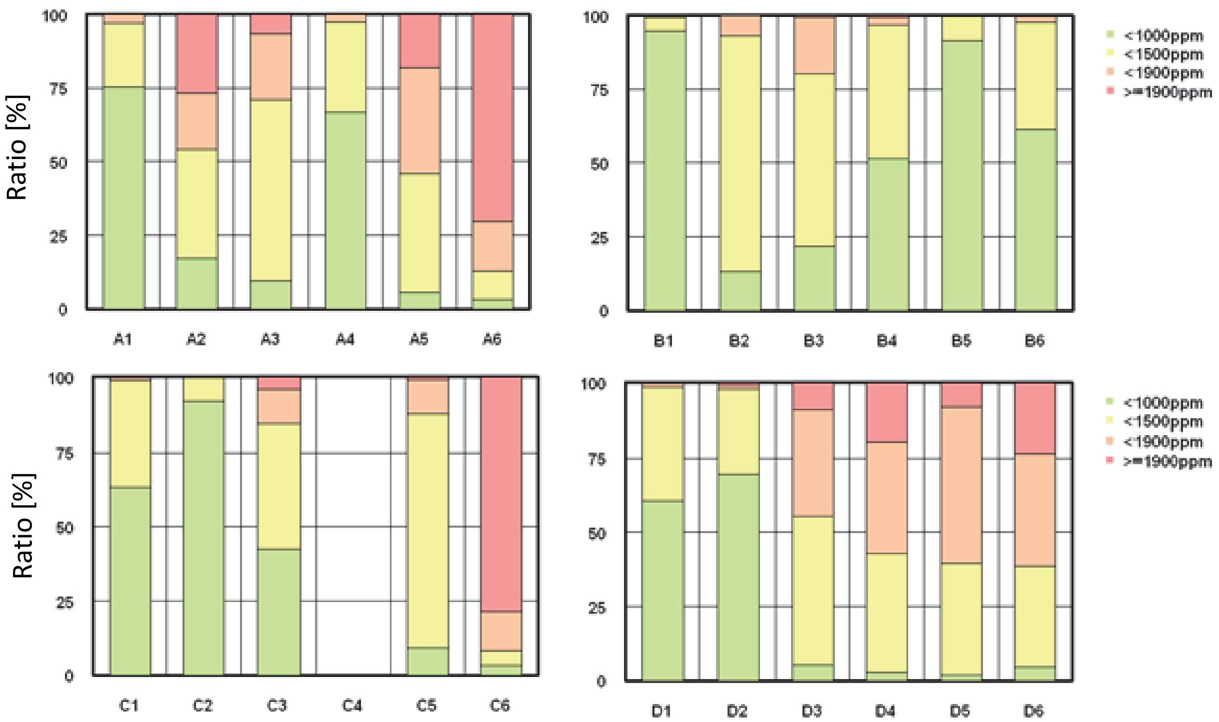


Figure 51:
Frequency of CO_2 Concentration in Buildings A, B, C and D in Winter (December - February)

$$n = \frac{[\ln C(t_2) - \ln C(t_1)]}{(t_2 - t_1)} \qquad (10)$$

Where:

n	Infiltration Air Change Rate	$[ACH]$
$C(t_1)$	Difference of CO_2 Concentration between Indoor and Outdoor at the Beginning of the Time Period	$[ppm]$
$C(t_2)$	Difference of CO_2 Concentration between Indoor and Outdoor at the End of the Period	$[ppm]$

Using the results of blower door test, the infiltration rate can be calculated according to DIN V 18599 using Equation (11). The wind shield coefficient will be different depending on the floor and surrounding buildings. In this study, the moderate shielding was assumed for the investigated buildings. According to Table C.1 in DIN EN 13789, the coefficient for Building D, which has only one envelope, is expected by default 0.02 and 0.07 for other buildings.

$$n_{\inf} = n_{50} \cdot e_{wind} \qquad (11)$$

Where

$n_{\inf}$	Infiltration Air Change Rate	$[ACH]$
n_{50}	Air Change Rate by 50 Pa Pressure Difference	$[ACH]$
e_{wind}	Windshield Coefficient	$[-]$

Table 28:
Air Tightness Measurement (Blower Door Measurement (n50))

n50	Building A [h-1]	Building B [h-1]	Building C [h-1]	Building D [h-1]
Dwelling 1	3.2	4.8	3.5	5.2
Dwelling 2	4.6	3.2	2.3	4.2
Dwelling 3	4			
Mean	3.9	4	2.9	4.7

The infiltration rate using CO_2 decay method will depend on the weather during non-occupant period, which varied between measurement dwellings. The average wind speed and temperature difference during these periods can be found in Table 29, with the infiltration air change rate of CO_2-decay method and blower door test method. The comparison of both methods show similar tendency of building tightness. Building D had the lowest infiltration rate due to its one side envelope in comparison to other buildings with two or three external walls. The infiltration rates in buildings varied between 0.1 in Building D and 0.25 ACH in Buildings A and B.

Table 29:
Infiltration Rate Calculation Based on CO_2 Measurements from [77]

	Building A	Building B	Building C	Building D
Date	08.12. – 11.12.2009	28.02. – 02.03.2010	24.12. – 27.12.2009	24.12. – 28.12.2010
Average Wind Speed [m/s]	2.0	2.7	2.0	1.7
Temperature Difference between Outdoor and Indoor [K]	18.7	16.5	22.7	24.6
Infiltration Air Change Rate [1/h] from CO_2 Measurement	0.24	0.26	0.13	0.12
Infiltration Air Change Rate [1/h] from „Blower Door Test“	0.28	0.28	0.2	0.1

Calculation of Air Change Rate

For the calculation of air change rates in 24 dwellings, the CO_2 generation in dwellings is assumed from the occupancy rates in questionnaires of the three seasons and from average gas consumption for cooking in a dwelling, which is estimated from the measurement data of gas provider. A ventilation rate can be estimated relatively well by measuring CO_2 concentration in equilibrium with a constant ventilation rate, a uniform and constant CO_2 generation rate and a constant outdoor CO_2 concentration [75]. In contrast to mechanical ventilation systems in office buildings, the window ventilations in residential buildings show neither a constant ventilation rate nor a constant CO_2 generation. The ACH varying time can be calculated from Equation (12) [78].

$$n(t) = \frac{\frac{C_{sou}}{V_R} - \frac{dC_{in}}{dt}}{C_{in} - C_{out}} \qquad (12)$$

Where:

$n(t)$	Air Change Rate during Period t	$[-]$
V_R	Air Volume of a Room	$[m^3]$
C_{sou}	CO_2 Generation of a Room during Period t by Volume	$[m^3]$
C_{in}	CO_2 Concentration of a Room by volume	$[m^3/m^3]$
C_{out}	CO_2 Concentration of Outdoor by volume	$[m^3/m^3]$

The information of CO_2 generation is only hourly available and based on the monthly average value, whereas the CO_2 concentration is measured in every minute or in 10 minute intervals in dwellings. The average ACH based on 10 minute balance or hourly balance is not the same, since the hourly average from 10 minute calculation based on Equation (12) varies mathematically from the calculation result with average hourly indoor CO_2 concentration in Equation (12) [76]. The calculation result of both periods shows that the ACH based on 10-minute calculation is 59 % higher than the calculation on hourly basis. As it can be assumed from the Equation (12), a very low difference of indoor and outdoor concentration in a short time yields an unrealistic high air change rate, especially in winter. The calculation based on the 10-minute interval shows some unrealistic high values, which massively affect the average ACH. If the information in a balance would be accurate, such error might not occur in the calculation. Therefore, ACH is estimated in this study based on the hourly balance and the uncertainty analysis is conducted in the aforementioned the work.

The analysed factors of errors are the following;

- Limitation of measurable concentration up to 2000 ppm of sensor.
- Inaccuracy of CO_2 sensors (±150 ppm).
- Non-perfect mixing between indoor and outdoor.
- Inaccurate calculation of room volume using CAD plan (± 8 %).
- Inaccurate information about occupancy number and period.
- Different cooking behaviour.

After consideration of these error factors, the error ratio for monthly average ACH calculation yields 22 % by the daily mass balance [77]. The average ACH in 24 dwellings can be found in Table 30, which should be considered abovementioned as rudimental information due to high inaccuracy in this study. The real ACH will be higher in summer due to non-prefect mixing between indoor and outdoor than results in Table 30.

Table 30:
Results of Air Change Rate Calculation (ACH [1/h]) Based on Daily and Hourly Mass Balance of CO_2 from [77] .

Month	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Daily Balance	0.64	0.86	1.05	0.73	0.44	0.34	0.38	0.38	0.34	0.37	0.38	0.45
Hourly Balance	0.81	1.06	1.29	0.99	0.60	0.41	0.43	0.45	0.38	0.41	0.44	0.63

5. Assessment of Existing Buildings

5.1 Energy Efficiency

In this section, the net heating energy efficiency will be assessed using Korean standard and German standard, along with a transient energy simulation tool. The German standard (DIN V 18599) provides calculation methodologies not only for heat energy but also for hot water, ventilation, light, and cooling energy. It also provides the calculation methodologies for the end energy demand, which depends on the performance of the systems. However, this performance information in DIN V 18599 is based on the typical German equipment in the German climate. Might the Korean district heating system work similarly efficient to German systems? This uncertainty restricts the assessment of energy efficiency to net energy demand in this study.

For the dwelling utilisation, light energy is irrelevant for an assessment. The net energy demand for hot water is determined in DIN V 18599 as 16 kWh/(m²·a) for an apartment building. The hot water consumption in Building A is approximately 0.57 ton /(m²·a) in 2009. If the temperature difference between supply and return hot water is assumed as 25 K, the calculated energy demand for hot water is approx. 16.5 kWh/(m²·a). The cooling energy for a split cooling system is defined in DIN V 18599 as 6 kWh/(m²·a), which is higher than the measured energy consumption in dwellings (see Chapter 4.1.2). The highest energy consumption for cooling in the four dwellings was 4.3 kWh/(m²·a). According to the average cooling energy consumption based on the survey in Korea is 480 kWh per dwelling [85]. The mechanical air supply ventilation system of the existing building is not relevant for energy consumption until now due to the low use of a system (Chapter 4.1.2). The Korean calculation tool for energy efficiency regards only heating energy for dwellings. Therefore, the assessment of energy efficiency of existing buildings based on the calculation is restricted to heating energy in this study.

5.1.1 Korean Standard

Calculation Tool

The Korean regulation "Building Energy Efficiency Rating Operating Regulation 2007"[20] defines the calculation method for net and final energy demand of heating. It is based on the "seasonal method" with variable heating degree-days, which can be calculated using the variable balance point temperature (Equation (13)).This balance point temperature is determined from the balance of heat gain and heat loss of an assessed building [79] .

$$DD = -0.0385x^4 + 1.9698x^3 - 32.163x^2 + 359.01x - 634.68 \quad (13)$$

Where:

DD	Heating Degree-days (K*days)
x	Variable Balance Point Temperature according to the Balance of Heat Gain and Heat Loss

If the heat balance is good, characterized through high heat gain and reduced heat loss, then the balance point temperature for heating becomes lower and correspondingly the heating degree-days.

When calculating the heat balance, the windows and walls facing the balcony should be considered as external windows and walls, because the balcony is glassed generally after the completion of construction work. It means that the Korean calculation method does not regard the buffer function of a glazed balcony. In contrast, the reduced energy loss of walls to non-heated rooms and the solar gain in heated, as well as in non-heated rooms is considered in the calculation. The other uncertain parameter in the calculation will be the used solar radiation values on the façade. The average solar radiation on the southern façade is 69.2 W/m² according to Korean standard. However, the lowest monthly average values during heating period (November - March) is 104 W/m² according to TRNSYS calculation using standard Korean climate data from SAREK [80]. The average solar radiation values in the Korean standard seem to be too low.

Boundary Conditions

The boundary conditions in the calculation tool can be found in Table 31 and the U value of the envelope of Building A can be seen in Table 32.

The SHGC (Solar Heat Gain Coefficient) of windows in heated rooms is assumed as 0.5, due to the reduced solar gain caused by the glazing of balcony windows. The SHGC of windows in the stairway is assumed as 0.75, which is a typical SHGC for clear double-glazing.

Table 31:
Boundary Conditions Defined in Korean Standard Calculation

	Korean Energy Efficiency Certification
Indoor Air Temperature	20 °C
Outdoor Climate	Variable Heating Degree Days
Time Used	0:00 -24:00
Heat Source	123 Wh/m²d (Korean code)
Hot Water Demand	Not Considered
Air Change Rate (h-1)	0.7

Table 32:
U-value and SHGC of the Envelope of the Building A

U-value and SHGC of Windows (Building A)	
U-value_ External wall to outdoor air	0.32 W/(m²·K)
U-value_ External wall to the balcony	0.43 W/(m²·K)
U-value_ Wall to non-heated room	0.58 W/(m²·K)
U-value_Window in heated room and in balcony area	3.3 W/(m²·K)
U-value_ Double window	1.1 W/(m²·K)
SHGC_ Window in heated room	0.5
SHGC_ Window in stairway	0.75

Calculation

The following two cases of Building A are calculated using the Excel program; the outside dwelling with the grey area in Figure 17 (Building A_ Plan) and the same dwelling with balcony extension to living area, the scratched area in Figure 17 (Building A_ current state).

The calculation result for Building A can be found in Table 33. The heating energy demand of the dwellings without balcony extension to the living area (Plan) was 10 % higher than the energy demand with an extension (current state). The difference of the specific heating energy demand per living area (kWh/m²·a) was still higher due to the extended living area by the current state from 95.3 m² to 106.8 m².

This higher energy demand in dwellings with balcony (plan) is based on the different U value of windows on the southern façade in the calculation (the scratched area in Figure 17). In the first case only the window of a living room towards the balcony (U value= 3.3 W/(m²·K) is taken into account, although the balcony has also a window with double-glazing (U value= 3.3 W/(m²·K)).

The insulation effect of this kind of a façade (window + balcony (1 m) + window) might be only slightly lower than the one of double windows (window + air layer (9 cm) + window) of 1.1 W/(m²·K) used in the second case, if the air change rate of the balcony to outdoor is not very high in winter. An investigation of the glazed balcony shows that it can reduce considerably heating energy demand in comparison to without a glazed balcony. The energy performance of a glazed balcony depends upon the ratio of air change rate from balcony to outdoor and to indoor. Especially if the air change ratio from indoor to balcony is equal with the one from balcony to outdoor, the heating energy can be reduced at most [81].

The Korean standard assesses the energy efficiency of a building in comparison to the efficiency of a reference building (see Chapter 2.1.2). Building A in current state will get the better qualification due to the good U-value of the windows than the reference U value (3.3 W/m²), while the building A_ plan might comply just the efficiency of the reference building.

Table 33:
Results of Heat Energy Demand According to Korean Calculation

	Building A: Plan	Building A: Current State
Heating Energy Demand (kWh)	10,838	9,533
Area (external dimension: m²)	95.3	106.8
kWh/m²	113.7	89.3

5.1.2 DIN 18599

Calculation Tool

The principle and structure of DIN V 18599 are already mentioned in the previous Chapter 2.1.3. In this section, only the calculation method on the difference to the Korean standard or sensitive parameters in the calculation of studied buildings are discussed.

- Shading

DIN V 18599 considers the shading effect caused by neighbouring buildings and a horizontal or vertical overhang as well as solar protection systems. Since the studied buildings have no solar protection systems, the solar gain is affected by other construction measures and surrounding buildings. For example, another high rise building in front of Building A will cut down solar radiation on the south-east façade of a dwelling in the 10th story into halves in winter, while the 1.2m wide balcony and side walls will reduce 10 % of the solar gain [7]. If a building is shadowed by one more parameter as in our example, the highest reduction factor, for our example the 0.5 factor, will be used in the assessment. The reduction factor in Korea could be slightly different due to the different solar altitude. According to this method, the solar gain varies strongly depending on the story of a dwelling, if a high-rise building faces another high-rise building.

- Air Temperature in Non-heated Room with Glazing

If a building faces a non-heated glazed area like a balcony of Korean residential buildings, DIN V 18599-2 provides two calculation methods for the determination of temperature in the non-heated area; a simple method based on the temperature correction factor and a detailed winter garden model. By simple method, the indoor temperature is calculated by means of the correction factor defined in the Table 3 in DIN V 18599-2. For example, the correction factor for the room with double-glazing is 0.7. The indoor air temperature for this room can be calculated using Equation (14).

$$\vartheta_u = \vartheta_i - F_x \cdot (\vartheta_i - \vartheta_e) \qquad (14)$$

Where:

ϑ_u	= Air temperature in non-heated room	[°C]
ϑ_i	= Indoor air temperature	[°C]
ϑ_e	= Outdoor temperature	[°C]
F_x	= Temperature correction factor	[°C]

The average outdoor air temperature in January in Korea is -3.5 °C calculated by the standard outdoor climate of SAREK. According to equation (15) the air temperature in the southern balcony in building A yields by 20 °C indoor air temperature 3.55 °C, which will reduce the heating energy demand clearly in contrast to the Korean calculation method.

The other detailed method is described as winter garden model in DIN V 18599 -2, which calculates the air temperature in consideration of heat loss and heat gain the through internal and external envelope.

$$\vartheta_u = \frac{\Phi_u + \vartheta_i (H_{T.iu} + H_{V,iu}) + \vartheta_e (H_{T,ue} + H_{V,ue})}{H_{T,iu} + H_{V,iu} + H_{T,ue} + H_{V,ue}} \qquad (15)$$

Where:

Φ_u = heat gain in the non- heated room $[W]$

$H_{T.iu}$ = Heat transfer coefficient for transmittance between heated and non heated room $[W/K]$

$H_{V,iu}$ = Heat transfer coefficient for ventilation between heated and non heated room $[W/K]$

$H_{T,ue}$ = Heat transfer coefficient for transmittance of non heated room to outdoor $[W/K]$

$H_{V,ue}$ = Heat transfer coefficient for ventilation of non heated room to outdoor $[W/K]$

The calculation of the air temperature in the southeast balcony in Building A, using software Epass-Helena® 5.2.Ultra [82] yielded 5.5 °C in January in the case of no air change between balcony and heated room and without internal heat source in the balcony. This solar gain can be calculated from the difference between total solar gain on the transparent envelope and the solar gain to the heated room.

Using this calculated air temperature in the non-heated room, the heat balance and the heating energy demand can be calculated monthly. In this study, the detailed calculation method is used for the assessment.

- Ventilation Heat Loss

As it was briefly mentioned in Chapter 4.4.2, the air change rate for window ventilation is determined from the measurement result of n50 by the air tightness test in DIN V 18599, as well as from the required ventilation rate for specific utilization defined in DIN V 18599-10. For a residential use, the minimum ventilation rate is determined for a demand-controlled ventilation of 0.45 [h-1] and for a not demand-controlled ventilation of 0.5 [h-1]. The higher the n50 by air tightness test, the higher the calculated air change rate of ventilation heat loss. For example, if the air change rate for a building with n50 result of 4 [h-1] is estimated as 0.7 [h-1] by the window ventilation and the wind factor e=0.07, then it will be in a same wind factor 0.65 [h-1] by the n50 result of 3 [h-1]. According to the blower door test in January 2010, almost all Korean residential buildings belong to air tightness category II in DIN V 18599. Thus, the calculated air change rate by means of DIN V 18599 calculation will be 0.7 ACH. However, the real ventilation rate in Korea seems to be evidently lower than the standard with 0.36 - 0.41 ACH for the four months from November to February in winter (see Table 30).

- Thermal Bridge

The heat loss due to the thermal bridge must be taken into account in German energy regulation. Either detailed thermal bridge calculation results or the default value (ΔU) defined in DIN V 18599 can be used in the assessment. By the detailed thermal bridge assessment, the linear thermal transmittance is calculated using thermal bridge software almost based on the ISO 10211 (see 4.4.1).

DIN V 18599 -2 provides the following three different default values for a case without a detailed analysis and DIN 4108 - 6 suggests the last two values.

Building with an internal insulation; ΔU =0.15 W/(m²·K)
Building with the standard joints; ΔU=0.10 W/(m²·K)
Building with state of the art joints according to DIN 4108 -2; ΔU =0.05 W/(m²·K)

According to the detailed thermal bridge calculation in 4.4.1, the average additional U-value of ΔU =0.17 W/(m²·K) can be applied for the DIN V 18599 calculation.

Calculation and Results

Boundary Conditions

The studied Building A faces another building in 60 m distance and Building B is not shadowed by another building on the southern side. The shading factor is determined for a dwelling in the 10th story. Moreover, both buildings have the same construction value of the Korean standard (Table 32) and the user profile of DIN V 18599 for residential use is changed for the Korean situation in Table 34.

Table 34:
User Profile for DIN V 18599

	DIN V 18599	DIN V 18599_Korea
Indoor Air Temperature	20 °C	20 °C and 23 °C
Outdoor Climate	German TRY (Wuerzburg) Monthly mean value	Korean Standard Climate Monthly mean value
Time Used	06:00 – 23:00	00:00 -24:00
Heat Source	100 Wh/(m²·d)	141 Wh/(m²·d) (Building A) 129 Wh/(m²·d) (Building B)
Hot Water Demand	16 kWh/(m²·a)	Not considered in this study
Air Change Rate (h-1)	Depending on air tightness of building	Calculated with 4 [h-1] by n50

Climate

For the DIN V 18599, the calculation of monthly outdoor climate data is generated from the hourly standard outdoor climate from SAREK (The Society of Air conditioning and Refrigerating Engineers of Korea). The monthly mean air temperature and radiation according to the azimuth and slope of surface is calculated using type 109, based on the Perez model in TRNSYS 17[83].

Calculation

One dwelling each from Building A and Building B in their current-state calculated using Epass-Helena® 5.2.Ultra, under the indoor air temperature of 20 °C. The dwellings are divided in the four following zones: living, stairway, southern balcony, and northern balcony. The result with boundary condition in German code can be found in Table 35 in comparison to the result of Korean code. Korean winter is warmer than the German one. That is why the demand for the heating energy will be reduced to 80 % under Korean climate. If Building A would have had a same envelop quality like German reference building and if the indoor air temperature could be kept at 20 °C, the annual heating energy demand would be reduced to 24 kWh/(m²·a). The annual heating energy demand with real boundary condition (ACH=0.4, Ta = 23 °C and ΔU=0.17) is of 61 kWh/(m²·a) could be reduced to 27 kWh/m² under indoor temperature of 21 °C with German reference building quality (Table 36).

Table 35:
Heating Demand (kWh/(m²·a)) of Building A According to Germany Code (EnEV 2009)

	Germany Code (20 °C) German Climate		Germany Code (20 °C) Korean Climate	
Korean Code (20 °C)	Building A	German Reference	Building A	German Reference
89.3	72.4	35	58.2	24

German Reference: Reference building EnEV 2009 (Ht`=0.65 W/(m²·K))

Table 36:
Heating Demand (kWh/m²) by the Building A According to DIN V 18599 Calculation

	DIN V 18599: with Real ACH and Thermal Bridge, (23 °C)	DIN V 18599: with German Reference Envelope,(21 °C)
Heating Energy Demand (kWh/(m²·a))	61	27

Comparison of Calculation to Energy Consumption

Although the real energy consumption cannot be compared to the calculation due to the different outdoor climate and different user behaviour, it can serve as a criterion for the judgement of the calculation.

The energy consumption in Korea is measured by the energy provider of each dwellings. Since Building A is heated through the district heating system, the data of Building A does not include the energy loss of heat generation, which the data of Building B includes. The heating energy is generated in the Building B in every dwelling, by using a gas boiler (efficiency: 0.87 according to manufacturer's specification). The heating, hot water and electricity, as well as cooking energy consumption data for Building A are available. The average heating consumption in the Building A (current- state) is 6,031 kWh in 40 dwellings. If the dwellings are extended like "current state", then the average specific heating energy is 56.9 kWh/(m²·a).

For Building B, the energy consumption during the measurement period is available but only as a gas consumption, which is used not only for heating but also for hot water and cooking. After a comparison with the energy consumption of dwellings of comparable size in Building A, the heating energy for Building B (current-state) could be assumed as 62 kWh/(m²·a) without heat loss of generation (Table 37). In the calculation from gas consumption to energy consumption, the lower heating value of LNG gas in Korea of 11.095 kWh/(Nm³) is used [84].

If it is considered that the average indoor air temperature in Korea is near 23.5 °C in winter and the energy consumption data of Building A and B include the delivery energy loss within a dwelling, the Korean standard overestimates clearly the real energy demand in Korea (see Table 33) .

Table 37:
Assumed Energy Consumption Without Heat Generation Loss in Building B

	Original data	Energy consumption
Average Total Gas Energy Consumption in Building B (n=25)	Gas: 1,204 Nm³	
Cooking (Building A, n=94, same size with Building B)	Gas:87 Nm³	
Gas Consumption for Hating and Hot Water	1,117 Nm³	12,408 kWh
Total Energy Consumption without Heat Loss Caused From Heat Generation (Efficiency of boiler:0.87)		10,794 kWh
Hot Water (Building A, n=94, same size with Building B) (Assumed temperature difference between supply water and hot water: 25 °C)	77 ton	2,234 kWh/a
Assumed Heating Energy Consumption in Building B (kWh /(m²·a))		62 kWh/(m²·a)

5.1.3 Transient Energy Simulation

While the heating and cooling energy demand can be calculated and assessed using the DIN V 18599, the indoor environment cannot be assessed with this monthly energy balance calculation. Since not only energy demand but also thermal comfort should be taken into account during the optimization process, the transient simulation besides the DIN V 18599 is additionally used. For this purpose, models of the Building A and Building B were built and validated on the energy consumptions and indoor air temperatures measured in the monitoring phase. The TRNSYS 17 software was used for the transient simulations. The results of the detailed thermal bridge calculation in 4.4.1 are considered in the simulation. The building of geometrical models in TRNSYS 17 in this study were performed with the help of [87].

Boundary Conditions

Other boundary conditions are same with the of DIN V 18599 calculation, only the internal heat source is considered more detailed in building energy simulation.

– Internal Heat Sources

The internal heat sources were divided into three parts. One part is the occupancy of the dwellings known from the questionnaire that has a daily pattern. For this analysis, the questionnaires in 3 comprehensive dwellings in the Buildings A and B were used. The other part of the internal heat sources representing the technical equipment of the dwellings was also divided into two subparts; a constant part during the 24 hours of one day and a variable part depending on its occupancy. The height of this constant internal heat sources based on the electric use was assumed as the average electric consumption of a refrigerator 578 kWh/a, kimchi refrigerator 245 kWh/a and rice cooker 103 kWh/a in [85]. The variable part was estimated from the difference between electric energy consumption data in Building A (35 kWh/(m²·a)) and in Building B (31kWh/m²·a), and their constant electric energy consumption [86]. In addition, the average cooking energy demand was taken into account as heat source.

Table 38:
Internal Heat Source Per Year (n: Number of samples)

	Building A	Building B
1. Occupancy [kWh/a]	1752	1524
2. Elec. energy consumption [kWh/a]	4027 (n=180)	5131 (n=25)
From 2: Constant elec. energy consumption [kWh/a]	926	1111
From 2: Variable elec. energy consumption [kWh/a]	3101	4020
3. Cooking energy [kWh/a]	821 (n=180)	966
Internal heat source [kWh/a]	6600	7621

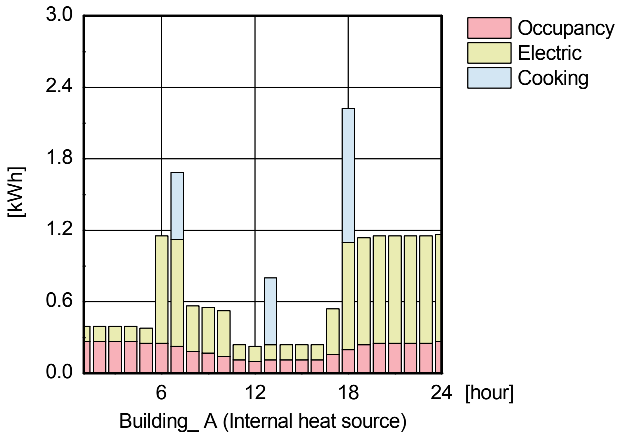


Figure 52:
Daily Internal Heat Source in Building A

Validation of Building Model

Determination of Airflows using Evaluation of Indoor Air temperature

From the air change rate calculation using CO_2 measurement, the air change rate between living area and outdoor can be estimated in each dwelling. However, this air flow occurs not only directly from living area to outdoor, but also includes the air flow from the living area through the balcony area to the outdoor and vice versa.

To model the airflows in the dwelling, it is assumed that five different kinds of airflows are present [87]. First, there is a direct airflow from outside through the windows, into the living area (orange arrow in Figure 53). On the south balcony, there are two different airflows: airflow between the dwelling and the south balcony (green arrow in Figure 53) and airflow between the south balcony and outside (blue arrow in Figure 53). On the north (west) balcony, two airflows exist similar to those on the south.

In the phase of the model validation, this airflow is segmented into all five different ways of exchanging air, direct and through the two balconies. These five air exchange rates are taken as unknown variables and are optimized by a simplex-down method in a way the that the calculated indoor air temperature of the living area fits the measured trend as good as possible. The evaluation of measurement and calculation of air temperature can be found in Figure 54.

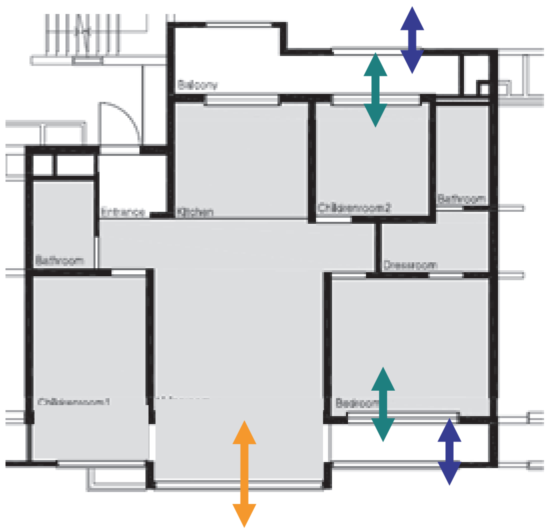


Figure 53:
Different Air Flow in Building A

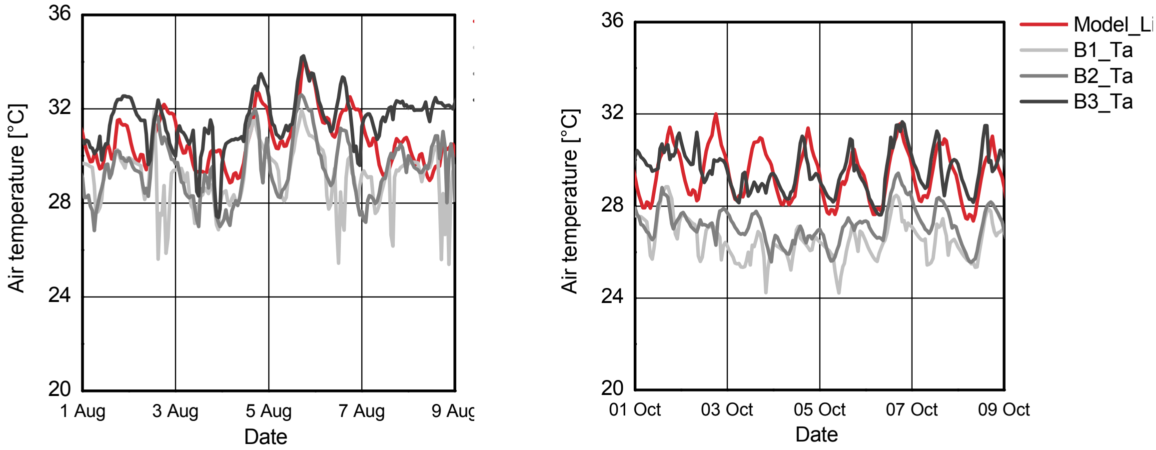


Figure 54:
Measured and Calculated Indoor Air Temperatures of the Living Room in Summer (August 01 - 09. 2009) and in Autumn (October 01- 09. 2009)

Table 39 shows the difference of the air change rate estimated from CO2 measurement and resulting of air flows in TRNSYS. The result from TRNSYS is based on the evaluation of the simulated and measured dwelling and balcony air temperatures. In order to fit measured and calculated air temperature, the air change rates in summer should be clearly higher than values determined from CO2 measurement. The inaccuracy of CO2 measurement for ACH calculation was discussed already in 4.4.2. In addition, the air change occurs more between dwelling and balcony than between dwelling and outside in winter. Approximately 80 % in Building A and 50 % in Building B's total air flow from the dwelling to outdoor would occur through the balcony. The air flow from dwelling to balcony is generally three times higher than the air flow from the balcony to the outside. That may cause the high air temperature as well as the high humidity in the balcony area during wintertime. The air change from the living area to the north balcony in Building A is especially seven times higher than the air change volume from the balcony area to the outside.

Table 39:
Air Change Rate Per Hour (ACH) Calculated from the CO_2 Measurement (hourly balance) and ACH Used in TRNSYS Calculation for the Evaluation

Air Flow Connection	ACH from the CO_2 Measurement (1/h)			ACH in TRNSYS (1/h)		
	Winter	Spring / Autumn	Summer	Winter	Spring / Autumn	Summer
Building A	0.39	0.72	0.80	0.32	0.85	2.65
Building B	0.42	0.64	0.91	0.43	0.7	1.39

Evaluation using Energy Consumption

The comparison of heating energy demand in model and the energy consumption data can be found in Table 40. Since the monthly heating energy consumption for the Building A exists, the monthly heating energy demand and consumption is compared in Figure 55. The transient simulation provides similar estimation of the heating energy demand like DIN V 18599.

Table 40:
Heating Demand (kWh/m²·a) of Buildings A and B According to TRNSYS Calculation

	Building A (kWh/(m²·a))	Building B (kWh/(m²·a))
Energy Demand (TRNSYS)	61	58
Heating Energy Consumption	56.7	62

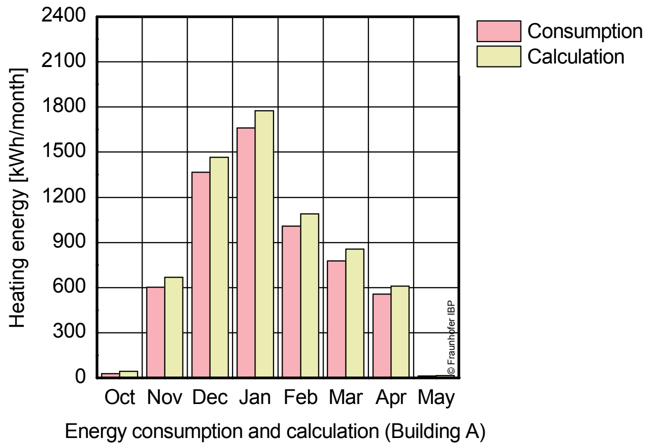


Figure 55:
Monthly Heating Energy Demand (Building A)

5.2 Assessment of Thermal Comfort

5.2.1 Assessment of Thermal Comfort Using Existing Tools

In this section, thermal comfort of residents in Korea is assessed based on the spot measurement and questionnaire in three seasons. In addition to the 20 minute spot measurement, the current thermal sensation and satisfaction are considered in the thermal comfort assessment. The seven points scale presented to the residents can be found in Figure 56. If participants judge an environment in the comfort scale better than "acceptable", then they are considered as "satisfied", otherwise as "dissatisfied" .

Currently, the temperature is….

Cold		Cool		Slightly Cool		Neutral		Slightly Warm		Warm		Hot	
-3		-2		-1		0		+1		+2		+3	

Currently, the thermal comfort is….

Very Comfortable		Comfortable		Slightly Comfortable		Acceptable		Slightly Uncomfortable		Uncomfortable		Very Uncomfortable	
3		2		1		0		-1		-2		-3	

Figure 56:
Seven Points Scale Presented to the Residents (assessed as satisfied in case of the judgement >=0 by comfort scale)

Generally, the residents are thermally more satisfied in autumn and winter than in summer in Korea. 35 % of the participating residents found the current thermal environment in summer not acceptable, while only 7 % and 1 % of the residents felt uncomfortable in winter and autumn (Figure 57).

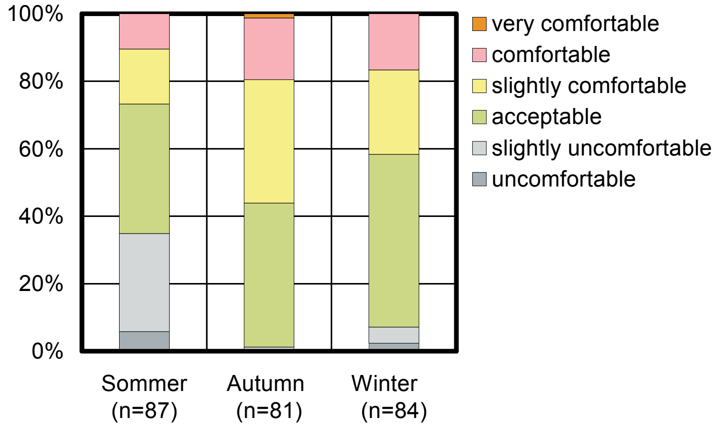


Figure 57:
Judgement of Thermal Comfort in Three Seasons

5.2.2 ISO 7730 (PMV and PPD Model)

PMV (Predicted Mean Vote) Calculation

Predicted Mean Vote (PMV) is calculated based on the spot measurement of air temperature, global temperature, air velocity, and relative humidity of every participant of the questionnaire. The clothing insulation value is calculated based on the questionnaire and notice of the interviewer. The metabolic rate is assumed as 1.0 met (58 W/m²), which corresponds to the quiet seated activity like reading and writing and is similar to the activity during the questionnaire campaign. The current thermal sensation and comfort are surveyed at the end of the questionnaire, so that the activity before the questionnaire action does not affect so much of the current thermal perception. If PMV is calculated by the typical activity level for the seated work in an office or in a house (1.2 met), the average PMV is 0.3 higher in summer and 0.4 in autumn and winter than PMV calculated by 1.0 met. The average PMV in all buildings can be found in Table 41. The detailed description of spot measurement can be found in Chapter 3.

Table 41:
Calculated PMV in Four Buildings

Building	All	A	B	C	D
Summer	0.7	0.3	1.2	0.8	0.8
Autumn	-0.1	-0.2	-0.2	-0.3	0.3
Winter	-0.2	-0.3	-0.1	-0.3	0.1

PMV / TSMV and PPD / PD Comparison

In Figure 58, the PMV calculated using the physical measurements is compared with TSMV (Thermal Sensation Mean Vote) of the questionnaire. The people perceive the thermal environment rather neutrally than PMV predicts, except for PMV=0, in which they feel warmer in summer and colder in autumn.

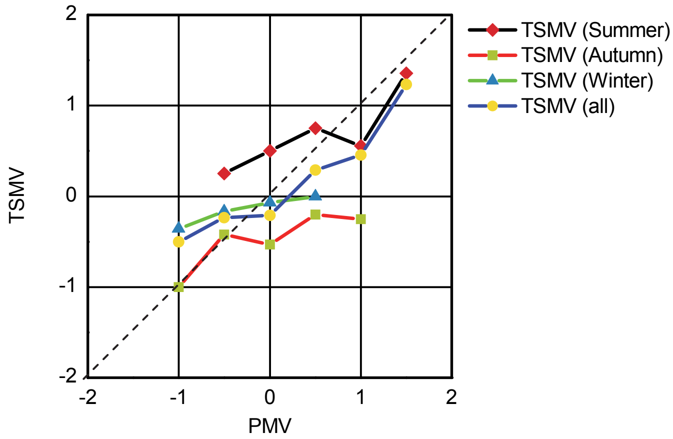


Figure 58:
Comparison of Calculated PMV and Questioned TSMV (all: n=253)

The following figures (Figure 59 - Figure 63) show the percentage of dissatisfied, however only if the frequency in each category is greater than five (see Table 42) in order to avoid an incorrect interpretation of the figures based on the small size (n) of samples in the category. The X-axis of Figure 59 (PMV) is calculated using the spot measurement. From the 73 Participants, whose measured environment is near to neutral zone (PMV=0), 14 % voted the environment as "slightly uncomfortable", "uncomfortable" or "very uncomfortable". In contrast to Figure 59, X-axis of Figure 60 is determined only by the questionnaire about thermal sensation and comfort (TSV). 132 participants out of 253 assess thermal environment "neutral" and 5 % of these 132 participants are dissatisfied.

Table 42:
Frequency (n) of PMV and TSV in the Study (grey: Percentage of Dissatisfaction analysed in this section)

	-2,5	-2	-1,5	-1	-0,5	0	0,5	1	1,5	2	2,5	3	All
PMV	1	1	4	21	47	73	54	34	17	1			253
TSV		3		54		132		48		14		2	253

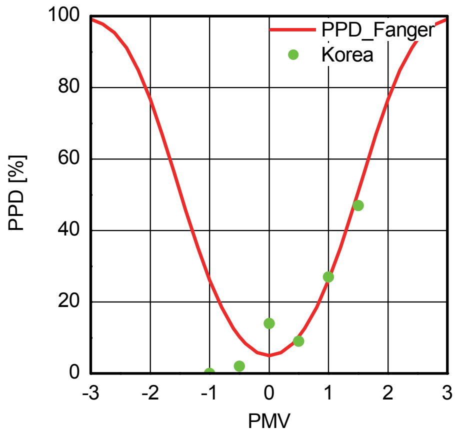


Figure 59:
Percentage of Dissatisfied (PD) Depending on PMV

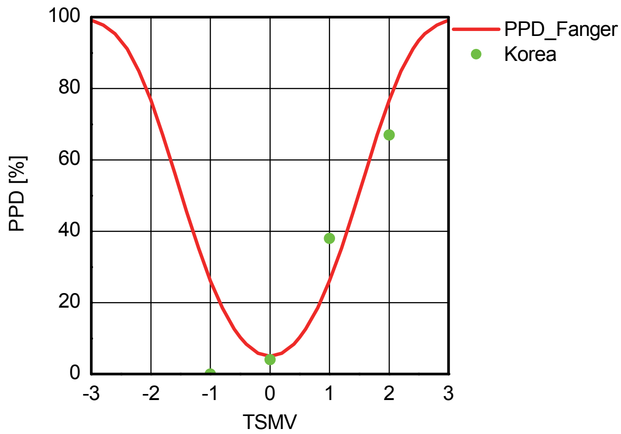


Figure 60:
Percentage of Dissatisfied (PD) Depending on TSMV

All in all, residents in high-rise building in Korea assess the slightly cool environment (PMV = -1) more comfortable than the warm environment. In addition, they are most satisfied, if they feel "slightly cool" (TSV = -1). This results differ on the observation in several experiments carried out in the climate chamber in Fraunhofer IBP, in which test persons judged the environment more comfortable, if they feel rather "slightly warm" than "neutral" or "slightly cool" [88]. In an experiment in aircraft cabin in Fraunhofer IBP [89] people felt almost comfortable at PMV=0 and TSMV=0.4. McIntyre [91] found similar results in his field experiment in winter, however the converse in the summer experiment. McIntyre as well as Humphreys and Nicol [90] explained these phenomena with subjective association of the word “cold” and “warm” depending on the outdoor climate. People in a cold climate or in winter probably associated the word “warm” as “comfort” and respectively the people in a warm climate for the word “cool”.

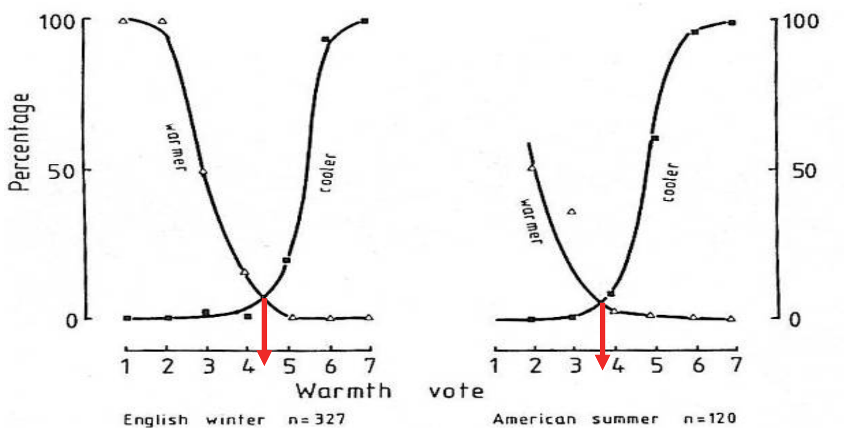


Figure 61:
PD in Winter in England and in Summer in America from [91].

According to this theory, Koreans associate the word "cool" rather as "comfort" in summer as well as in winter (Figure 62). Maybe the regional effect is greater than the seasonal influence, although Korea has not only hot summers but also very cold winters with an average outdoor air temperature of -3.5 °C in January. However, the Korean preference for the slightly cool environment cannot be explained only by verbal psychology, since they feel the most comfortable by PMV = -1, which physically is a slightly cool environment (Figure 63).

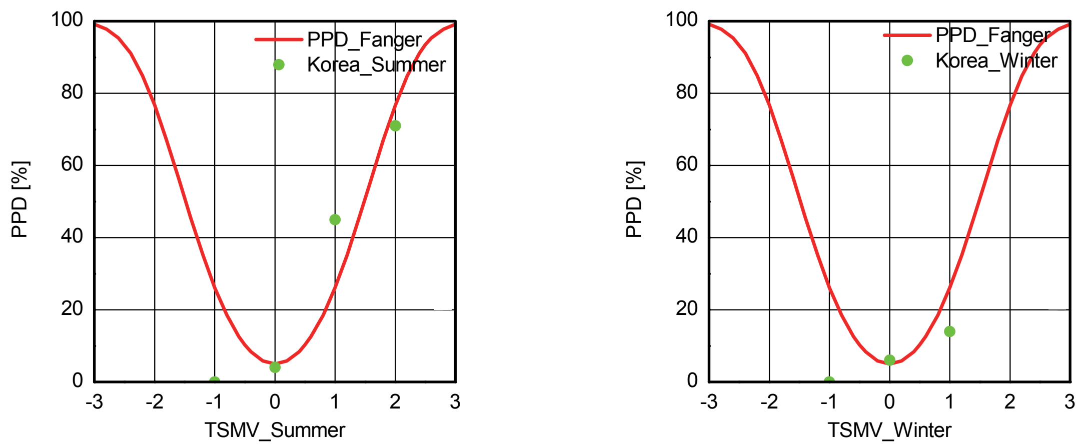


Figure 62:
PD Depending on TSMV in Korea in Summer and in Winter

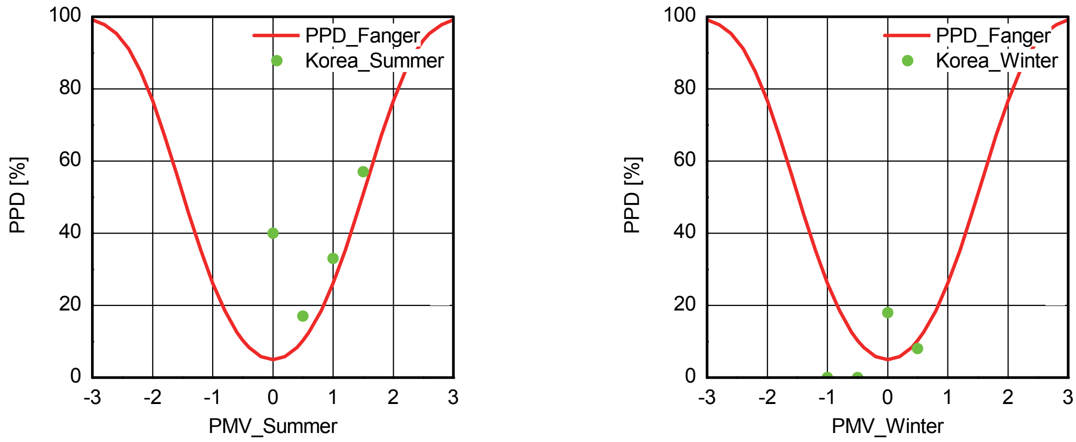


Figure 63:
PD Depending on PMV in Korea in Summer and in Winter

According to [92], warm environment in winter causes a dry skin and poor air quality perception. These parameters are not thermal influence factors but might affect the thermal comfort judgement in this study, since the questionnaire analyses on air quality and dryness perception depending on PMV show the correlation according to descriptive analysis. The higher PMV is, the dryer people perceive the environment. In addition, they perceive the air quality better in a slightly cool environment than in a slightly warm environment (Figure 64). Whether these differences between PMV groups are significant or not, it can be assessed using statistic tests.

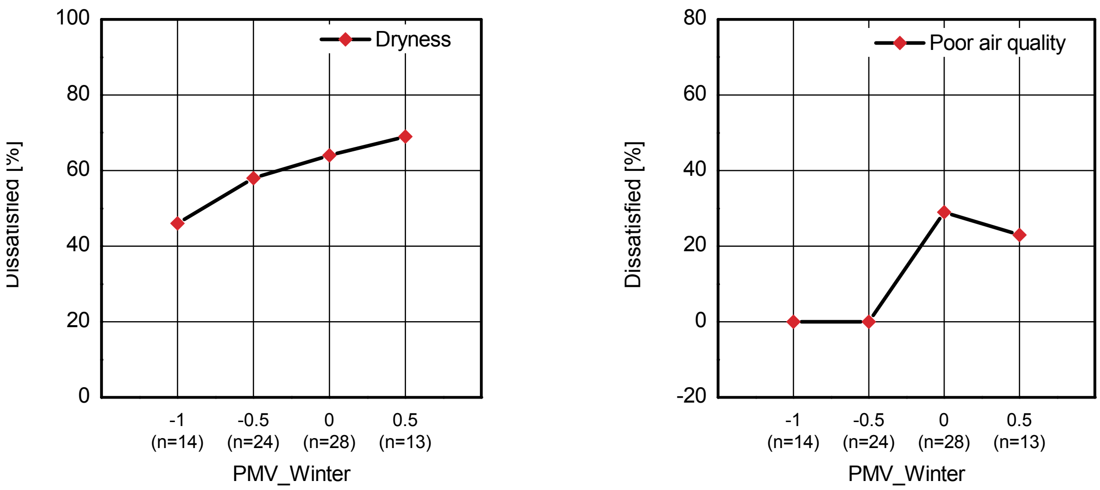


Figure 64:
Ratio of Dryness Perception (left) and Poor Air Quality Perception (right) Depending on PMV

Significance Test

The Median Test based on CHI-SQUARE test and Kruskal-Wallis ANOVA test are applied to assess the significance of air quality and dryness perception differences between PMV groups. According to ISO 10551, the ASHRAE 7-scale can be concerned as interval scale and other scales as ordinal scale in statistical analysis. A questionnaire scale is generally an ordinal scale. On the judgement about air quality, one scale discrepancy between "very good" and "good" cannot be exactly the same discrepancy between "good" and "acceptable". This ordinal scale shows only a rank order, while the temperature difference between 20 °C and 19 °C is the same with the temperature difference between 10 °C and 9 °C with 1K. A variable based on measurement is generally concerned in an interval scale (see [94] about scales in statistic). An interval scale allows a parametric analysis like t-test, while non-parametric statistical analysis should be applied for an ordinal scale. Therefore, the non-parametric analyses are carried out for a significance test between PMV groups. There are two different methods for comparing more than two groups; the case of k-related samples and k-independent samples [93].

The case of k-related samples requires that the samples have the equal size and are matched according to their criteria. If the perception difference between summer, autumn and winter are tested by each individual, the tests for "related sample" should be used. For the second case, the same size in compared samples is not necessary as the k groups have random samples.

Since the four PMV groups have different size (n) and are independent of each other in our case, the statistical test for k-independent samples can be applied. For this test, STATISTICA 9.0 [101] provides the CHI-SQUARE Median Test and Kruskal-Wallis ANOVA test. The CHI-SQUARE test compares the observed frequencies (in our case, the air quality perception) in each groups (in our case: PMV = -0.5; 0; 0.5; 1) and expected frequencies calculated from the whole population combining all groups. The greater the difference between observed and expected values, the higher the probability that the groups are significantly different. In this study the five air quality (dryness) perception scales are reduced to two categories: >= median, < median and the CHI-SQUARE test is carried out.

In contrast, the Kruskal-Wallis ANOVA test is non-parametric ANOVA test based on the variance analysis of ranks in place of the mean values in case of a parametric test. The whole population also determines these ranks. If the groups come from the same population, they have no differences. It means that the average ranks in compared groups should be about the same. If the difference is so great, the samples in the groups may come so significantly different from other population. The detailed mathematical difference between two tests can be found in [93].

The null hypothesis in our case is that the air quality (dryness) perception does not vary depending on PMV categories groups.

In this study a significance level of 0.05 is considered, i.e. the null hypothesis can be rejected and a difference between the groups can be identified.

Table 43:
Significance Tests for Air Quality and Dryness Perception between Four PMV groups (-0.5, 0, 0.5, 1.0)

	CHI SQUARE test	Kruskal-Wallis ANOVA	Results
Air Quality	P= 0.007	P= 0.005	Significant
Dryness	P= 0.5	P=0.2	Not significant

According to the significance tests (Table 43), it can be concluded that the satisfaction of air quality varies as a function of PMV categories. However, the observed difference of dryness perception depending on the PMV cannot be identified as significant in this study.

Maybe the high satisfaction in slightly cool environment in winter could be based on the better air quality perception in such environment. The higher dissatisfaction on PMV=0 than on PMV=0.5 in summer may be based on the low air temperature and high humidity caused from the two raining days during the spot measurement. It will be further discussed in the next Chapter.

5.2.3 EN 15251 (Adaptive Model)

Although the adaptive model of EN 15251 cannot be applied in case with a cooling equipment (most of the studied dwellings have a split air conditioner, 9 dwellings out of 86 dwellings do not have any air conditioner), at the beginning of the project, it was assumed that the adaptive model may be best suited for the prediction of thermal comfort in summer and autumn for high-rise residential buildings in Korea. Since the dwellings are ventilated and thermally controlled generally by using window opening, the residents hardly used any air conditioner (see Chapter 4.1)

The weekly running outdoor air temperature varied during the summer spot measurement from 22 °C to 26 °C. The required operative temperature for three categorical acceptances (90 %, 80 %, and 65 %), depending on the weekly running outdoor air temperature can be calculated according to EN 15251. The results can be found in Table 44.

Table 44:
Required Operative Temperature for Three Categorical Acceptance depending on the Weekly Running Outdoor Air Temperature (Calculated according to EN 15251)

Weekly Running Outdoor Air Temperature (Trm)	Category I 90 %	Category II 80 %	Category III 65 %
22 °C	28.1 °C	29.1 °C	30.1 °C
23 °C	28.4 °C	29.4 °C	30.4 °C
24 °C	28.7 °C	29.7 °C	30.7 °C
25 °C	29.1 °C	30.0 °C	31.1 °C
26 °C	29.4 °C	30.4 °C	31.4 °C

The frequency of the indoor operative temperature depending on weekly running outdoor air temperature can be found in Table A 21. This result include only the dwellings (n=70), where the air conditioner was not in operation during the spot measurement. According to this result, 86 % of 70 dwellings belong to the first category in EN 15251. However, the genuine satisfaction ratio is obviously lower than the prediction of EN 15251 (See Table 45). Instead of 90 %, only 57 % of 21 residents are satisfied with indoor operative temperature until 28 °C in the case of 23 °C weekly running outdoor air temperature.

Table 45:
Ratio of Satisfaction Depending on the Weekly Running Outdoor Air temperature and Indoor Operative Temperature (Row (Trm): weekly running outdoor temperature; column (To): indoor operative temperature; grey: 90 % acceptance area according to EN 15251, red: 80 % acceptance area)

	<= To: 27 °C	<= To: 28 °C	<= To: 29 °C	<= To: 30 °C
Trm 23 °C (n=21)	65 % (n=17)	57 % (n=21)		
Trm 24 °C (n=8)			67 % (n=6)	63 % (n=8)
Trm 25 °C (n=30)	82 % (n=11)	76 % (n=21)	75 % (n=28)	70 % (n=30)
Trm 26 °C (n=6)				67 % (n=6)

The most important finding of the adaptive model and the comfortable temperature may extend over a wide range under high outdoor air temperature, and it could be confirmed partly in this study. The satisfaction ratio under equal indoor operative temperature increases if the outdoor air temperature becomes higher, except 26 °C (n=6). However, these results could be based on the high humidity. It had rained on the first two days during the summer spot measurements and this rain forced a strongly lower outdoor air temperature and increased outdoor and indoor humidity. It means that the higher ratio of dissatisfaction in lower outdoor temperature than higher outdoor temperature could be based not on the adaptation, but on the high dissatisfaction caused from high humidity.

Korean residential buildings probably require a new adaptive model with lower comfort operative temperature than the European standard. However, the analysis of summer and autumn spot measurement shows that the operative temperature may be not the single determining factor for thermal comfort, since the high operative temperature of 27 °C - 29 °C in autumn does not make the residents uncomfortable (see Figure 65). Therefore, it could be assumed that the operative temperature and outdoor temperature alone cannot determine the comfort range in Korea.

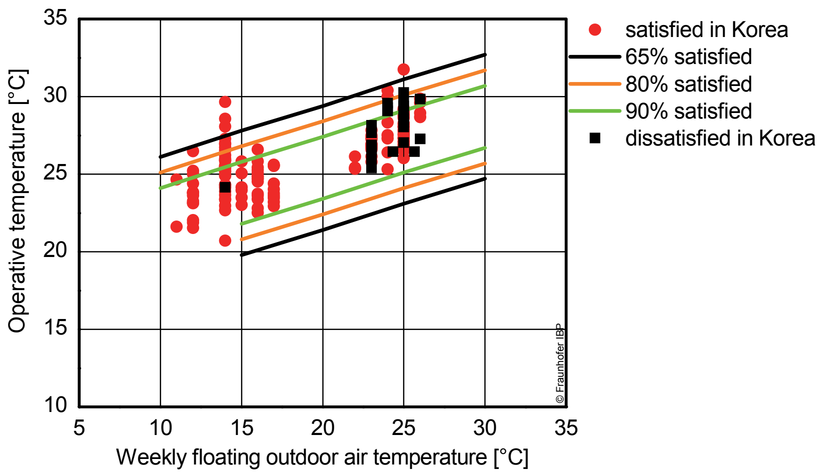


Figure 65:
Thermal Satisfaction in Free Running Mode against to the Outdoor Air Temperature

5.2.4 ASHRAE 55 -2004 (Graphical Method)

The difference of the ASHRAE comfort range to the other two standards is the upper limit of the absolute humidity of 12 (g/kg) (see Chapter 2.2.2).

If the operative temperature for PMV = 0.5 is calculated on the basis of a computer model method using the average air velocity (0.13 m/s), clothing value (0.5 clo), and relative humidity (67 %) during the summer spot measurement, then the upper limit of operative temperature is indeed 27.2 °C. However, it cannot belong to the ASHRAE 80 % comfort range by means of graphical method, since the absolute humidity of this case (27.2 °C, 67 % RH) is 16 g/kg beyond the upper comfort limit. To comply with ASHRAE 55- 2004, relative humidity should be under 54 % in this exampled case. Only six dwellings out of the measured 82 dwellings can comply with the ASHRAE humidity limit and only one dwelling without the air conditioner. The monthly average measured outdoor absolute humidity for July and August are respectively with 14.3 g/kg and 14.5 g/kg, obviously higher than 12 g/kg. Only 10 % of this period has a lower absolute humidity than 12 g/kg. It is likely that the buildings in Korea cannot comply with the ASHRAE comfort range in summer without the dehumidification. The 42 % of all measured dwellings (n=82) and 39 % of 70 dwellings without cooling can comply with the required acceptable operative temperature (27.2 °C) according to ASHRAE in summer.

The comfort range for the winter does not differ from the ISO 7730.

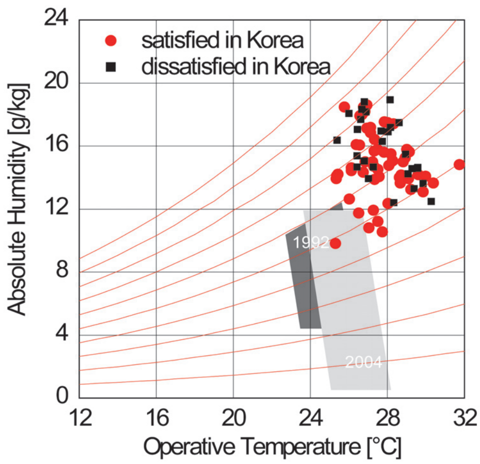


Figure 66:
Assessment of Thermal Comfort in Summer According to ASHRAE 55-2004.

6. Development of Comfort Criteria in Korea

6.1 Determination of Influence Factors for Thermal Comfort

6.1.1 Statistical Analysis

Thermal Sensation

Table 46 and Table 47 show the Pearson correlation coefficient of thermal sensation and thermal comfort in different indoor parameters. The coefficient shows only a relation between two variables without to say which variable is a dependent (outcome) variable. It means that a positive coefficient of air velocity to thermal sensation should not be interpreted so that the high air velocity results warm thermal sensation. In this case, it may indicate that people let a window open or a ventilator in operation (high air velocity as "dependent (outcome) variable"), if people feel warm (thermal sensation as "independent (predictor) variable"). This interpretation refers to also a clothing insulation value in the analysis for all season. The warmer the people feel, the thinner they dressed. In a climate chamber study, the clothing insulation value will be an independent variable to thermal sensation, if the clothing is arranged from an investigation team with defined clothing insulation value. In this case, the thinner the subjects´ dress, the lower the TSMV (Thermal Sensation Mean Vote) will be. Thus, clothing is a controlled independent variable and thermal sensation is a dependent variable. However, in a field study like this study, it is not clear which parameter (clothing or thermal sensation) is a dependent variable, since occupants can change their clothing themselves (See [94] for more information about variables in statistic).

In addition, the correlation between humidity and thermal sensation for "all season" can be based only on the seasonal difference, since Korean summer is warm and simultaneously very humid. If the Pearson correlation is calculated separately according to seasons and control mode, TSV in autumn has not only with the operative temperature but also with the absolute humidity in a significant relation. In summer, if a ventilator or an air conditioner is on operation, thermal sensation is not significantly correlated with any parameter.

Table 46:
Pearson Correlation of Thermal Sensation Vote (TSV) to Indoor Environment Parameters: (x -no significant correlation)

	Operative Temperature	Relative Humidity	Absolute Humidity	Air Velocity	Clothing Insulation
All Seasons (n=248)	0.55	0.39	0.50	0.29	-0.32
Summer (n=82)	0.28	x	x	x	x
Autumn (n=81)	0.29	x	0.27	x	x
Winter (n=85)	0.5	x	x	x	x
Free Running (n=150)	0.62	0.5	0.62	0.28	-0.31
Summer_Win (n=51)	0.41	x	x	x	x
Summer_ventilator (n=19)	x	x	x	x	x
Summer_air con. (n=11)	x	x	x	x	x

Free Running: Without cooling and heating in summer and in autumn.
Summer_Win: Without any operation of a ventilator or an air conditioner.
Summer_Ventilator: Ventilator in operation.
Summer_air con.: Air conditioner in operation.

Table 47:
Pearson Correlation of Thermal Comfort Vote (TCV) to Indoor Environment Parameters: (x - no significant correlation)

	Operative Temperature	Relative Humidity	Absolute Humidity	Air Velocity	Clothing Insulation
All Seasons (n=248)	-0.3	-0.22	-0.28	-0.14	0.16
Summer (n=82)	x	x	x	x	x
Autumn (n=81)	x	x	x	x	x
Winter (n=85)	-0.28	x	x	x	x
Free Running (n=150)	-0.34	-0.27	-0.34	x	0.28
Summer_Win (n=51)	x	x	x	0.3	x
Summer_ventilator (n=19)	x	x	x	x	x
Summer_air con. (n=11)	x	-0.87	-0.89	x	x

While thermal sensation is affected mostly from the operative temperature, independent of season, thermal comfort is affected from different indoor thermal parameters in dependence of seasons or control modes. The correlation for all season may be affected also from high dissatisfaction in summer in this study. TCV in summer and autumn shows no correlation to all indoor parameters, while TCV in winter indicates a negative correlation to operative temperature. It means that the higher the air temperature, the lower the thermal comfort vote.

Thermal comfort in summer without an operation of a ventilator or an air conditioner is influenced only from the air velocity. If air speed in dwellings is high, occupants feel more comfortable in summer. However, this positive effect of high air velocity in summer does not significantly influence the thermal comfort vote, if it is induced from a ventilator. If an air conditioner is in operation, the influence factor for thermal comfort is the humidity in this study.

6.1.2 Theoretical Analysis

Winter

As already explained in Chapter 2, the convective and radiative heat transfers decide the heat balance of people in cold and neutral indoor temperature. The convective (Equation (16)) and radiative heat losses (Equation (17)) are determined from the difference of air (radiant) temperature and the skin (clothing) temperature as well as from the heat transfer coefficients.

$$C = f_{cl} h_c (t_{cl} - t_a) \qquad (16)$$

$$R = f_{cl} h_r (t_{cl} - \bar{t}_r) \qquad (17)$$

Where:

h_c	Convective heat transfer coefficient	$[W/(m^2 \cdot K)]$
h_r	Radiative heat transfer coefficient	$[W/(m^2 \cdot K)]$
f_{cl}	Clothing area factor	
t_{cl}	Clothing surface temperature	[°C]
$\bar{t}_r$	Mean radiation temperature	[°C]

While the radiative heat coefficient is nearly constant for typical indoor temperatures, the convective heat transfer depends on air movement in a space [44]. Therefore, a constant value (h_r=3.1 ~5.1) is often suggested for a space with low air velocity (V_a< 0.15 m/s) [44]. According to ISO 7730, h_c can be calculated as the highest value of the following values of Equation (18) and Equation (19).

$$h_c = 2.38\,(T_{cl} - T_a)^{0.25} \qquad (18)$$

$$h_c = 12.1\,(V_a)^{0.5} \qquad (19)$$

Where

V_a	Air Velocity	$[m/s]$

Air velocity in dwellings without mechanical ventilation under closed windows is usually very low as shown also in this study. The average air velocity in 85 dwellings was 0.04 m/s in winter. Therefore, the heat loss in cold and neutral temperature will be influenced besides clothing insulation property from air temperature (convective heat transfer) and mean radiant temperature (radiative heat transfer) rather than from air velocity.

Summer

When a person begins to sweat, the evaporative heat transfer considerably influences the heat loss of the person, besides the convective and radiative heat loss. The evaporative heat transfer depends on the evaporative heat coefficient and air vapour pressure difference between skin surface and environment (See Equation (20)). Since the skin temperature in a warm environment does not change sensitively [43], the saturated water vapour pressure at skin temperature between 34 °C and 36 °C may be relatively constant with 53 ~ 59 hPa, while the water vapour pressure varies depending on the absolute humidity in a space. (The water vapour pressure at 70 % relative humidity is 28 hPa in comparison to 16 hPa at 50 % in same air temperature of 29 °C [95]) .

$$E_{\max} = h_e \cdot F_{pcl} \cdot (p_{sk,s} - p_a) \qquad (20)$$

Where:

$E_{\max}$	Maximum possible evaporative heat loss	$[W/m^2]$
h_e	Evaporative heat coefficient	$[W/(m^2 \cdot kPa)]$
F_{pcl}	Permeation efficiency	
$p_{sk,s}$	Saturated water vapour pressure at skin temperature	$[kPa]$
p_a	Water vapour pressure in ambient air	$[kPa]$

The evaporative heat coefficient can be estimated in analogous to the convective heat coefficient, which will be determined usually in summer, rather from air velocity than the low temperature difference between skin (clothing) temperature and air temperature.

$$h_e = LR \cdot h_c \qquad [W/(m^2 \cdot kPa)] \qquad (21)$$

Where

LR Lewis Ratio, which equals approximately 16.5 K/kPa according to ASHRAE Handbook [44] or 16.7 K/kPa according to ISO 7933 (1989) [45] at typical indoor conditions

Therefore, the efficiency of evaporative heat loss will depend on the air velocity (h_e) and water vapour pressure (P_a). Since convective, radiative, and evaporative heat transfer affect heat loss of people in warm environment, absolute humidity, air velocity and operative temperature will determine the thermal comfort in summer.

Although the humidity (water vapour pressure) will influence thermal comfort strongly only in summer, the comfortable (recommended) humidity area in winter can be determined from the hygienic aspect. The low humidity in many cases can cause the dryness of mucous membrane, whereas a high humidity can cause mould growth. The dissatisfaction of indoor factor caused by dryness in this study is very high in winter, following the noise. The evaporation in winter will be influenced from the air temperature (due to the low air velocity in winter) and water vapour pressure. The Pearson correlation between relative humidity and the perception of dryness is low (0.25) but significant, while the satisfaction of humidity in winter depends rather on the operative temperature (Pearson Correlation = -0.27) than relative humidity (not significant).

The summary of influence factors from the empirical and theoretical consideration can be found in the following table.

Table 48:
Empirical and Theoretical Influence Indoor Environment Factors for Thermal Comfort and Humidity Comfort

	Empirical	Theoretical
Winter :Thermal Comfort	Operative temperature	Operative temperature
Winter: Dryness	Relative humidity	Relative humidity , Air temperature
Thermal Comfort in Free-running Mode (Without Any Cooling or Heating)	Operative temperature Absolute humidity Air velocity (Only in summer without ventilator)	Operative temperature Absolute humidity Air velocity

6.2 Assessment Tool for Thermal Comfort

In previous Chapter, the influence factors for thermal comfort are determined empirically by using the data of this study and theoretically by based on the heat transfer of human body. Comfort range can be defined by means of these indoor environment influence factors or using comprehensive indices like PMV, which considers all physical factors and the individual factors. According to de Dear and Humphreys (see Table 4), a simple temperature explains thermal sensation of occupant more than comprehensive indices like PMV. It will be evaluated in the following Chapter.

6.2.1 Correlation of TSV with PMV and Temperatures

The results of Pearson correlation (Considered ASHRAE scale as interval scale) between Thermal Sensation Vote (TSV) and physical indices can be found in Table 49. The correlation for all seasons is comparable to the result of de Dear database (Table 4), in which the correlation of TSV with air temperature respectively operative temperature was some 0.52 in contrast to 0.46 with PMV. However, the correlations strongly vary depends on the season. No index is strong correlated with TSV in summer and in autumn, while all temperature indices show a strong correlation in winter. It means that temperature could be a good index for thermal assessment in winter in Korea, but not in summer or autumn. After all, a comprehensive index PMV cannot explain TSV better than other simple temperature indices as shown in other previous field study. It can be based on the clothing insulation value and air velocity, which are not independent variables to thermal sensation in field study (See Chapter 6.1) and may disturb the correlation between PMV and TSV. Therefore, the comfort range will be defined in this study using single indoor influence factors determined Chapter 6.1.

Table 49:
Pearson Correlation of Thermal Sensation Vote with Physical Parameters and PMV: All Indices Correlated Significantly

TSV	Air Temperature	Operative Temperature	Globe Temperature	PMV
All Seasons (n=248)	0.56	0.55	0.54	0.48
Summer (n=82)	0.26	0.28	0.27	0.22
Autumn (n=81)	0.28	0.27	0.27	0.30
Winter (n=85)	0.52	0.50	0.44	0.36

6.2.2 Thermal Neutrality and Thermal Comfort Analysis

The discrepancy between thermal neutrality and comfort has already been discussed using PMV-PPD analysis in Chapter 5.2.2. The following figures show the different mean comfort and neutral vote depending on operative temperature. If the thermal neutrality can transfer to thermal comfort, the highest comfort vote can be found in the case of thermal sensation of vote= 0. However, occupants in Korea feel more comfortable in winter under 23 °C than over 23 °C, although they feel rather neutral over 23 °C. In a free running mode, the neutral temperature is about 26 °C, but the comfortable temperature is between 23 °C and 25 °C. In summer, the difference of average thermal comfort vote between 26 °C and 29 °C is not considerable, as the thermal sensation in this range increases. This indicates that not only the operative temperature but also other parameters determine the thermal comfort in summer, as shown in Chapter 6.1. If operative temperature is higher than 26 °C, significantly different variables between satisfied and dissatisfied groups are absolute humidity ($p= 0.02$) and the floor of dwellings ($p=0.03$) from the four indoor parameters and other subject parameters, such as age, gender, floor and dwelling size. The higher absolute humidity reduces the thermal comfort judgement, whereas the higher floor influences positive to thermal comfort in summer.

The objective of this study is not to develop a thermal neutral but a comfortable residential buildings; by initially using the thermal comfort scale not the thermal sensation scale, a comfortable operative temperature and a humidity range will be defined.

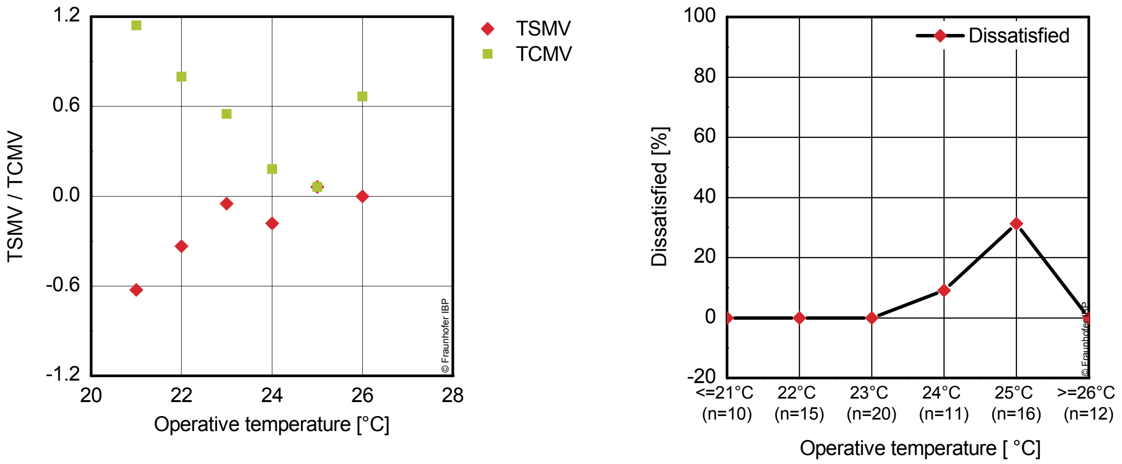


Figure 67:
Mean Vote According to Operative Temperature (Left) and Percentage of Dissatisfied in Winter (Right). TSMV: Thermal Sensation Mean Vote; TCMV: Thermal Comfort Mean Vote

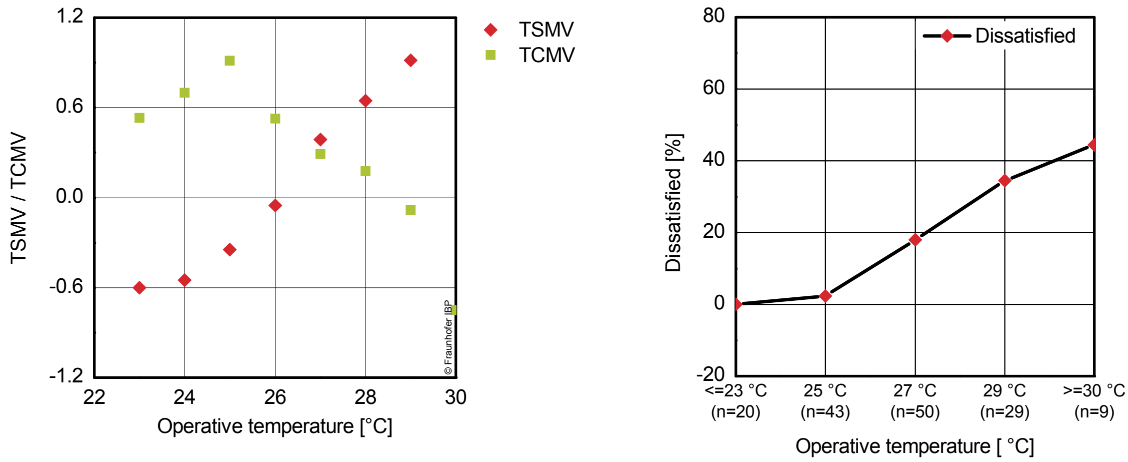


Figure 68:
Mean Vote According to Operative Temperature (Left) and Percentage of Dissatisfied (Right) in Free Running Mode. TSMV: Thermal Sensation Mean Vote; TCMV: Thermal Comfort Mean Vote

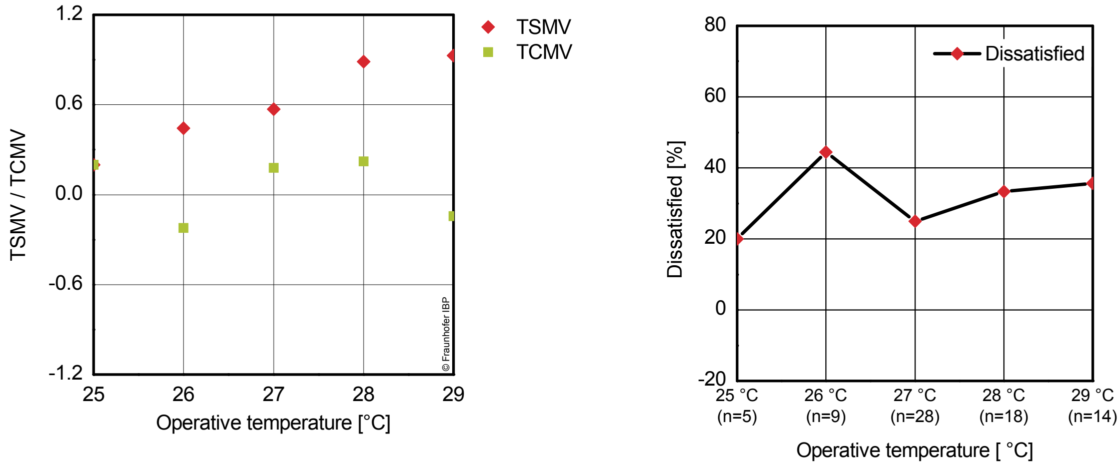


Figure 69:
Mean Vote According to Operative Temperature (Left) and Percentage of Dissatisfied in Summer (Right). TSMV: Thermal Sensation Mean Vote; TCMV: Thermal Comfort Mean Vote

6.3 Determination of Operative Temperature and Humidity for Thermal Comfort

6.3.1 Determination using Adaptive Model Approach

Determination from Comfort Temperature for Summer

The "comfort (neutral) temperature" of an individual subject can be calculated according to the Humphreys` study by using the Griffith's constant of 0.5 (see Chapter 2). From this methodology, the mean comfort temperature is estimated as 26. 3 °C in summer except air conditioner use (n=70) and as 25.5 °C in autumn (n=81).

The comfort area for 90 % acceptance or 80 % acceptance could be determined using different approaches.

According to Fanger, the increase or decrease of 0.5 or 0.85 PMV scale from the PMV=0 will cause respectively 10 % and 20 % dissatisfaction. Under the average indoor parameters in summer (RH=67 %, clothing=0.5 clo, Va = 0.14 m/s), ±1.3 K of operative temperature from the optimal temperature causes the 0.5 PMV difference and respectively ± 2.1 K and 0.85 PMV difference. In our case with the comfort temperature of 26.3 °C, the 80 % acceptance range can be determined between 24.2 - 28.4 °C.

In contrast to this, according to EN 15251 annex-A, the 90 % acceptance is determined with ± 2.5 K discrepancy from comfort temperature, and 80 % with ± 3.5 K. In our case with the comfort temperature of 26.3 °C, the 80 % acceptance range can be determined between 22.8 - 29.8 °C.

Nicol and Humphreys [54] have suggested the acceptable comfort area in SCATS study for EN 15251 by looking at the proportion of satisfied subjects in comparison to the difference (Tdiff) between the measured indoor and comfort temperatures. This analysis was performed using the data of this study [Figure 70]. In contrast to SCATs, the ratio of satisfaction is not symmetrically decreased against to discrepancy from comfort temperature (Tdiff). In this study, lower temperature than comfort temperature is perceived in a free-running mode as always "acceptable", while the increased temperature difference is not "acceptable" for residents in Korea.

The determination of maximum temperature difference of comfort temperature for 90 % and 80 % acceptance is difficult in summer due to the high dissatisfaction by all temperatures. If the scale "slightly cool", "neutral" and "slightly warm" would be defined as "comfortable" or "acceptable" like Fanger and SCATs project, 2K difference from the comfort temperature can achieve the 80 % acceptance. The result is similar with 2.1K according to the heat balance approach by means of PMV.

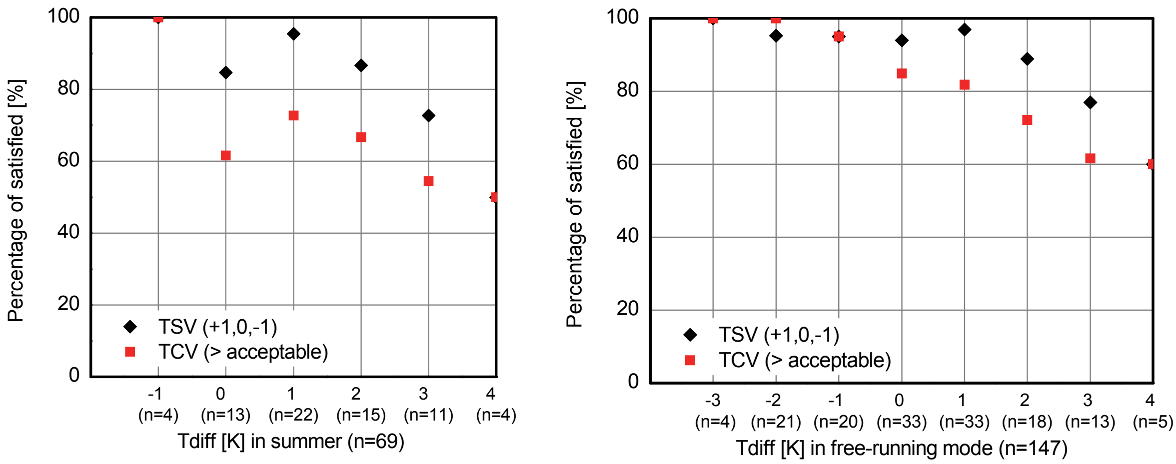


Figure 70:
Percentage of Satisfied and Tdiff in Summer (Left) and in Free-Running Mode: Summer and Autumn (Right). Black point: "Satisfied" Derived from TSV (Thermal Sensation) Questionnaire. Red point: "Satisfied" derived from TCV (Thermal Comfort) Questionnaire

Determination from Comfort Temperature for Winter

The calculated comfort temperature with Griffith's Constant of 0.5 in winter is 23.8 °C.

The weekly running outdoor temperature in Figure 71 is estimated according to EN 15251 with ($a = 0.8$) using the measured temperature data of weather station in the Building B. The adaptive approach of the increased comfort temperature, according to increased outdoor temperature cannot be confirmed in this study. Scatter plots of comfort temperature against the weekly running outdoor temperature in Figure 71 and Figure 72 show no relation between comfort temperature and outdoor temperature in autumn or a positive relation in summer. However, this positive relation may be based on the considerably high absolute humidity from the outdoor temperature of 23 °C, which caused warm sensation and high thermal dissatisfaction (See Chapter 5.2.3). Then the warmer sensation at lower outdoor temperature with higher absolute humidity will effectively decrease the comfort temperature.

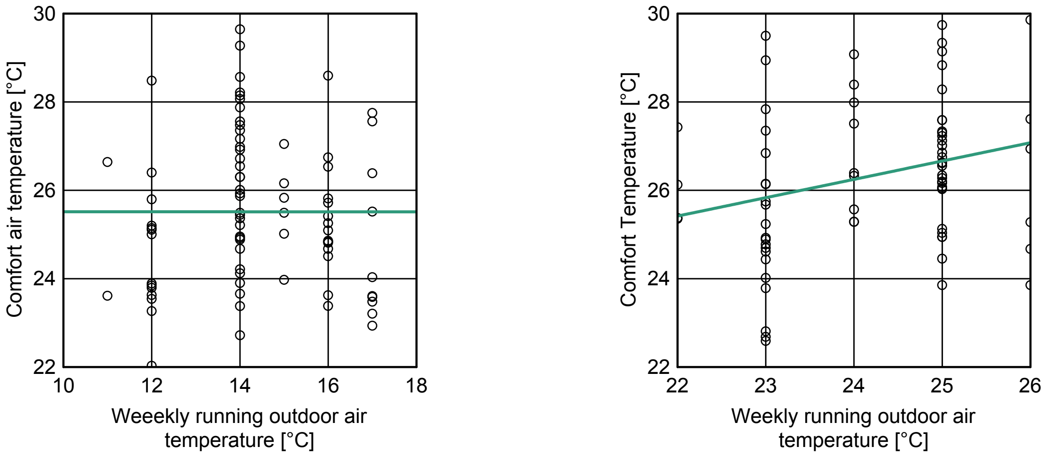


Figure 71:
Comfort Temperature with Griffith's Constant 0.5 in Autumn (r^2=0) and in Summer (Tcomf= 16.3 + 0.42*Trm; r^2 = 0.07)

If the comfort temperature is considered in a free-running mode in both seasons, a very slight increase of comfort temperature (0.09 K increase per 1K outdoor temperature increase) against the outdoor temperature can be observed. In comparison to the increase factor of 0.31 in EN 15251, it is very low and is rather comparable with the factor of 0.04 for buildings with HVAC in the study of de Dear [27].

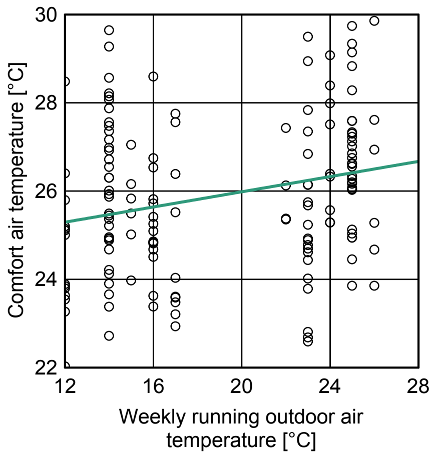


Figure 72:
Comfort Temperature with Griffith's Constant 0.5 in Free Running Mode (Tcomf=24.3+0.09*Trm; r^2=0.06)

This slightly increased comfort temperature of warm outdoor temperature can be explained in this study without any other adaptive parameters but only with decreased clothing insulation value and increased air velocity in summer (See Figure 73).

The calculated PMV with comfort temperature (25.38 °C), average clothing insulation (0.66 clo) and air velocity (0.03 m/s) at 12 °C outdoor temperature is 0.26. For this PMV (0.26), the comfort temperature should be 27.2 °C at 28 °C outdoor temperature, under average clothing insulation (0.46 clo) and air velocity (0.17 m/s) (see Figure 73). According to the regression from Figure 72, however, the comfort temperature at 28 °C outdoor temperature is 26.8 °C, which is lower than PMV estimation of 27.2 °C. It indicates that the adaptive approach, estimation of comfort temperature according to outdoor temperature, cannot provide a wider comfort range than PMV in this study.

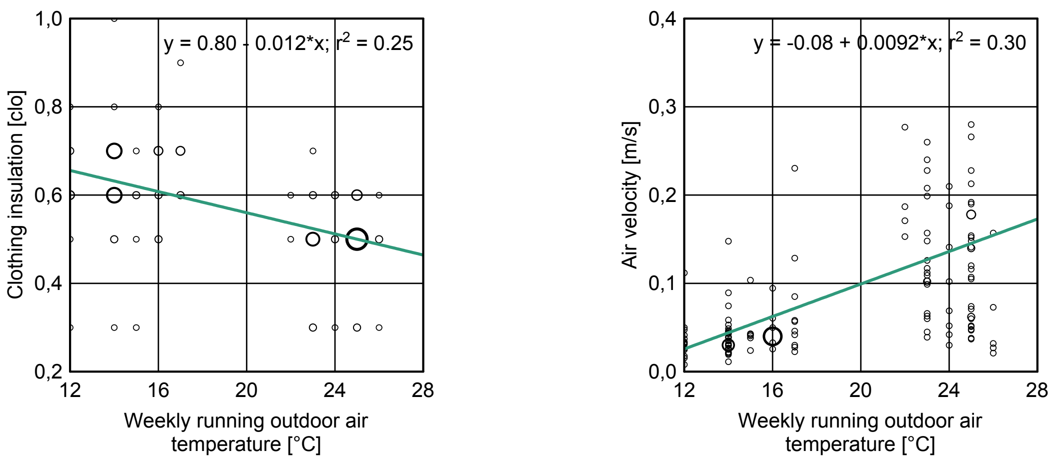


Figure 73:
Scatter Plot of Clothing Insulation Value (Left) and Air Velocity (Right) Against Weekly Running Outdoor Temperature

6.3.2 Determination using Logistic Regression Model

Thermal comfort is a dichotomous outcome variable defined as either "satisfied (acceptable)" or "dissatisfied (not acceptable)". The relation between such dichotomous variables and predictor variables cannot be described well with conventional linear regression, because their outcomes do not regard dichotomous result (0 or 1). The outcome increases or decreases endlessly against a variable predictor. The judgement of comfort will also not be the linear function but a rather nonlinear function, where the judgement changes strongly between certain points and does not change from a definite point. In addition, the linear regression assumes a normal distribution of error and a constant error across the entire range of data [96], which appears rarely in a comfort research, especially with small samples. In this situation, the logistic regression is well suited for describing the relation between dichotomous outcome variable and one or more categorical or continuous predictor variables. In the following, the principle of logistic regression is explained on the basis of [96]- [99].

Logistic Regression

The central concept of logistic regression can be explained with a natural logarithm of odds on outcome variable (Y), so called "logit (Y)", Z in the Equation (22).

$$\ln\left(\frac{p(y)}{1-p(y)}\right) = Z \qquad (22)$$

Where:

$p(y)$	Probabilities of Y (Outcome variable) Happening
$\frac{p(y)}{1-p(y)}$	Odds of Y
Z	Logit (Y)

The odds are defined as ratios of probabilities of Y-happening to probabilities of Y-not-happening. If the odd of thermal comfort is 3 at operative temperature 24 °C, it is three times as likely that a random occupant is satisfied at 24 °C than he or she is not satisfied. The odd of outcome variable depends generally on the predictor variables. By logistic regression, the "logit"- natural logarithm of odds - is used for describing the relation between outcome variables and predictor variables. The logit (y), Z in the Equation (22) can be described with one or more predictor variables using linear function (Equation (23)). On the other hand, the odds of outcome variable can be described with Z, using an exponential function (Equation (24)), which can be expressed in odds by getting rid of the log from Equation (22). From the Equation (24), the probability of outcome variable (y) can be calculated as Equation (25). By logistic modelling, the coefficients in Equation are generally estimated using ML (Maximized likelihood) method.

$$Z = \beta_1 x1 + \beta_2 x2 + \beta_3 x3 ..... + \beta_0 \quad (23)$$

Where:

x = Predictor Variables

β = Coefficients

$$\frac{p(y)}{1 - p(y)} = e^z \quad (24)$$

$$P(y) = \frac{1}{1 + e^{-z}} \quad (25)$$

$x1, x2, x3 ......$	$\rightarrow$	Z	$\rightarrow$	$\frac{p(y)}{1-p(y)}$
Predictor variables	Linear fuction	Logit	Exponential fuction	Odds of outcome variable

Figure 74:
Functions in Logistic Regression

Modelling

Two comfort models (summer and winter) are developed using the generalized linear model function with R.2.10.1[100], since STATISTICA 9.0 [101] does not provide statistical tests of individual predictors in logistic regression. The difference of results using both software is not considerable.

The summer comfort model is based on the summer and autumn questionnaire actions (n=167), while the winter comfort model is developed using only winter questionnaire action (n=86). According to the analysis about influencing factors in Table 48, the predictor variables for summer were operative temperature and absolute humidity, while the winter was determined by the thermal comfort alone with the operative temperature (see Chapter 6.1 for the choice of predictor variables). The results of modelling can be found in Equation (26) for summer and in Equation (27) for winter.

$$P(comfort\_summer) = \frac{1}{1 + e^{14.6 - 0.31 * To - 0.34 * Ah}} \quad (26)$$

Where:

To Operative Temperature

Ah Absolute Humidity

$$P(comfort\_winter) = \frac{1}{1+e^{10.46-0.33*To}} \quad (27)$$

Overall Evaluation of Model

A Likelihood-Ratio-Test is used for the overall evaluation, where it is compared when a model with predictor variables fits significantly better than a model only with an intercept, so called null model.

Null hypothesis: All coefficients in a model equal zero

(ß1=ß2=ß3=0).

A rejection of the null hypothesis means that the predictor variables have an influence on the outcome variable and the suggested model predicts the probability of the outcome significantly better than the null model.

For the summer model, the null hypothesis can be rejected with p=0.000 ($x^2 = 38.2, df=2$). For the winter model, the null hypothesis cannot be rejected with p=0.11 ($x^2 = 2.6, df=1$). The summer comfort model can predict significantly better than a null model, while the winter model cannot. It is based on the sample size (bigger size in summer than in winter) and on the low dissatisfaction ratio in winter.

Statistical Tests of Individual Predictors

As it can be shown in Table 50, the coefficients of operative temperature and absolute humidity in summer model are significant. For a unit increase in temperature [1K] and absolute humidity [g/kg], the odds of being satisfied decrease by a factor of 0.74 and 0.71 respectively. The influence of absolute humidity is in the model slightly higher than operative temperature. The coefficient of operative temperature in winter model is not significant like overall winter model. An increase of operative temperature of 1K will reduce the odds of comfort in winter 0.72 times, since the occupants feel more comfortable in low temperature also in winter according to this study.

Table 50:
Statistical Tests of Individual Predictors for Summer Model

Predictors	ß	p	e^{β}
Constant	10.5	0.001	
Operative Temperature	-0.31	0.05	0.74
Absolute Humidity	-0.34	0.000	0.71

Table 51:
Statistical Tests of Individual Predictors for Winter Model

Predictors	ß	p	e^{β}
Constant	14.6	0.03	
Operative temperature	-0.33	0.10	0.72

Determination of 80 % and 90 % Comfort Area

The probability of comfort, $P(y)$, can be expressed in the logistic model as Equation (25) and graphical as Figure 75. For the 90 % probability of satisfaction, Z should be above of 2.19 and for 80 % probability, 1.39.

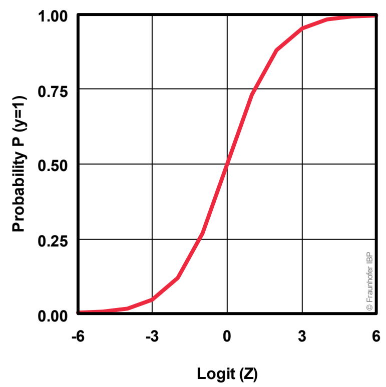


Figure 75:
Probability (y) against to Logit as z

Summer

If z is determined, the relation between operative temperature and absolute humidity can be explained with linear function for the summer model. The result can be found in Figure 76. If the absolute humidity is limited as 12 g/kg like ASHRAE 55-2004, the maximal operative temperature for 90 % satisfaction is

26.9 °C, which is very similar to Figure 10 in ASHRAE 55-2004. For 80 % satisfaction, up to 29.5 °C is acceptable by the absolute humidity of 12 g/kg.

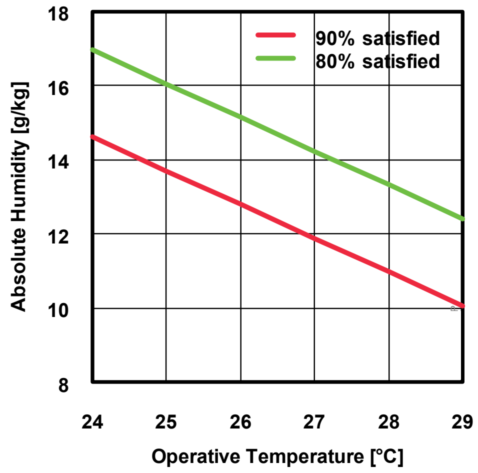


Figure 76:
Determination of Operative Temperature and Absolute Humidity for 90 % and 80 % Satisfaction by Summer Model.

Winter

Due to the high satisfaction in winter in contrast to summer, a determination of 80 % satisfactory comfort range will not make sense (See Figure 77). Therefore, the 95 % and 90 % satisfaction area is defined using the winter model. The minimal operative temperature could be defined from the frequency. Although the ratio of satisfaction up to 21 °C is very high (100 %), the frequency is very low (Only 6 from n = 86). An increased frequency can be found from 21 °C with 14 between 21 °C and 22 °C. For 95 % satisfaction ($Z = 2.945$) and 90 % satisfaction ($Z = 2.19$), the maximal operative temperature should be under 23.0 °C and 25.3 °C respectively.

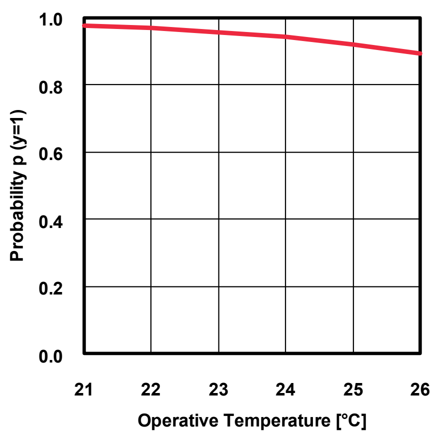


Figure 77:
Probability of Comfort Against Operative Temperature in Winter

Although humidity does not influence thermal comfort in winter, a recommended humidity range could be determined from the hygienic aspect and high skin dryness complaint in winter between 30 % and 60 % RH.

Table 52:
Comfort Range for Summer and Winter

Summer	90 % Satisfaction	80 % Satisfaction
Summer (To and Ah)	$0.31*To + 0.34*Ah < 12.41$	$0.31*To + 0.34*Ah < 13.21$
Winter	95 % satisfaction	90 % satisfaction
Winter_To	21 °C ~ 23 °C	~ 25.3 °C
Winter_RH	30 % - 60 %	30 % - 60 %

Evaluation of Classification

Most of the dwellings achieve the required operative temperature in autumn and absolute humidity of 90 % satisfaction ($Z = 2.19$), while only 6 dwellings comply with this requirement in summer. 18 dwellings in summer reach 80 % satisfaction requirement and 83 % of them judge the environment more than acceptable (Table 53). In winter, 69 from 86 dwellings (80 %) achieve the 90 % satisfaction requirement and 94 % of them are actually satisfied (Table 54).

Table 53:
Summer Model Evaluation

	Summer and Autumn Questionnaire (n=167)		Summer Questionnaire Only (n=83)	
	n (satisfied/all)	Percentage of Satisfaction	n (satisfied/all)	Percentage of Satisfaction
Z > 2.19 (90 %)	88/89	99 %	6/6	100 %
Z > 1.39 (80 %)	98/102	96 %	15/18	83 %

Table 54:
Winter Model (n=86) Evaluation

	n (satisfied/all)	Percentage of Satisfaction
Z > 2.95 (95 %)	34/34	100 %
Z > 2.19 (90 %)	65/69	94 %

The logistic regression model with operative temperature and humidity as predictors in summer respectively with operative temperature in winter provided better comfort range in Korea than an adaptive model with indoor and outdoor temperature as predictors.

6.4 Determination of Comfort Ventilation

6.4.1 Summer

According to ISO 7730 and ASHRAE 55-2004, an elevated air velocity can increase the maximum acceptable temperature above 26 °C, if the occupants are able to control air velocity. The reference point (0) in the Figure 78 is 26 °C operative temperature and 0.2 m/s air velocity. In our study, the average air velocity in summer is 0.17 (m/s), which is not very high, although most of the residents let the windows open (62 %) or ventilators in operation (23 %) during the spot measurements. However, they do not open windows in living rooms, but windows of balcony in front of bedroom and a door from living room to this balcony. They control small opening size using sliding window. This user behaviour reduces the air velocity in living rooms. The residents place ventilators not directly to themselves but with 1 or 2 meter distance with turning function, maybe considering the comfort of visitors or regarding to recommendation for use of ventilator. The use of ventilator is still a common measure following a window opening for thermal comfort in summer, more than an air conditioner in Korea.

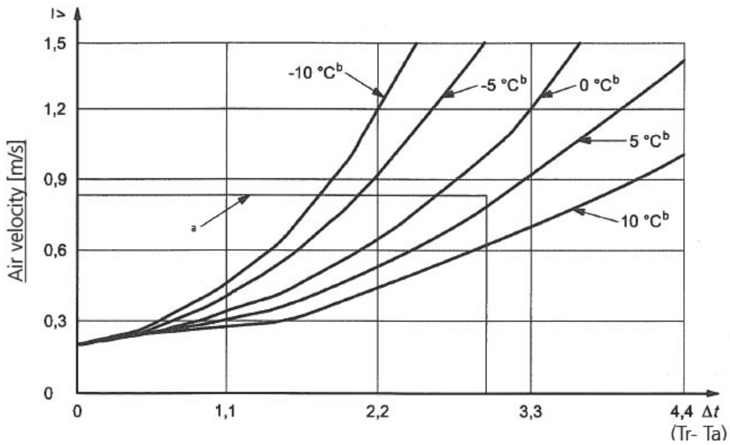


Figure 78:
Air Speed Required to Offset Increased Temperature: a) Limit for light, primarily sedentary activity, b) (tr-ta) from [26].

The air velocity under ventilator operation is 0.18 [m/s], which is significantly higher than 0.13 [m/s] with window opening (p=0.05). However, this higher air velocity induced from ventilator does not significantly account for thermal comfort whereas it does under an opened window condition (Table 47) (Figure 79). It is difficult to understand why only the flow caused by window opening can account for thermal comfort.

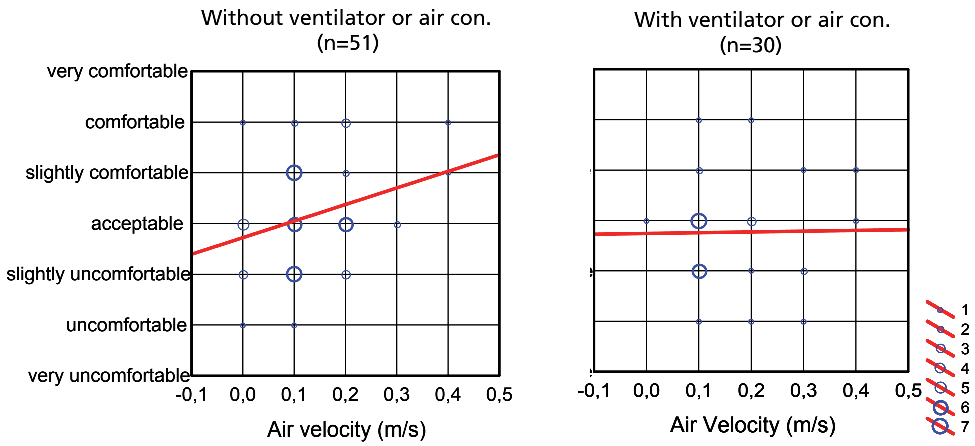


Figure 79:
Relation Between Thermal Comfort and Air Velocity in Summer (Left: window opening, Right: ventilator)

A high air velocity could contribute high convective and evaporative heat coefficients to thermal comfort in summer. The discussion about the effectiveness of air velocity on the thermal comfort can be found in [102][103]. It could be assessed in comparison of thermal comfort between different air velocity under similar thermal load determined from absolute humidity and operative temperature. If airflow positively influences a thermal comfort, the thermal comfort under high air velocity should show significantly higher satisfaction by similar thermal load. Since the logit (Z) in previous Chapter includes these two influences, the correlation between air velocity and thermal comfort is analysed depending on the logit (Z). Under the defined z range, the correlation between air velocity and thermal comfort is not significant independent of source of airflow (window or ventilator). The air velocity and thermal comfort has a positive correlation by the window ventilation only regarding to entire summer data.

The non-significant correlation between air velocity and thermal comfort in defined z range could be based on the small sample size in this study. On the other hand, the contribution of high air velocity to thermal comfort by window ventilation could be resulted from the higher indoor air temperature than outdoor air temperature. By monitoring the 24 dwellings, the indoor air temperature is almost higher than the outdoor temperature, as well as during the daytime. It indicates that high air change rate will reduce the indoor temperature. This positive effect of high air change in summer can be distinguished from the result of simulation with different air changes in Figure 80. Above 2K discrepancy is observed between low air change rate and high air change rate in August. The higher the air change rates with outdoor air, the more comfortable the indoor climate in summer is. Finally, not the high air velocity but the high air change rate may account for thermal comfort in summer in this study. The positive influence of high air velocity based on the high heat transfer coefficients could not be approved in this study within the moderate range of air velocity by means of the measurements and questionnaire.

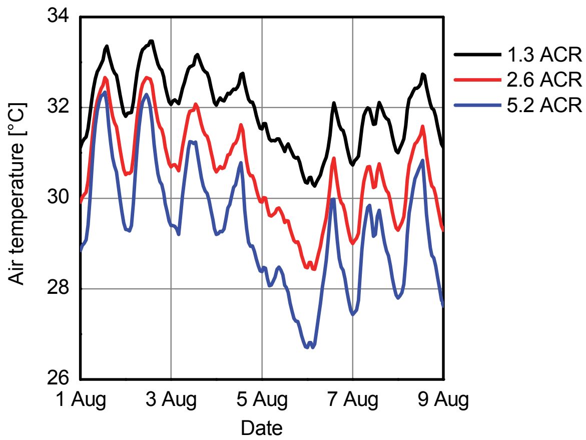


Figure 80:
Indoor Climate According to TRNSYS Calculation with Different Air Change Rate per Hour in August in Building A

6.4.2 Winter

While a highest air change rate should be achieved for a high thermal comfort in summer in Korea in case of without active cooling, the air change rate in winter should be limited for a requirement due to energy saving. The required air change rates for 1000 ppm carbon dioxide concentration are calculated for 24 dwellings using occupancy rate in winter questionnaire. These required values are compared with air change rate estimated from the CO2 measurements as ventilation ratios in Table 55 and Table 56. A low ventilation ratio has a relation to mould occurrence, while a high ventilation ratio causes a low indoor relative humidity. An unnecessary high ventilation ratio above 150 % to required ventilation rate for CO2 concentration of 1000 ppm will result not only a high energy consumption but also dryness of skin or mucous membrane, based on the low relative humidity (B1, B5, C2, D2). On the other side, too low ventilation ratio under 70 % caused strong mould growth in some dwellings (A3, A6, C6). The mould occurrence does not depend only on ventilation ratio but also the humidity generation in a dwelling and air temperature. If indoor air temperature is high, the relative humidity is relatively low instead of a low ventilation ratio, which prevents a mould risk. However, this variant will not be especially energy efficient. The energy efficient and comfortable air change rate could be determined according to occupancy rate in a dwelling for carbon dioxide concentration of 1000 ppm or 1500 ppm for dwellings with very low humidity generation.

Table 55:
Comparison of measured Air Change Rate with Required Air Change Rate for CO_2 Concentration 1000 ppm and Mould Growth in Buildings A and B

Dwelling	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6
ACH_Winter [1/h]		0.25	0.29	0.39	0.40	0.23	0.48	0.26	0.32	0.28	0.47	0.46
Required ACH for 1000 ppm [1/h]	0.42	0.38	0.44	0.29	0.77	0.59	0.20	0.33	0.43	0.26	0.24	0.35
Ventilation Ratio [%]		66 %	65 %	135 %	52 %	38 %	236 %	80 %	74 %	108 %	196 %	133 %
Mould		x	xxx			xx			x			
Winter (RH) [%]	31.6	40.6	52.5	27.9	41.6	58.2	22.5	28.5	29.1	23.0	20.9	28.8
Winter (Ta) [°C]	21.5	25.2	21.1	24.9	24.0	23.3	23.3	23.4	25.5	22.6	23.9	22.0

ACH_Winter: ACH (Air Change Rate per Hour) determined from the CO2 measurements (see 4.4.2)

Required ACH for CO2 concentration of 1000 ppm: determined from occupancy rate

Ventilation Ratio: Measured ACH / Required ACH for CO2 concentration of 1000 ppm

RH (Relative Humidity), Ta (Air Temperature): Measured values during winter months (Nov. - Feb.)

Table 56:
Comparison of Air Change Rate with Required Air Change Rate for CO_2 Concentration 1000 ppm and Mould Growth in Buildings C and D

Dwelling	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
ACH_Winter [1/h]	0.50	0.76	0.39		0.38	0.19	0.47	0.46	0.18	0.24	0.19	0.20
Required ACH for 1000 ppm [1/h]	0.39	0.36	0.31	0.39	0.52	0.48	0.39	0.25	0.33	0.48	0.37	0.40
Ventilation Ratio [%]	129 %	213 %	128 %		74 %	39 %	120%	186%	55 %	50 %	51 %	50 %
Mould				x	X	xxx						x
Winter (RH) [%]	27.4	20.6	37.4	41.5	55.7	67.8	24.1	22.7	45.2	36.6	49.5	37.7
Winter (Ta) [°C]	24.0	23.2	23.2	21.8	19.0	20.3	26.2	26.2	23.3	25.8	25.3	24.1

ACH_Winter: ACH (Air Change Rate per Hour) determined from the CO2 measurements (see 4.4.2)

Required ACH for CO2 concentration of 1000 ppm: determined from occupancy rate

Ventilation Ratio: Measured ACH / Required ACH for CO2 concentration of 1000 ppm

RH (Relative Humidity), Ta (Air Temperature): Measured values during winter months (Nov. - Feb.)

7. Relation between Energy Efficiency, Thermal Comfort and User Behaviour

7.1 Low Air Temperature in Winter vs. User Heating Behaviour

Requirement: Reduction of air temperature from 23.5 °C to 21 °C

It is generally believed that Koreans feel more comfortable in high air temperature in winter, because the Koreans live at a higher temperature than Europeans do, as showed in this study. However according to this study, Koreans are more comfortable at operative temperature of 21 °C and slightly on a cool environment of PMV = -1 than on neutral environment of PMV = 0 in winter. This could be from the better air quality perception in low air temperature as reported in literatures, as well as it was also verified in this study (See Chapter 5.2.2).

Reasons of User Heating Behaviour to High Air Temperature

For saving energy and thermal comfort in winter, it is important to keep the air temperature low. However, why do some occupants heat their homes up to 27 °C although they can control the thermostats themselves? All investigated buildings have an individual control system in every room. The high air temperature could be from the lack of motivation for saving energy, as the energy cost is low. However, questionnaires about heating cost and heating behaviour, to the comparison with the results of measurement in Chapter 4.1.2 do not corroborate this assumption. The residents in dwellings with high air temperature claim that the heating energy cost is too expensive. The clothing insulation value depending on the air temperature is not significantly different.

The analysis of air temperature depending on buildings shows the conspicuous difference of air temperature between buildings in the spot measurement as well as in continuous measurement (Chapter 4.1.2). The mean air temperature of 25.4 °C in Building D is significantly above than other three buildings ($p = 0.007$ according to ANOVA test). The ratio of overheating above 26 °C in Building D is with 47 %, which is clearly higher than 7-10 % of other buildings (Table 24).

- Low Performance of Window

The big constructive difference between Building D and other buildings is the window and the type of ventilation. The other buildings have better insulated windows with U-Value between 1.1 W/(m²·K) and 1.4 W/(m²·K) in contrast to Building D with U-Value of 3.3 W/(m²·K). This impact was also found in the comparison of air temperature and radiation temperature during the spot measurement. The radiation temperature in Building D is average 1.5 K below than air temperature, while the difference in other three buildings is approximately 0.5 K. For the same operative temperature, the Building D should theoretically have higher air temperature than other buildings.

The theoretical example of calculations in Figure 81 clearly shows the effects of U-Value of envelope on the air temperature. In Figure 81, the required air temperature is calculated on each 0.1 - 0.5 m grid in a 5 m * 5 m room for the same operative temperature 24 °C, in case of two different U-Values (3.3 and 1.1 W/(m²·K)) of building envelope. The room has five internal walls with one external wall of different U-Value. This example is computed with the outdoor air temperature of -5 °C. Initially, the surface temperature is calculated under the assumption of 24 °C air temperature for each case using Equation (28).

$$T_s = T_i - R_{si}(U \cdot (T_i - T_o)) \qquad (28)$$

Where:

T_s	Surface temperature	$[°C]$
T_i	Indoor temperature	$[°C]$
R_{si}	Heat resistance on the interior surface	$[(m^2 \cdot K)/W]$
U	U-value	$[W/(m^2 \cdot K)]$
T_o	Outdoor temperature	$[°C]$

According to ISO 7726, the mean radiant temperature on each point can be determined for a seated person from the Equation (29), using the plane radiant temperature of six orientations (ceiling, floor, left -, right -, front - , back walls). The plane radiant temperature can be calculated from surface temperature and angle factors of each point.

$$\bar{t}_r = \frac{0.18(t_{pr}(up) + t_{pr}(down)) + 0.22(t_{pr}(right) + t_{pr}(left)) + 0.30(t_{pr}(front) + t_{pr}(back))}{2(0.18 + 0.22 + 0.30)} \qquad (29)$$

$$\bar{t}_{pr} = t_1 F_{p-1} + t_2 F_{p-2} + \ldots + t_N F_{p-N} \qquad (30)$$

t_{pr}	Plane radiant temperature	$[K]$
t_N	Surface temperature of surface N	$[K]$
F_{p-N}	Angle factor between small plane element and surface N	

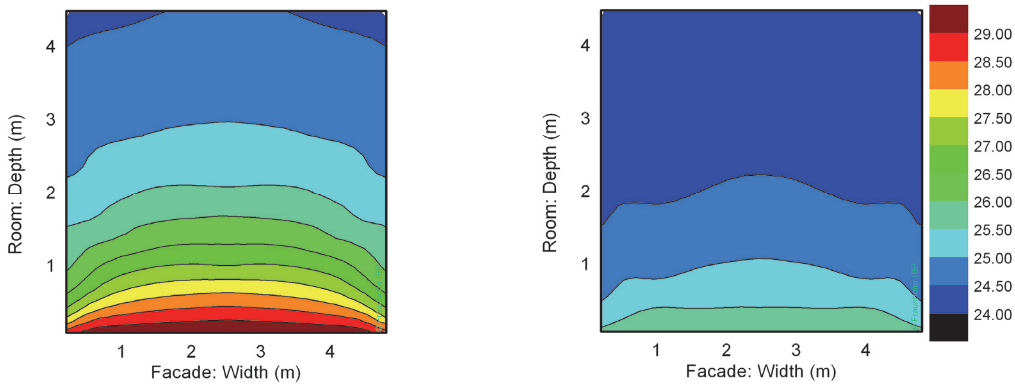


Figure 81:
Required Air Temperature Depending on the U-Value of Window for the Same Operative Temperature of 24 °C (Left: window with U-value of 3.3 W/(m²·K) on the facade, Right: window with U-value of 1.1W/(m²·K) on the facade).

For the same operative temperature, a room with a window, which has the U-value of 3.3 W/(m²·K) should have an air temperature of 27 °C on a place of 1 m distance from external envelope, while the other room requires only 25 °C on the places. However, the same operative temperature in two variants does not provide the same thermal comfort due to the local discomfort. The radiation asymmetries caused by the difference of the front and back plane radiant temperature is higher by window with U-value of 3.3 W/(m²·K) than by the other window. In this case, the higher radiation asymmetries could result a high discomfort (Figure 82). Therefore, the high performance windows will increase not only by reducing the transmission heat loss but also by reducing the air temperature and increasing the thermal comfort in winter due to the reduction of local thermal discomfort.

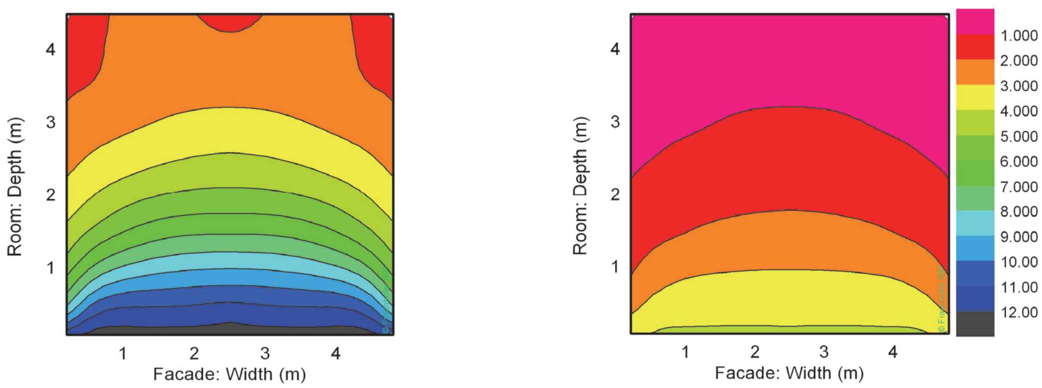


Figure 82:
Radiation Asymmetries Depending on the U-Value of Windows at the Same Operative Temperature of 24 °C (Left: 3.3 W/(m²·K)window on the facade, Right: 1.1W/(m²·K) Window on the Facade).

- Indoor adaptation

The high indoor air temperature in Building D could be explained with the high U-value of windows, however the air temperature in Building C is clearly lower than in Building A or Building B by spot-measurement also by monitoring. The air temperature in Building C is lower than other buildings also in summer and in autumn without heating. Therefore, it is assumed that the indoor air temperature in summer might influence the air temperature in winter. The adaptive models in EN 15251 or in ASHRAE 55-2004 is based on the field investigations, which indicated that the people in warm outdoor climate perceive the higher indoor operative temperature acceptable to outdoor climate due to the acclimatization or adaption using clothing. In this study, it is observed that the residents in dwellings with high air temperature in summer also adjust the dwellings warmer in winter than in other cooler dwellings (Figure 83).

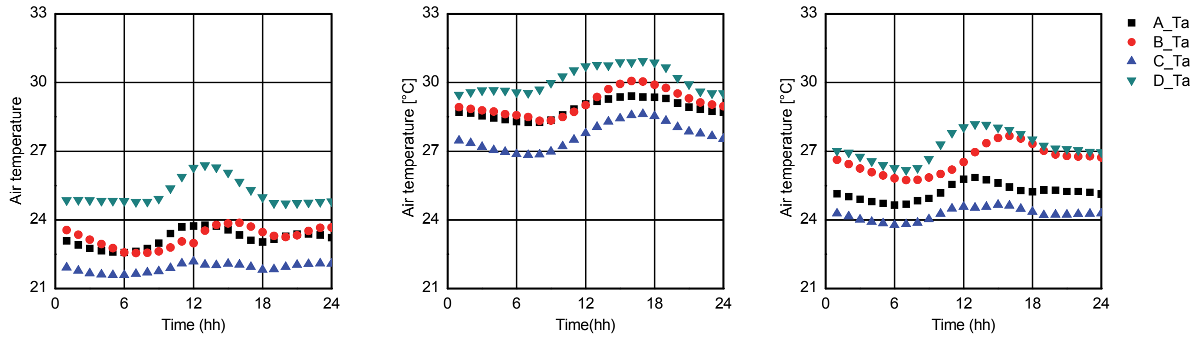


Figure 83:
Monthly Average Air Temperature in August, October and January in Four Buildings

For this reason, a hypothesis of thermal adaptation to indoor climate, has been established:

The warm indoor climate during the summer season might result a thermal comfort perception in higher indoor air temperature for other seasons. There is acclimatization to indoor climate.

If the hypothesis is accepted, a building should be kept cool in summer for the low indoor air temperature in winter. Then, the solar protection measures, which can decrease the internal heat load and increase the thermal comfort in summer also account for the energy efficiency in winter. In order to test this hypothesis, the mean air temperatures in 24 dwelling during the three summer and three winter months are compared. The following figure shows the tendency of the relations of the both air temperatures.

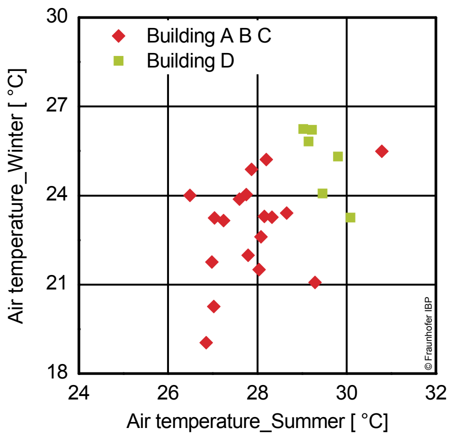


Figure 84:
Relation of Air Temperature in Summer and Winter in 24 building

Since the high air temperature in winter period in Building D is influenced rather from the low surface temperature, the hypothesis can be accepted if the air temperature in winter between low and high air temperature groups in summer without the Building D is significantly different. However, the statistical t-test between the high and low air temperature group is insignificant excluding the Building D (p=0.2) and significant including the Building D (p=0.03).

Table 57:
Average Air Temperature in Winter by Two Groups (High air temperature in summer / low air temperature in summer) Including and Excluding the Building D

	Average Ta in Winter Including Building D	Average Ta in Winter Excluding Building D
High Ta Group in Summer	24.4 °C (n=12)	23.4 °C (n=9)
Low Ta Group in Summer	22.7 °C (n=12)	22.4 °C (n=9)
t-test	P=0.03	P=0.2

This result could be based on a small number of study, therefore the hypothesis "indoor adaptation" requires a further investigation.

7.2 High Air Change Rate in Summer vs. User Ventilation Behaviour

Requirement: High Air Change Rate in Summer

The consequent question from the obvious analysis is why the air temperature in the Building C during summer period is lower than other buildings. At first, it could be from a high rate of the air conditioner operation; however, it is rejected according to the analysis in Chapter 4.1.2. Both the measurement on the duration of the air conditioner operation performed in one dwelling each from Buildings A and C as well as two dwellings in Building B, in addition to the analysis of frequency of the strong air temperature decrease based on the air conditioner; all showed the reduced use of air conditioner in dwellings in Building C.

The possible explanation might be the high air change rate in Building C, since the outdoor air temperature in Korea in summer is usually lower than the measured indoor air temperature. The general lack of solar protection and high internal load in Korea force the indoor air temperature to exceed the outdoor air temperature also during the daytime. Therefore, a high air change rate can result a low air temperature close to the outdoor temperature (Figure 85).

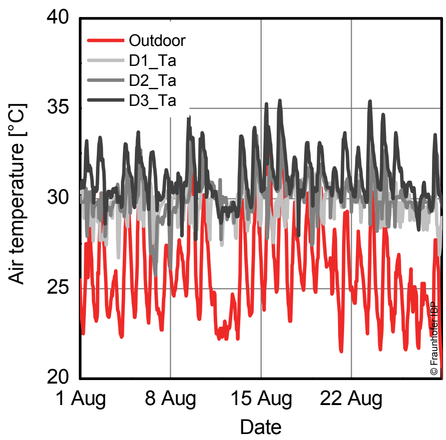


Figure 85:
Indoor Air Temperature and Outdoor Temperature in August

Reasons of User Ventilation Behaviour to Closing Windows

The leading causes for restricting an air change rate using the windows according to questionnaires are noise and dust for all buildings except Building D, where the first reason for closing window is the air conditioner in use. Thus, an alternative system providing a high air change rate with filter and sound attenuation is required for the thermal comfort and energy efficiency in summer. About 70 % of outdoor air temperature in three summer months is below than 27 °C. If the indoor air temperature can be kept close to the outdoor, the use of air conditioner can be reduced and the thermal comfort can be increased due to the low air temperature and high evaporative heat loss due to the high air velocity.

7.3 Active Cooling and Dehumidification vs. User Cooling Behaviour

Requirement: Active Cooling and Dehumidification in Summer

Aforementioned passive thermal control alternative for high air change rate cannot provide a high thermal comfort due to the high absolute humidity in Korea (see Table 58). About 76 % of outdoor humidity in three summer months exceeds the upper limit (12 g/kg) of high thermal comfort and 54 % of the upper limit (14 g/kg) for acceptable area at 27 °C in Chapter 6.3.

Table 58:
Frequency of Outdoor Absolute Humidity in Three Summer Months

Outdoor Absolute Humidity in Summer (June – August)		
	Hours (h)	Percentage (%)
<12 g/kg	521	24 %
12<=x<14	480	22 %
14<=x<16	423	19 %
16<=x<18	376	17 %
18<=x<20	303	14 %
>20 g/kg	105	5 %

Therefore, the high thermal comfort in Korea can be achieved in summer only with dehumidification. The conventional electrically powered air conditioner, which is installed in most of the dwellings in Korea, works now also as a dehumidifier. A compression chiller installed on the balcony area produced the chillness, which is then transferred to the indoor equipment of air conditioner. The warm and humid indoor air is drawn though the indoor equipment of the air conditioner, where a condensation forms and this condensed water then flows to the balcony area. The cold and dehumidified air is supplied to the indoor.

Reasons of User Cooling Behaviour to Non-Use of Air-Conditioner

The disadvantage of this conventional system is the 100% recirculation air supply, besides the high electric energy consumption. The residents generally do not open windows during the operation of air conditioner due to high-energy consumption, which can result a bad air quality in a room. On the other side, in case of the window ventilation during the active cooling operation, the fresh but humid outdoor air results not only the high energy demand but also could result the mould growth especially by the operation with low air temperature. Therefore, the fresh and dehumidified air supply is necessary for the high comfort and high air quality.

7.4 High Insulation of Building Envelop vs. Thermal Comfort in Summer

Requirement: High Insulation of Building Envelope

Until now, the Interior insulation is used common in high-rise residential building in Korea due to the cost efficiency. The future political trend will require always the strong energy efficiency in the building and it means at first the higher thermal insulation of building envelope. However, U-value does not decrease parallel to the increase of the thickness of insulation. The 8 cm increase of insulation from 16 cm to 24 cm reduce only 0.06 W/(m²·K), while the 8 cm from 8 cm to 16 cm force down the u-value 0.17 W/(m²·K). The additional U-Value due to the thermal bridge amounts 0.17 W/ (m²·K) in this study, which will not decrease according to the increase of insulation. By the existing internal insulation, the ratio of additional heat loss due to the thermal bridge is now about 17 % of whole transmission heat loss and will become about 51 % with the approximately 75 % reduction of U-Value of building envelope (Table 64).

Table 59:
Required Insulation Thickness for the 25 %, 50 %, 75 % Reduction of U-Value of Building Envelope and the Ratio of Thermal Bridge on the Total Heating Energy Demand. (Calculation with DIN V 18599 without interzonal ventilation)

	Wall: current Window: current (1.1/3.3)	Wall: U 25 % Reduction Window: (1.1/2.5)	Wall: U 50 % Reduction Window (0.8/1.65)	Wall: U 75 % Reduction Window (0.8/0.8)
Side Wall	9.5 cm	13 cm	20.5	42 cm
Balcony	6.5 cm	9 cm	14.5	30 cm
Stairway	4.5 cm	6.5 cm	10.5	22.5 cm
Window (to Balcony)	3.3W/(m²·K)	2.5 W/(m²·K)	1.65 W/(m²·K)	0.8 W/(m²·K)
Window (to Outdoor)	1.1 W/(m²·K)	1.1 W/(m²·K)	0.8 W/(m²·K)	0.8 W/(m²·K)
Heating Energy Demand (Total) [kWh/m²a] (23 °C)	61	49	32	20
Ratio of Thermal Bridge	17 %	21 %	32 %	51 %

It shows that at any time, the increased insulation under an internal insulation is more expensive than exterior insulation for the same reduction of average U-value. Therefore, the cost efficiency between high internal insulation with high thermal bridge and low external insulation with low thermal bridge should be compared before the increase of insulation of the wall. The external insulation systems with relatively thin thickness provide in comparison to internal insulation a reduction of place, a reduction of mould risk as well as the better protection of the concrete construction, which can increase the whole durability of the building construction. Such aspects should be considered by the cost efficiency analysis. The energy saving potential of the improvement of insulation is strong depending on the user ventilation behaviour. The calculation of Table 59 is based on the case without interzonal ventilation between living area and balcony area. If the residents ventilate rather through the balcony area as observed in this study, the energy saving potential of the building envelope improvement will not be large (see Chapter 7.6).

Indoor Climate in Summer with High Insulation

Due to the solar radiation, the external surface temperature of building envelope is in the daytime considerably higher than outdoor air temperature [104] . Therefore, a high insulation of envelope can decrease heat transmittance from the outdoor to the indoor also with a higher indoor air temperature than outdoor temperature. In addition, the reduction of solar heat load e.g. using an external solar protection or a reduction of a window area and the increase of ventilation rate are more efficient for thermal comfort in summer than an increase of heat loss from indoor to outdoor using low thermal insulation in summer [105].

However, without aforementioned measures for thermal comfort in summer, only the high insulation of building envelope could result the increased thermal discomfort in summer and in transitional period due to the decreased transmission heat loss in these periods. As shown in Figure 85, the indoor air temperatures in some studied buildings are clearly higher than outdoor temperature, also in the night. These are resulted from high internal load, high window ratio without solar protection and low ventilation rate of Korean high-rise residential buildings. Especially the transitional months as May, September and October will be warmer than now, because during the daytime stored heat in the building construction cannot be transmitted to the outdoor in the cold night. The hot hours over 28 °C will increase 22 % from the current 1145 hours to 1399 hours in case of the 52 % reduction of heating energy due to the high insulation (Table 60)

Table 60:
Comparison of Hot Hours According to Insulation Level Based on the TRNSYS Calculation

	Now	Heating Energy Reduction 21 %	Heating Energy Reduction 51 %
Over 28 °C [Hours]	1145	1180	1399
Over 30 °C [Hours]	375	383	445

Therefore, the reduction of solar gain and internal heat load and natural ventilation system for high air change rate should be achieved before the high insulation measure.

7.5 Air Change Rate: Air Quality, Defect Free vs. Dryness Complaint, Energy Efficiency

Requirement: Sufficient Air Change Rate for Defect-free and Air Quality

The increase of air tightness cannot be ruled out for the energy efficiency. However, an improvement of building tightness from the category II (now) to category I, according to DIN V 18599 can cause the increased mould growth on the thermal bridge or in balcony under the same user behaviour in existing buildings. Since the users do not actively ventilate using window, and the existing ventilation rate strongly depends on the infiltration rate, the improvement of air tightness could result a higher humidity load than now. Especially a good building envelope in living area or a high heating energy cost in future could yield a low indoor air temperature at same time. It means a high relative humidity in living area and the high risk of mould growth. In the case of a good construction without thermal bridge in the future, the mould risk will not be very critical, since the surface temperature of building envelope is near to indoor air temperature. In this case, even the bad air quality is rather problematic as shown by the analysis of CO_2 concentration in Chapter 4.4. Therefore, the minimum air change rate for defect free and good air quality should be provided independently of the user behaviour. As a result, a defined air change rate like 0.7 or 0.5 ACH is preferred by a mechanical ventilation system to guarantee a good air quality. However, such determined air change rates independent of occupancy rate can result another problem in the residential building with low occupancy rate.

Low Air Change Rate for Avoiding the Dryness Complaint and Energy Efficiency in Winter

According to spot measurements, the dissatisfaction on indoor humidity clearly increased in winter. About 62 % from all participants in the winter spot measurement judged the indoor as slightly-dry to very-dry. The ratio of residents indicating the indoor humidity as the most dissatisfactory component in winter is about 25 %. The dryness is the most complained dissatisfactory element along with noise, among the questioned six indoor climate factors: thermal, humidity, air quality, noise, sunlight, and lighting.

Table 55 and Table 56 in Chapter 6.4.2 showed the comparison of the required air change rate for the 1000 ppm CO_2 concentration in 24 dwellings depending on the occupancy rate specified in the questionnaire and the results of air change rate calculation using the CO_2 concentration measurement. As assumed, the low ventilation ratio result the high relative humidity and often the mould growth, if the air temperature is not high enough. In contrast to it, if the ventilation ratio is higher than required, then the low relative humidity is produced as a result. Such low relative humidity can cause the dryness complaints. Especially in big sized dwellings with low occupancy rate, already an air change rate of 0.4 ACH can cause a low relative humidity. The width of required ventilation rate varied from the 0.2 ACH to 0.8 ACH according to the occupancy rate. This result indicates that 0.4 ACH can be too high for some dwellings and too low for others. Thus, a new ventilation control system depending on occupancy rate is required. Ideally, a control system based on the CO_2 concentration will be an optimal solution, where the optimal set CO_2 concentration is investigated with the consideration of the relative humidity. If such control systems cannot be applied and only a constant or maximum three variable airflows based on the manual control are possible, the set values for the airflow should be determined according to the occupancy rate or the size of dwellings. A user handbook should provide an optimal air change rate and setting value according to the occupancy rate.

7.6 Balcony Area: Buffer Zone vs. User Behaviour

According to the TRNSYS calculation in 5.1.3, a high airflow between living area and balcony area was observed. This user behaviour affects the humidity load and air temperature in balcony, therefore it increases the mould risk on the cold surface of external wall and the energy demand caused by the high ventilation heat loss (see 5.1.1).

High Ventilation Heat Loss

The balcony with glazing is energy efficient only if the airflow between living and balcony area is very small, as well as, the airflow from the balcony to the outdoor. However, the measurements and calculations in this study indicate the high airflows of the two areas because of the high use of balcony as a storage or laundry room. This fact requires a high air change to outdoor in order to avoid the mould risk and demand a high heating energy. Under this consideration, the optimization of building envelops using the high insulation cannot account for the energy efficiency in the future as shown in Figure 86. If indoor air in a dwelling is changed directly with outdoor, the heating energy demand can be reduced by more than 50 % in case of "TB measure (Without thermal bridge and 50 % reduction of U-value of envelope) in Figure 86". However, the efficiency of heating energy reduction is very low by the same measure, if the air change between indoor and outdoor is performed indirectly through a balcony as it presently is. Currently, dwellings often have an air un-tight door or window to balcony and the residents let balcony window open to outdoor, in order to prevent mould growth on the balcony.

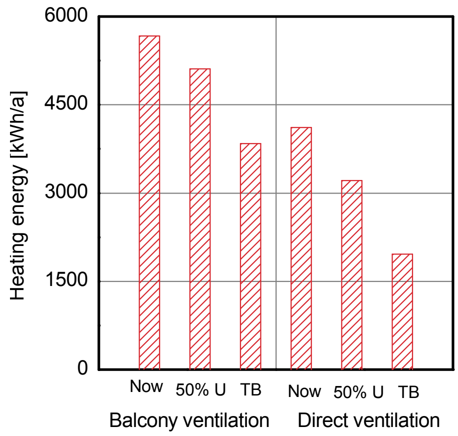


Figure 86:
The Effect of Ventilation Behaviour on the Energy Efficiency According to the High Insulation (Now: current; 50 % U: 50 % reduction of U-value of envelope; TB: without thermal bridge and 50 % reduction of U-value of envelope)

On the other hand, the reduction of the airflow from living area to balcony (Airtight window or door to balcony) and the high air change to outdoor in balcony area can result the air temperature below the freezing point in the north balcony area, which may lead to other complaints from the residents. For the defect-free and energy efficiency, the balcony area should be insulated like any other external building envelopes and required to a specially controlled ventilation system. The question is whether such measures are really worth the effort. It might make a sense to obtain the south balcony for the fire security, but an unheated room in the middle of living area could also undertake the existing utilization of the north balcony. The existing children rooms could have good insulated walls and tight windows with a direct view to the outdoor, which is obviously more energy efficient than the existing situation.

Thermal Comfort in Summer

Givoni, B. recommended for warm climate in 1994 [106]:

"The design of the building should enable natural ventilation also during the rainy period, even when accompanied by high winds, with effective prevention of water penetration through the open window or doors. A combination of wide balconies or verandas and shutters with details which enable air flow but block rain can be a good solution."

The big disadvantage of a case without a balcony is the lack of prevention on driving rain in summer while the windows are open. The residents cannot let windows open during the absence. Now the residents let windows open almost for the whole day, except for the nights in summer. This possible reduction of air change in the case of no-balcony will yield the higher air temperature in summer.

An alternative is to develop a facade system with the prevention of driving rain system for high-rise residential building. One of them is a glazing pane in front of windows, which is applied in Germany for the acoustic and driving rain protection. For the effective air change, such facade can be used in a combination with a small exhaust system in living area, which can also operate in absence.

8. Practical Recommendation for Maximal Comfort, Minimal Energy and Defect Free

8.1 Handling of Balcony

According to the Chapter 7.6, the glazed balcony in existing dwellings can result high heating energy demand by the existing utilization of balcony as household area (high air change between living area and balcony area) and high mould risk in winter. In contrast to it, a balcony allows residents to keep windows open during the daytime absence, consequently resulting high air change rates in summer. In addition, it functions as a horizontal solar protection. Both of these advantages considerably account for thermal comfort in summer without any active system as of now.

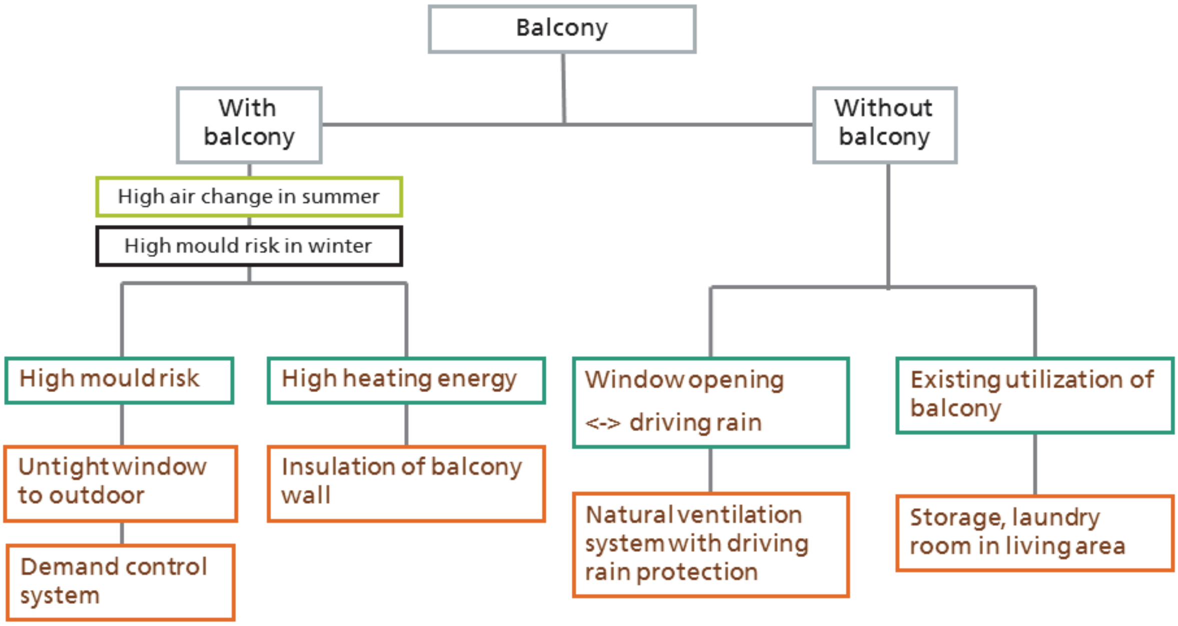


Figure 87:
Decision Tree for Balcony Area (light green- advantage, black- disadvantage, dark green - problems, orange - solution)

The case of "with balcony" requires measures against "high mould risk" and "high heating energy" in Figure 87, while the case "without balcony" needs measures against overheating risk in summer and measures for the existing utilization of balcony as storage or laundry room.

The possible measures against "high mould risk" could be an increase of the air tightness from living area to balcony area, and a simultaneous increase of ventilation rate in balcony area.

The following measures could be undertaken:

- Use of airtight window with low U-value from living room to balcony area.
- Use of air un-tight window from balcony to outdoor (Figure 88) and the window should have a higher u-value than balcony wall.
- Demand controlled ventilation system, which was developed in Europe mostly for the detached house. For its use in the high-rise buildings, the storm security should be proved before the application.

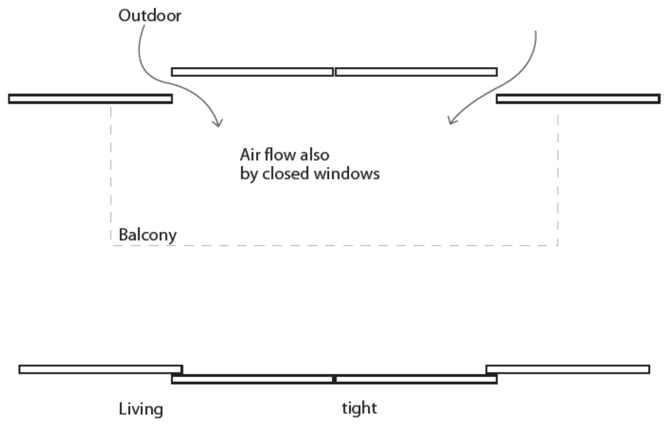


Figure 88:
Principle Sketch in Order to Avoid the Mould Growth

The additional possible measure to "high mould risk" and "high heating energy" of existing balcony can be the insulation of the balcony wall. The U-value of the external wall in balcony should be better than U-value of window in order to avoid the mould growth on the wall. Condensation water on windows can be found by user and relatively easily removed in contrast to the condensation on walls. Theoretically, a 1cm or 2cm insulation already on the wall and ceiling could avoid the mould risk by normal humidity load. However, even the high insulation on balcony wall cannot prevent the mould growth without a ventilation measure by the high humidity in a room, but they can be accounted for reduction of heating energy.

In the case of "without balcony", measurers for high air change rate in summer or some alternatives for thermal comfort in summer should be provided, as presented in Chapter 8.3.

The Alternatives 1 and 2 cannot accomplish the high-energy efficiency of passive house level in the future. The high heating energy demand based on the high ventilation heat loss in balcony area will not comply with a future request. For a high-energy efficient building and under consideration of increased value of spaces, the Alternative 3 and 4 should be chosen in future.

8.2 Cost-Effective High Thermal Insulation System

It is clear that a high-energy efficient building cannot be achieved without a reduction of transmission heat loss of existing building. The question is which measure will be the most cost-efficient for this aim. According to the Chapter 7.4, the ratio of heat loss caused by a thermal bridge can be increased up to 50% by high thermal insulation in the future. Therefore, either thermal bridge should be avoided before the increasing of thermal insulation in (Figure 89) or an external thermal insulation can be developed in the future in (Figure 89).

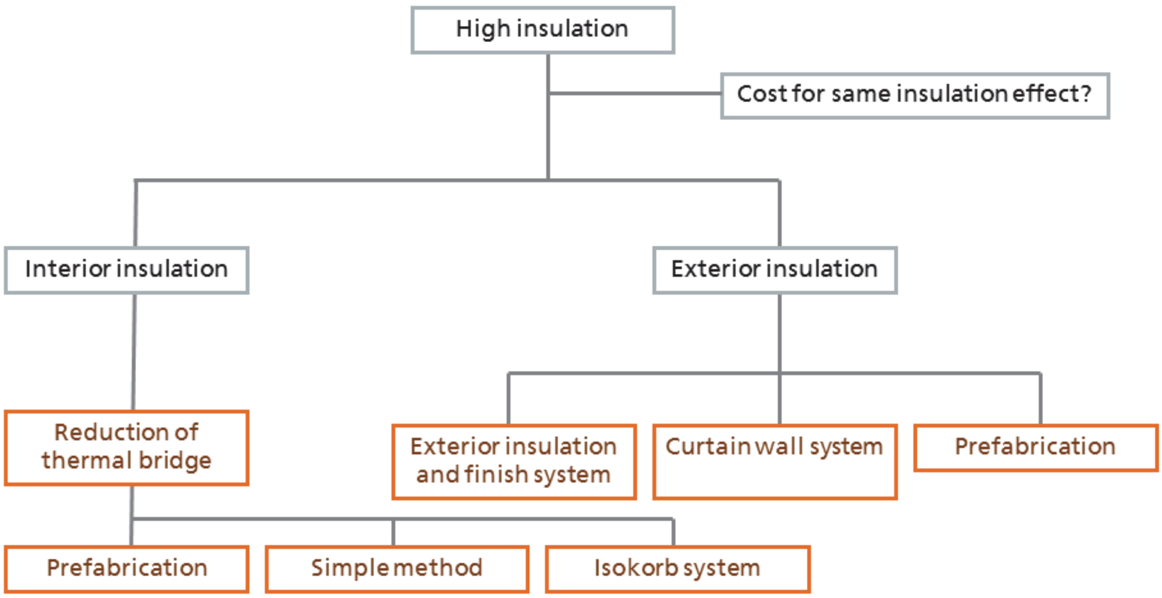


Figure 89:
Decision Tree for the High Insulation

The following measures could be considered in practice for optimization of thermal bridge by the internal insulation.

- Prefabrication of joint parts with external insulation

The thermal bridge calculation on joint area between wall and floor (Section 1b in Table 27) in the existing residential buildings show a high ratio of 13 % of the total thermal bridge heat loss. Such details can be constructed using prefabrication with external insulation. In addition, this joint element will be used as a concrete formwork.

- Simple method (change of material)

The detail 4 in Figure 70 in Chapter 4.4.1, the joint of cross internal wall and external side wall, also shows a high ratio of thermal bridge heat loss. This detail can be optimized using aerated concrete or cement brick in place of the concrete internal wall. Another measure will be an extension of internal insulation without break, as in the illustration on the right figure in (Figure 90), whereat a measure against the sound transfer should be considered.

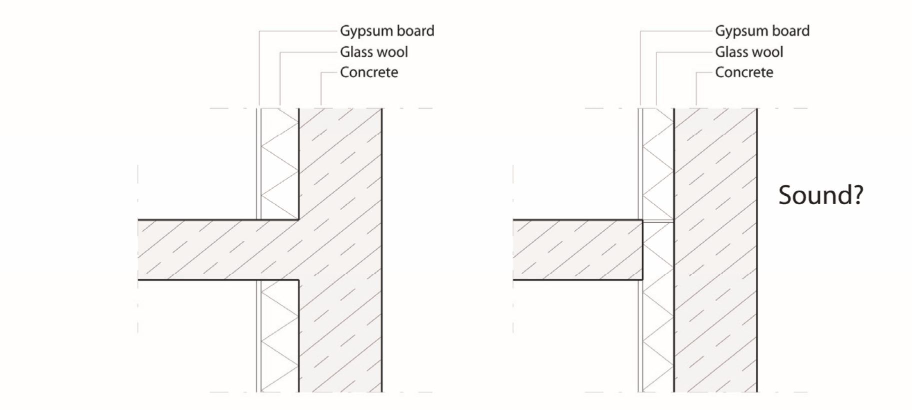


Figure 90:
An Alternative (right) for Detail 4

– Isokorb

In Germany, so-called Isokorb system [107] is widely used in place of the thermal bridge. This system is developed in order to cut the heat transfer from living floor to the balcony floor by the external insulation system. Before the application, the static requirement should be proved for a high-rise building. In addition, the insulation side (internal or external) should be proved for Korean situation.

The following external insulation systems or cavity wall insulation system can be applied:

– Exterior Insulation and Finish System (2)

In Germany, the EIFS has been often applied for multi-story buildings since 1960s as a cost efficient external insulation system. A long-term investigation over 30 years [108] shows that some minor and major defects could be found at the beginning of application of EIFS in the1960s, which were removed by the optimized refurbishment measures in the 1970s. By the last investigation in 2004, the system shows a high durability despite the small thickness of its exterior plaster, however a high susceptibility to microbial growth, presented especially in the case of high insulation. The requirement of firebreaks and effort of scaffolding in high-rise residential building would be a challenge besides the microbial growth for the application of the system in Korea.

– Curtain wall system (3)

The curtain wall system has been often used in Korea for high-rise office buildings as an element construction system, which requires a careful plan to avoid thermal bridge in joints between elements.

– External system using prefabrication (4)

Although prefabrication is seldom used in Korea, steel concrete facade with the prefabrication might be one of the cost and energy-efficient measure for high-rise residential buildings.

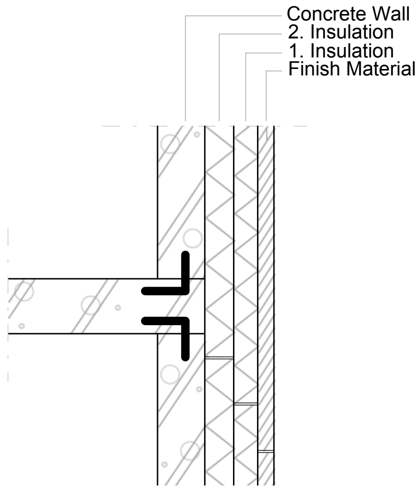


Figure 91:
Principle Sketch for External Insulation Using Prefabrication

8.3 Thermal Comfort in Summer

A high insulation of building envelope provides not only high-energy efficiency but also high thermal comfort in winter. In case of active cooling or moderate solar and internal load, it can increase energy efficiency and thermal comfort also in summer. However, high insulation in Korea can intensify thermal discomfort in summer and in transition period due to current high internal and solar load of high-rise residential buildings and a reduced transmission heat loss (Chapter 7.4). Therefore, measures for thermal comfort in summer are required before the application of high insulation.

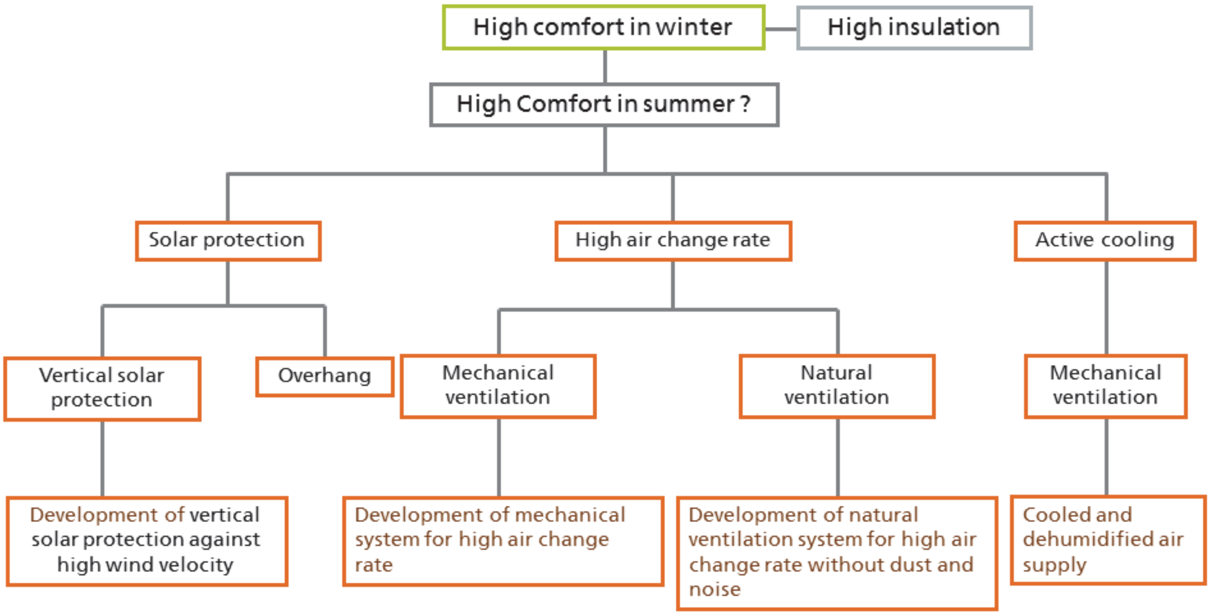


Figure 92:
Decision Tree in Case of High Insulation

As it is well known, an external solar protection is effective for the reduction of solar gain, which cannot be applied in high-rise buildings without any comprehensive measure against a high wind speed. The following measures can be initially considered in order to reduce the solar gain and internal heat gain, whereat the latter effect (reduction of internal heat gain) is more distinguished in Korea in comparison to Germany.

- Use of the bright blind on the balcony window or between two windows in a case of balcony extension.
- Control system for the blind.
- An overhang on the façade.
- Application of energy efficient lighting and electronic equipment.

Measures for the high air change rate by means of mechanical systems or natural systems can take account in to reduction of air temperature and high thermal satisfaction.

A possible measure will be a natural ventilation system, which could provide filtering and sound attenuation. The existing air inlet systems on the window frame or the walls in Europe provide the sound attenuation and filtering of dust. However, such systems focus on the minimum air change rate in winter and not for the high airflow, which Korean residential buildings require. On the market, such system does not exist as of now. In addition, a mechanical ventilation system can offer the required high airflow in theory, however it might not be the best alternative due to the low user acceptance, low energy efficiency and its noise, which is often a problem also under the low air flow. Therefore, a natural ventilation system without dust and noise should be developed in the future for Korean residential buildings.

The suggested system in this study consists of the external window layer and internal ventilation façade element with filter and sound attenuation (left in Figure 93). In summer, the external window can be moved into the middle and the solar protection can come down between two windows (right in Figure 93). In winter, the warm air between the ventilation façade element and the external window can be used for ventilation.

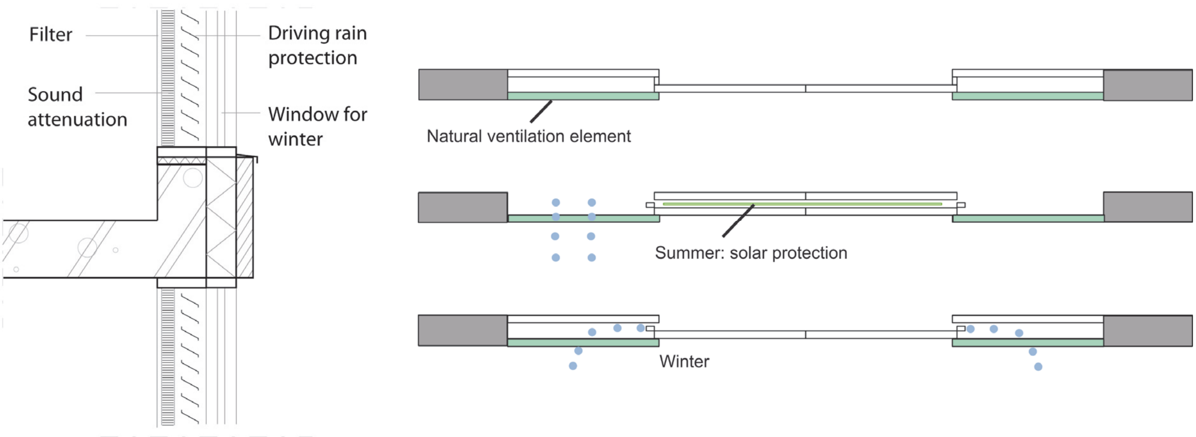


Figure 93:
Concept of New Facade for High Air Change Rate

– Active cooling system with fresh air supply

The centralized cooling generation and central air distribution system is conventionally used in most of all the non-residential buildings for providing a cool and fresh air supply. However, the acceptance of a user of such system is generally low due to the bad individual control possibility. Consequently, many local ventilation systems with cooling and heating options are developed in recent years. The other possibility would be a central cooling generation and local air ventilation system, which might be a cost efficient measure than the local system. The cooling energy could be centrally generated for a high-rise building or even for a whole complex. This cool energy can be transferred by using a cool medium, such as water, to each dwelling in order to cool and dehumidify the fresh air. In Korea, many new high-rise buildings currently use the Combined Heat & Power System for a district heating system, for example. The seasonal fluctuation of heat demand reduces the efficiency of such system. This surplus heat in summer can be used for the cooling production through an absorptive chiller as requiring only a heat source for the changing form gas to liquid of refrigerator in the cooling cycle. The supply temperature is normally between 6 and 7 °C and the typical temperature in the return pipe is between 12 °C and 17 °C. Thus, the supply temperature will be also low enough for the dehumidification [109].

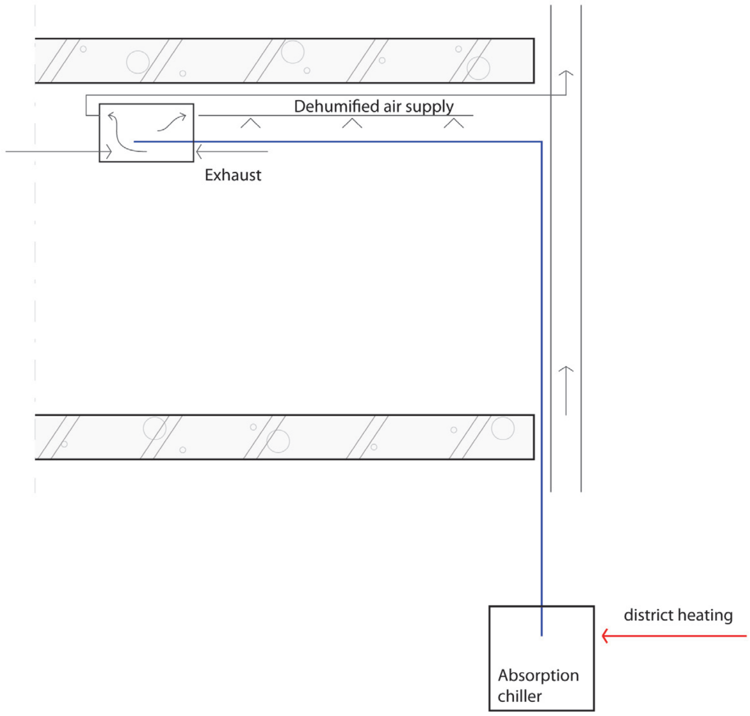


Figure 94:
Principle of Active Cooling System in Summer

8.4 Assurance of Minimum Air Change Rate and Increase of the Air Tightness

Since most of the residents in Korea rarely open the windows in winter, the ventilation energy loss is very low. However, this user behaviour results a high mould growth or a condensation problem in winter. One of the possible alternatives is to keep buildings current tightness (category II) and to use a control system of a mechanical exhaust system in order to ensure a required ventilation rate (see Figure 95).

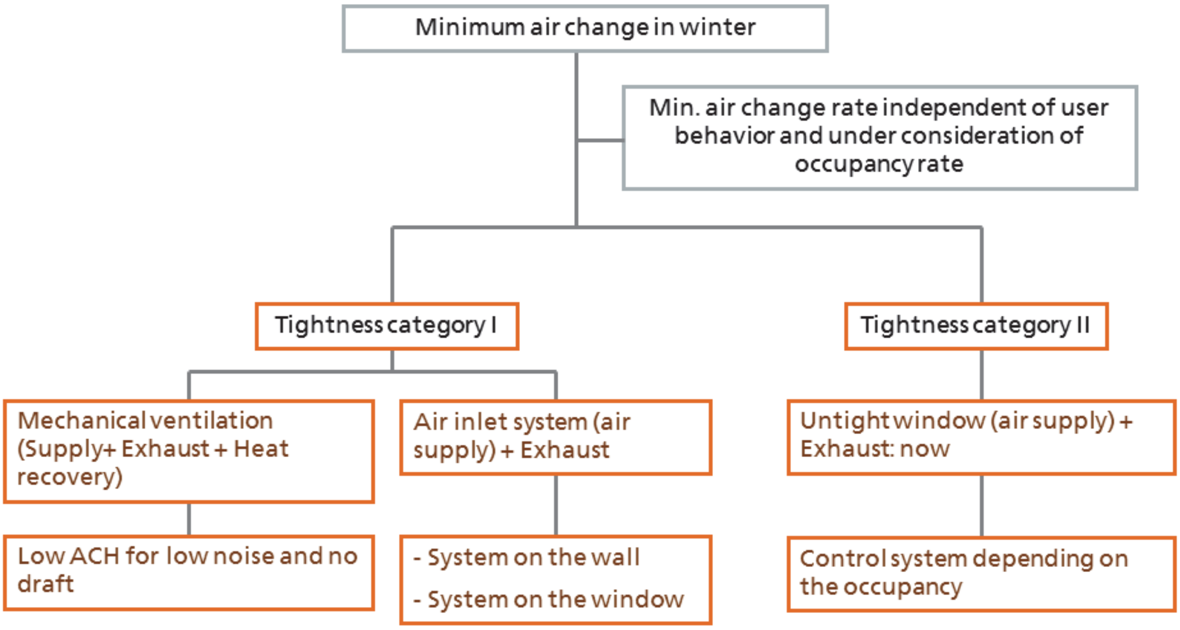


Figure 95:
Decision Tree for the Minimum Air Change Rate

The difference of the existing system will only be the control system on the side of exhaust system. A disadvantage of this alternative may be low energy efficiency, besides a high draft risk due to an uncontrolled leakage on the facade. Another alternative will be an intended leakage as air inlet on walls or windows, while the air tightness of entire building envelope is increased. This alternative method could reduce the draft risk of previous alternative (untightness of category II), but it still is not energy efficient. There are more energy efficient systems, in which the openings are controlled depending on humidity (see Figure 13).

From the aspect of energy efficiency, only a mechanical ventilation system with heat recovery could be an alternative in future. For the high user acceptance and the application in the practice, however, a user considerate control system, a low noise, and filter maintenance service are more important than the energy efficiency of the system. Instead of the heat recovery, the ventilation rate by the mechanical system should be limited to a minimum required air change rate, since a high air change rate using the mechanical system often increases in practice of the draft risk, noise, high-energy demand, and dryness problem in a room. Therefore, it makes more sense to install a mechanical system controlled depending on the occupancy rate or dwelling size. The heat recovery system could be installed in each dwelling for a pre-heating of fresh air or can be installed as a central system, for hot water, for example. In contrast to the exhaust air, the fresh air should be supplied as a local system for a high user acceptance (see Figure 96).

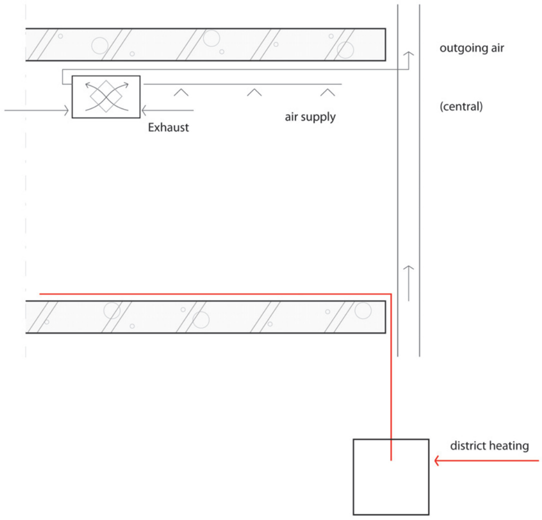


Figure 96:
Principle Sketch for the Ventilation in Winter: Local Air Supply with Heat Recovery and Central Outgoing Air

Increase of the air tightness of the wall and window

Without an improvement of the air tightness, the mechanical ventilation system with heat recovery is not energy efficient due to the high infiltration rate. On the other hand, the improvement of air tightness without a guaranteed minimum air change rate could cause the mould growth. Therefore, these two measures should be performed at the same time. The German code provides for a reference building an air tightness Category I, which requires lower than 1.5 [1/h] by n 50-pressure test for the building with mechanical ventilation system. Generally, the joints of concrete walls and floors build an airtight layer. The weak points in Buildings A and C are mostly a connection area between a window and a wall or a joint point in a slide window often observed as air untight points during the blower door tests in this study (Figure 97).

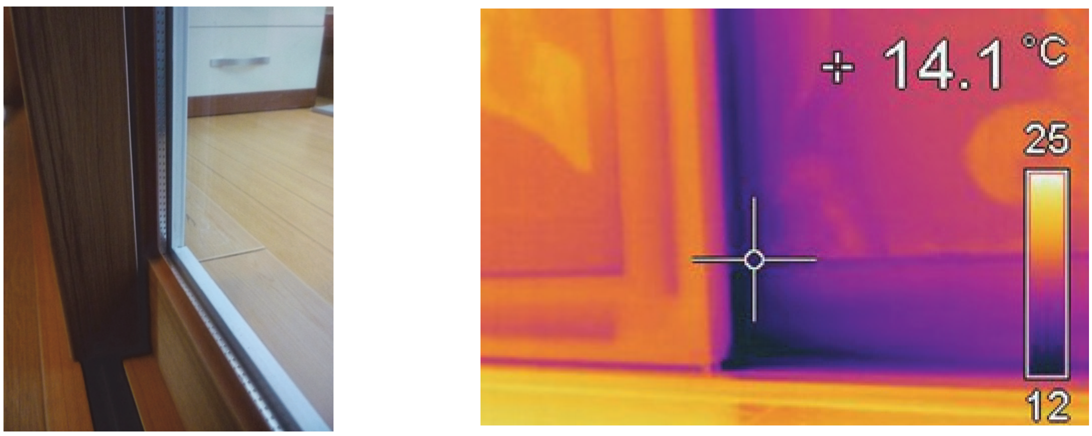


Figure 97:
Air Un-tight Points in a Slide Window (photo during the blower door test)

Especially a light construction as the Building B and the Building D should be carefully planned for the air tightness. German standard DIN 4108-7 [110] provides several joint details for the airtight construction.

8.5 Further measures

A user's handbook, which includes the following information and recommendation:

- Relation between reduction of internal heat load (use of energy efficient equipment) and thermal comfort in summer.
- The use of a bright solar protection in balcony area in summer.
- Keep the window in balcony and door or window to balcony open in absence during the summer.
- Information about the energy efficiency, air temperature, thermal comfort and skin dryness in winter.
- Information about the window ventilation and CO_2 concentration, humidity load and relative humidity in winter.
- The minimum and maximum window opening during the winter.
- How to use the exhaust system in bathroom and kitchen and information about the energy demand per use.
- How to use the mechanical air supply system and information about the energy demand per use.
- Information about cleaning and filter maintenance of the mechanical systems.
- Information about the fresh air supply during the use of air conditioner in summer.
- The range of energy consumption per square meter in the building complex

Increase the energy efficiency of systems (Energy generation, distribution and transfer systems)

The difference between the energy demand and final energy consumed is over 30 % according to DIN V 18599 calculation by Building A. Therefore, the German standard requires not only the high quality of building envelope but also the efficiency of systems, including the energy generation, distribution and transfer. The optimization of control system especially influences besides the energy efficiency as well as the thermal comfort. For example, the existing floor heating system responses often too slowly, thereby results the overheating. If the building envelope is improved better than now, the heating demand of user will be smaller and shorter as well as more variable. The control and emission system should response to this changed situation in the future.

Use and production of regenerative energy source

The future building should produce no carbon emission during the operation or should even produce more energy itself than it requires. It cannot be achieved without the use and production of a renewable energy. The German government aims to increase the ratio of renewable energy consumption for heating, cooling and hot water up to 14 % by the year 2020. For this aim, the new renewable energy heat law became in effect as of 2011 [111]. The new buildings in Germany have to use the regenerative energy like geothermal, solar, bio energy or district heating from the waste heat in a determined ratio.

The solar radiation is annually from 10 % to 20 % higher in Korea than in Germany (Analysis using Wuerzburg TRY and Seoul SAREK data). Therefore, the use of solar energy as PV or solar collector for hot water is more beneficial in Korea than in Germany. Another technology interest for Korean residential building maybe is the use of waste-water. In Germany, several building complexes and urban quarters had applied this technology for the heating [112]. The efficiency of the system depends on the amount of waste-water produced. Since the Korean high-rise residential buildings produce a mass quantity of waste-water, the efficiency will be higher than in Germany. For a future building with a high insulation and ventilation system with a heat recovery system, the ratio of heating energy in whole energy consumption will become less, while the hot water consumption will remain unaffected or will even increase with the improved life style. This aforementioned new situation will require in the future a strongly effective energy use of a hot waste-water.

9. Conclusion and Outlook

The existing building envelope of high-rise residential buildings in Korea shows a relatively low performance compared to the current German Energy Standard. However, the heating energy consumption in such buildings is not apparently higher than a typical apartment building with five floors in Germany [113]. It is due to the compactness of high-rise buildings and warmer Korean winter than in Germany. The heating energy consumption will clearly be lower, if residents do not heat dwellings to current mean air temperature of 24 °C, but rather to a temperature of 21 °C, at which the residents are more satisfied than at a 24 °C. The thermal comfort analysis in this study shows that Koreans indeed feel thermally neutral at 24 °C operative temperature. However, they feel more comfortable at lower temperatures between 21 °C and 23 °C. It is due to the better perception of air quality in lower air temperature, as the analysis of air quality perception and thermal comfort judgement showed. The currently observed higher air temperature in Korean buildings, which is above the expected comfort temperature, might have resulted from the typical high ratio of windows in the high-rise residential buildings and the low performance of these windows. The air temperature in one building with high U-value of windows is significantly higher than in other buildings. This indicates that the different user heating behaviour between buildings would be influenced by the performance of windows, which determine the mean radiation temperature, and thus the operative temperature for thermal perception.

A trend of an increased performance of windows and the insulation of walls in Korea could yield a high surface temperature and low air temperature in dwellings as well as a decreased transmission heat loss in the future. Thus the heating energy demand will be reduced as a result. The future challenge for the energy efficiency of passive house or zero energy house levels might be the reduction of thermal bridges resulted from the internal insulation and the reduction of ventilation energy loss. The existing mechanical ventilation systems have not been accepted by the users. Most of the users did not use the mechanical air supply system. Apart from the technologies for the energy efficiency of systems, a control system, which considers different ventilation requirements depending on its occupancy rate, should be investigated for a higher user acceptance. In addition, the development of cost efficient external insulation systems will be inevitable for future energy efficient high-rise residential buildings. This will be especially required for the retrofitting of old high-rise buildings from the 1990s in Korea.

The heating energy consumption is still dominant in these buildings in Korea, since residents abandon the use of air conditioners in summer in spite of a high temperature and a high humidity in dwellings. As a result, the thermal dissatisfaction in summer is at the highest with 35 % dissatisfaction in comparison to a 7 % dissatisfaction in winter and 1 % in autumn. Besides this high thermal dissatisfaction in summer, this study shows an increased use of the air conditioning in one building, where only one side of walls faces to outdoor in most of its dwellings. This one sided envelope compared to the six outside oriented surfaces of a detached house in Germany will clearly reduce the transmission heat loss for the benefit of heating energy consumption. However, such construction considerably decreases effective ventilation, which plays an important role for the thermal comfort in the summer season in Korea. Due to a high ratio of windows, high consumption of electrical appliances and the lack of external solar protection, the indoor temperatures in investigated buildings show higher air temperatures than outdoors during summer. In this case, the indoor temperature in dwellings depends on the ventilation effectiveness in relation to the outdoors. This could be observed in this study by means of monitoring. Buildings with cross ventilation possibility show a low use of air conditioning, with an even lower indoor temperature than the one with single sided ventilation. Firstly, the ventilation effectiveness depends on the building floor plan (single sided or cross ventilation), and secondly, on the location of the building, which influences the user ventilation behaviour regarding window opening. Although most of residents have air conditioners, they prefer controlling the indoor climate using passive methods such as the window opening. However, they opt for an active method, if they notice that window opening does not provide the desired air exchange (in the case of single sided ventilation) or that they cannot open windows due to the noise or dust from the streets (location). While the building plan can be influenced by the planner for the optimization, the location or surrounding environment would be difficult to change. Therefore, an alternative facade system with sound attenuation, filter, and driving rain protection is suggested in this thesis for high ventilation rate in a big city.

The trend of the high-rise residential building in Korea shows, however, the abandonment of cross ventilation, which will result in an increased cooling energy consumption in the future. The existing cooling technology cannot comply with this changed requirement. The existing room-split-cooling air conditioner is operated from re-circulated indoor air, which will be acceptable for a short duration, but not for long occupancy. If the correct user behaviour is being followed, the residents should open the windows before beginning of operation and close the windows during the operation of air conditioners and they should repeat this process every hour for fresh air supply. However, it is neither comfortable nor energy efficient especially due to the high outdoor humidity in Korea. According to the questionnaire in this study, the reasons for avoiding the air conditioners are the high-energy consumption and the low air quality during their operation, which exactly indicates the problems of the existing system. Therefore, an alternative for a fresh air supply and its energy efficient cooling or the alternatives for a high ventilation rate with cross ventilation should be developed.

In addition, the high indoor air temperature in summer might influence the comfort perception of residents in winter. It was observed that the residents in the building with higher air temperature in the summer tend to heat their dwellings more in winter. However, an "indoor adaptation" hypothesised in this study could not be confirmed by means of statistical significance tests, although this tendency could be observed in the spot measurements as well as in the monitoring.

Besides the analysis of user behaviour, energy efficiency, and thermal comfort for practical recommendation, the existing comfort models, PMV-PPD model and adaptive models, are approved using the questionnaire and spot measurements from this study and a statistical thermal comfort model is developed for Korean residential buildings. The first question regarding the comfort analysis is the choice of scale to assess the thermal comfort or satisfaction of the subjects. The established ASHRAE scale delivers the information about thermal sensation of subjects, but not about thermal comfort. Many thermal comfort studies have been based on the assumption that the thermal sensation and comfort will be interchangeable, but it was rejected in the previous comfort study carried out in an aircraft cabin and also in this study. The environment in which a subject feels thermally comfortable or neutral is not identical. The judgement of indoor comfort in practice could be influenced not only from thermal parameters but also from other parameters, such as the air quality perception, while the judgement of thermal sensation would show the quality of thermal parameters such as temperatures. Since the aim of this investigation is to provide a comfortable environment, the analysis of thermal comfort in this study is based on the 7 scale of comfort (very comfortable - very uncomfortable) with its middle point as acceptable. The lowest dissatisfaction ratio is observed in Korean residential buildings not by neutral environment with PMV=0 but by slightly cool environment with PMV=-1 in summer as well as in winter.

Simple indices like air temperature or operative temperature can predict the thermal sensation of subjects in this study better than PMV. The reasons will be the specificities of the field studies in residential buildings, where the subjects can adjust their clothing, metabolic rate and air velocity by means of opening windows or turning on ventilators. Such variables are generally predictor variables for outcome variables (thermal sensation or thermal comfort) in climate chamber studies. In field studies, it is difficult to determine whether such variables are the predictor variables for an outcome variable or are themselves outcome variables, which are influenced by the predictor variables (thermal sensation or thermal comfort). In this case, it would be statistically better to exclude such variables in a model. Therefore, temperatures can predict better thermal comfort of subjects in field studies than PMV, as shown in this study and in other previous studies. In contrast to it, the adaptive models exclude too many variables for the prediction of thermal comfort. The humidity is a deciding variable for thermal comfort in summer in Korea, which is not considered in the existing adaptive model. Thus a new comfort model with temperature and humidity as predictor variables is developed in this study for Korean residential buildings using a logistic regression model.

In the future, for comfort investigations in field studies, firstly we should define which thermal parameters are influencing factors in the studied cases. Secondly, the preferred range of the parameters should be defined, and finally, it should be investigated why these parameters could not be achieved in the existing situations. The reasons would be determined not only from thermal parameters but also from other parameters, which would affect user satisfaction and user behaviour regarding thermal control. This comprehensive approach would improve thermal comfort in the field and could provide a basis for the detailed climate chamber studies with such parameters as the controlled predictor variables. This way, we could better understand the relationship between thermal parameters and other indoor environment parameters in the future, accounting for a high user satisfaction.

10. References

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Annex

A.1 Annex_ Table

Table_ A 1:
Gender of Participants in Spot Measurements (MD: Missing Data)

	Gender (Woman)	Gender (man)	Gender (MD)
Summer	77	9	3
Autumn	79	3	2
Winter	75	10	0

Table_ A 2:
Age of Participants

Age (years)	Frequency	Percentage
25 - 34	13	15 %
35 - 44	35	41 %
45 - 54	21	24 %
55 - 64	13	15 %
> 65	4	5 %

Table_ A 3:
Number of Residents in One Dwelling

No. of residents	Frequency	Percentage
2	10	12 %
3	26	30 %
4	41	48 %
5	7	8 %
6	2	2 %

Table_ A 4:
Size of Dwellings

Size (m^2)	Frequency	Percentage
< 86 m^2	7	8 %
86 - 106	11	13 %
107 - 149	60	70 %
150 - 178	7	8 %
> 179	1	1 %

Table_ A 5:
Average Daily Occupancy Duration

Building	Adult1	N	Adult2	N	Adult3	N	Adult4	N	Chil1	N	Chil2	N	Chil3	N
A	11.0	27	20.2	26	14.1	9	13.3	3	10.4	20	18.3	14	18.0	2
B	12.8	10	18.9	10	16.8	6	15.0	3	8.8	8	17.4	5		0
C	13.2	25	19.2	25	13.4	7	11.0	5	9.3	16	17.8	8		0
D	10.7	23	18.4	23	12.3	3	11.0	1	10.4	16	18.0	8		0
All	11.8	85	19.3	84	14.4	25	12.6	12	9.9	60	18.0	35	18.0	2

Table_ A 6:
Average Value of Measurements during Summer Spot Measurement

Building	n	Air temperature [°C]	Relative humidity [%]	Air velocity [m/s]	Radiation temperature [°C]	Clothing insulation value [clo]	PMV [-]	Absolute humidity [g/kg]
Building A	27	26.8	76.4	0.16	26.6	0.5	0.3	16.7
Building B	9	29.0	58.9	0.11	28.6	0.5	1.2	14.5
Building C	26	27.9	66.8	0.14	27.6	0.5	0.8	15.6
Building D	20	28.4	54.6	0.15	28.3	0.5	0.8	13.1
All	82	27.8	66.1	0.14	27.5	0.5	0.7	15.2

Table_ A 7:
Average Value of Measurements during Autumn Spot Measurement

Building	N	Air temperature [°C]	Relative humidity [%]	Air velocity [m/s]	Radiation temperature [°C]	Clothing insulation value [clo]	PMV [-]	Absolute humidity [g/kg]
Building A	27	24.4	46.7	0.04	24.1	0.6	-0.2	8.9
Building B	8	24.8	43.7	0.06	24.4	0.6	-0.2	8.5
Building C	25	23.9	45.7	0.05	23.7	0.6	-0.3	8.6
Building D	21	26.2	38.5	0.03	25.9	0.6	0.4	8.2
All	81	24.7	44.0	0.04	24.5	0.6	-0.1	8.6

Table_ A 8:
Average Value of Measurements during Winter Spot Measurement

Building	n	Air temperature [°C]	Relative humidity [%]	Air velocity [m/s]	Radiation temperature [°C]	Clothing insulation value [clo]	PMV [-]	Absolute humidity [g/kg]
Building A	27	23.3	34.2	0.04	22.9	0.8	-0.3	6.2
Building B	10	24.3	28.5	0.04	23.8	0.8	-0.1	5.0
Building C	25	23.1	38.9	0.04	22.7	0.8	-0.3	6.9
Building D	23	25.4	38.2	0.03	23.9	0.7	0.1	7.8
All	85	23.9	36.0	0.04	23.2	0.8	-0.2	6.7

Table_ A 9:
Air Temperature during the Spot Measurements

Season	n	Mean [°C]	SD [°C]	25 % [°C]	Median [°C]	75 % [°C]
Summer	82	27.8	1.3	26.9	27.5	28.7
Autumn	81	24.7	1.6	23.7	24.5	25.7
Winter	85	23.9	1.9	22.5	23.6	25.1

Table_ A 10:
Relative Humidity during the Spot Measurement

Season	n	Mean [%]	SD [%]	25 % [%]	Median [%]	75 % [%]
Summer	82	66.1	11.0	57.1	66.9	73.7
Autumn	81	44.0	7.0	39.0	44.3	49.7
Winter	85	36.0	8.9	28.7	34.5	41.8

Table_ A 11:
Air Velocity during the Spot Measurement

	n	Mean [m/s]	SD [m/s]	25 % [m/s]	Median [m/s]	75 % [m/s]
Summer	82	0.14	0.10	0.07	0.12	0.19
Autumn	80	0.04	0.03	0.03	0.04	0.05
Winter	85	0.04	0.02	0.02	0.04	0.05

Table_ A 12:
Radiation Temperature during the Spot Measurement

Season	n	Mean [°C]	SD [°C]	25 % [°C]	Median [°C]	75 % [°C]
Summer	82	27.5	1.3	26.6	27.4	28.5
Autumn	81	24.5	1.6	23.4	24.4	25.4
Winter	85	23.2	2.5	22.1	23.0	24.7

Table_ A 13:
Clothing Insulation Value during the Spot Measurement

Season	n	Mean [clo]	SD [clo]	25 % [clo]	Median [clo]	75 % [clo]
Summer	82	0.5	0.1	0.5	0.5	0.5
Autumn	82	0.6	0.1	0.6	0.6	0.7
Winter	85	0.8	0.1	0.7	0.7	0.9

Table_ A 14:
PMV during the Spot Measurement

Season	n	Mean [-]	SD [-]	25 % [-]	Median [-]	75 % [-]
Summer	82	0.7	0.6	0.3	0.8	1.0
Autumn	81	-0.1	0.6	-0.4	0.0	0.2
Winter	85	-0.2	0.6	-0.6	-0.2	0.2

Table_ A 15:
Absolute Humidity during the Spot Measurement

Season	n	Mean [g/kg]	SD [g/kg]	25 % [g/kg]	Median [g/kg]	75 % [g/kg]
Summer	82	15.2	2.1	14.1	15.0	17.0
Autumn	81	8.6	1.4	7.6	8.7	9.3
Winter	85	6.7	1.9	5.3	6.6	7.9

Table_ A 16:
Monthly Average Air Temperature [°C] in 24 Dwellings from June 2009 to May 2010

	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
A1_Ta	27.3	28.1	28.7	26.7	24.8	22.6	21.7	20.9	21.9	22.0	22.4	23.6
A2_Ta	27.6	28.3	28.7	27.9	25.2	24.5	24.8	25.2	25.7	25.2	25.4	25.8
A3_Ta	28.9	29.0	30.0	28.0	25.2	22.5	21.5	21.1	20.6	20.6	21.6	24.7
A4_Ta	27.2	27.8	28.6	27.0	25.8	25.0	24.6	24.8	25.3	25.1	25.2	25.9
A5_Ta	27.1	27.7	28.5	27.0	25.7	24.6	24.1	23.7	24.4	24.6	24.8	25.7
A6_Ta	27.6	28.3	28.6	26.7	24.4	21.2	22.5	23.4	23.9	23.9	24.4	25.4
B1_Ta	27.5	28.5	29.0	27.6	26.2	25.0	23.8	22.7	23.4	23.1	24.3	25.7
B2_Ta	28.5	28.2	29.2	28.0	26.4	25.1	23.5	23.4	23.3	24.0	24.3	26.1
B3_Ta	31.0	30.4	31.0	30.1	29.3	27.5	25.9	25.1	25.5	25.6	26.2	28.0
B4_Ta	27.4	28.1	28.7	27.8	25.5	23.3	22.5	22.7	22.6	21.9	23.5	25.7
B5_Ta	26.9	27.4	28.5	27.5	26.6	25.1	24.2	23.6				
B6_Ta	27.4	27.8	28.2	27.4	25.7	23.2	22.0	21.9	22.1	21.8	22.7	25.3
C1_Ta	25.6	26.4	27.5	25.4	24.2	23.9	23.5	24.5				
C2_Ta	26.3	27.1	27.7	26.3	24.9	24.1	23.8	22.5	23.5	23.9	24.4	25.8
C3_Ta	26.7	27.1	27.9	26.5	25.3	23.6	23.1	23.1	23.2	23.2	23.8	25.6
C4_Ta	26.3	26.8	27.9	25.7	23.6	22.2	21.5	22.2	21.6	21.3	22.1	23.5
C5_Ta	26.4	26.8	27.4	25.7	23.4	20.4	18.8	18.9	19.4	20.1	20.3	23.2
C6_Ta	26.6	26.9	27.6	26.1	24.1	21.6	19.8	20.2	20.8	20.6	21.3	24.1
D1_Ta	28.7	29.3	29.7	29.0	27.1	26.3	25.6	26.1	26.9	26.1	26.6	26.9
D2_Ta	28.0	29.0	30.0	29.1	27.6	26.6	26.0	26.6	26.1	26.4	25.8	26.5
D3_Ta	29.1	30.1	31.1	29.9	27.1	24.2	23.2	23.3				
D4_Ta	28.7	29.2	29.5	28.5	26.8	25.0	25.2	26.1	26.1	26.0	26.0	26.9
D5_Ta	29.8	29.7	30.0	29.5	27.8	25.8	25.2	25.3	25.5	25.3	25.8	27.6
D6_Ta	28.7	29.1	30.5	28.7	26.6	25.4	24.1	23.7	24.4	25.0	25.1	26.5
Mean	27.7	28.2	28.9	27.6	25.8	24.1	23.4	23.4	23.6	23.6	24.1	25.6
Min	25.6	26.4	27.4	25.4	23.4	20.4	18.8	18.9	19.4	20.1	20.3	23.2
Max	31.0	30.4	31.1	30.1	29.3	27.5	26.0	26.6	26.9	26.4	26.6	28.0
Mean_A	27.6	28.2	28.8	27.2	25.2	23.4	23.2	23.2	23.6	23.6	24.0	25.2
Mean_B	28.1	28.4	29.1	28.0	26.6	24.9	23.7	23.2	23.4	23.3	24.2	26.2
Mean_C	26.3	26.8	27.7	26.0	24.2	22.6	21.7	21.9	21.7	21.8	22.4	24.4
Mean_D	28.8	29.4	30.1	29.1	27.2	25.6	24.9	25.2	25.8	25.8	25.8	26.9

Table_ A 17:
Monthly Average Relative Humidity in 24 Dwellings from June 2009 to May 2010

	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
A1_RH	54.4	63.3	61.5	54.6	51.7	43.8	32.3	28.2	34.3	37.1	44.1	58.7
A2_RH	52.0	63.2	60.7	54.9	50.0	50.3	42.8	36.9	42.0	45.6	49.1	52.7
A3_RH	46.9	58.8	56.5	48.8	47.4	62.3	53.6	49.7	54.3	53.9	47.3	46.8
A4_RH	53.0	65.4	62.0	52.0	44.9	43.4	32.1	24.6	27.0	28.9	32.6	45.2
A5_RH	53.2	65.1	63.6	56.2	51.7	49.8	41.9	40.0	42.9	43.5	46.3	51.4
A6_RH	55.7	67.7	65.4	60.2	58.8	68.6	59.6	56.8	58.1	61.5	61.3	60.4
B1_RH	49.5	60.0	57.9	49.1	41.9	34.7	23.8	19.7	23.9	26.9	30.5	43.5
B2_RH	53.2	59.6	56.2	46.1	41.2	36.3	32.1	25.7	27.6	30.3	33.5	44.9
B3_RH	49.3	55.2	53.3	44.3	38.8	32.7	28.7	27.6	31.0	31.3	36.3	46.9
B4_RH	48.7	57.6	55.1	44.8	37.8	33.9	24.5	20.8	23.6	26.4	30.1	41.7
B5_RH	48.0	62.3	58.4	46.3	34.3	29.2	22.4	19.4				
B6_RH	48.3	61.8	60.4	47.3	41.7	37.5	29.4	26.0	31.1	33.8	37.5	46.0
C1_RH	55.8	70.5	67.1	56.7	46.3	40.0	30.1	24.6				
C2_RH	51.9	65.9	64.2	51.1	39.7	32.3	21.9	17.4	22.6	24.8	29.8	42.7
C3_RH	51.5	66.3	63.4	51.8	49.9	51.7	40.4	31.1	40.8	36.6	42.3	48.9
C4_RH	54.5	66.9	63.0	54.9	47.0	53.3	40.1	38.6	45.9	49.3	50.4	55.5
C5_RH	54.6	67.5	65.6	54.4	46.0	56.3	56.6	51.2	59.4	51.8	45.4	50.7
C6_RH	54.5	66.9	64.1	54.6	52.2	63.1	69.1	69.8	64.6	64.8	63.4	57.8
D1_RH	43.6	53.8	51.7	43.2	35.0	31.8	24.8	23.2	24.3	26.5	29.1	37.5
D2_RH	47.6	59.5	54.9	44.7	40.1	34.4	23.9	21.2	23.0	26.7	30.7	45.0
D3_RH	49.0	56.7	53.5	45.7	48.8	55.0	48.7	41.6				
D4_RH	44.8	56.1	54.9	44.3	39.0	46.2	40.3	31.5	38.0	38.9	42.1	43.7
D5_RH	58.0	62.0	57.6	53.8	56.6	55.8	52.3	45.1	51.2	53.2	56.4	60.5
D6_RH	46.8	58.5	53.8	45.5	41.3	40.7	37.5	35.4	40.2	36.9	40.4	42.9
Mean	51.0	62.1	59.4	50.2	45.1	45.1	37.9	33.6	38.4	39.5	41.8	48.7
Min.	43.6	53.8	51.7	43.2	34.3	29.2	21.9	17.4	22.6	24.8	29.1	37.5
Max.	58.0	70.5	67.1	60.2	58.8	68.6	69.1	69.8	64.6	64.8	63.4	60.5
Mean_A	52.5	63.9	61.6	54.4	50.8	53.0	43.7	39.4	43.1	45.1	46.8	52.5
Mean_B	49.5	59.4	56.9	46.3	39.3	34.0	26.8	23.2	27.4	29.7	33.6	44.6
Mean_C	53.8	67.3	64.6	53.9	46.8	49.5	43.0	38.8	46.7	45.5	46.3	51.1
Mean_D	48.3	57.8	54.4	46.2	43.5	44.0	37.9	33.0	35.3	36.4	39.7	45.9

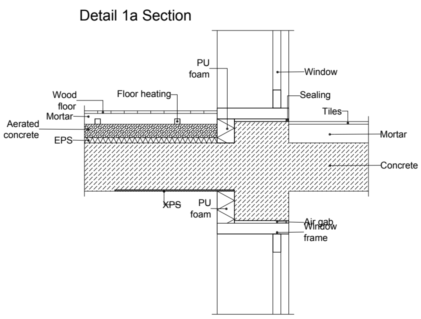
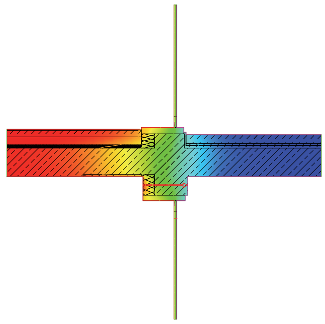
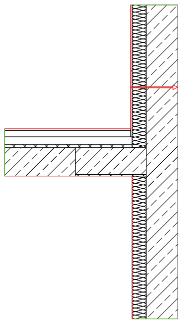
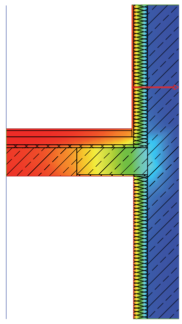
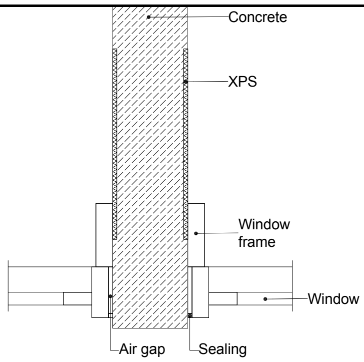
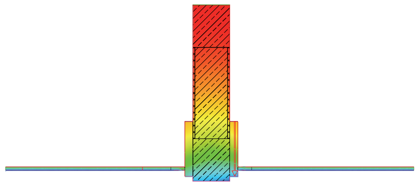
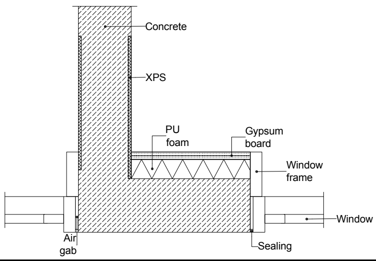
Table_ A 18:
Monthly Average Absolute Humidity in 24 Dwellings from June 2009 to May 2010

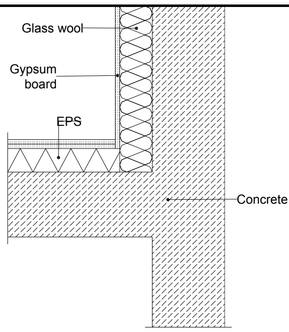
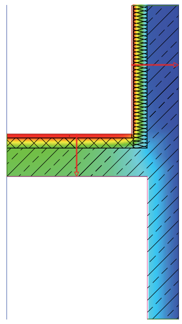
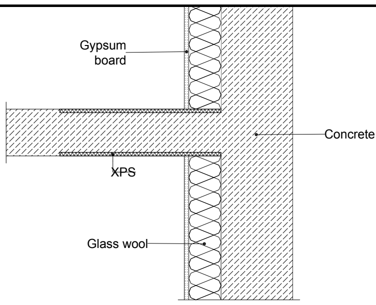
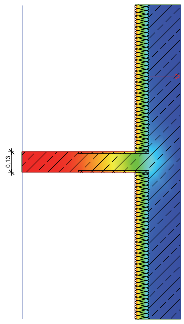
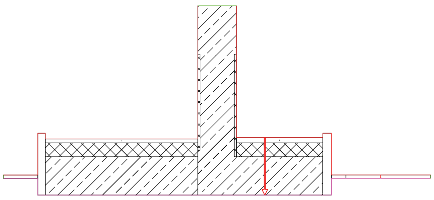
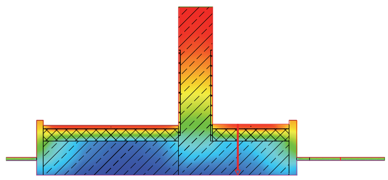
	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
A1_AH	12.3	14.9	15.0	11.9	10.2	7.7	5.4	4.5	5.8	6.2	7.6	10.8
A2_AH	12.0	15.1	14.7	12.9	10.1	9.8	8.5	7.5	8.8	9.2	10.0	10.9
A3_AH	11.6	14.5	14.8	11.4	9.5	10.8	8.8	7.9	8.4	8.3	7.8	9.2
A4_AH	11.9	15.2	15.0	11.5	9.3	8.6	6.2	4.8	5.5	5.8	6.6	9.4
A5_AH	11.9	15.0	15.3	12.5	10.7	9.7	7.9	7.4	8.3	8.4	9.1	10.6
A6_AH	12.8	16.1	15.8	13.2	11.3	11.0	10.3	10.3	10.9	11.5	11.8	12.3
B1_AH	11.3	14.4	14.4	11.2	8.9	7.0	4.4	3.5	4.4	4.8	5.8	9.0
B2_AH	12.8	14.1	14.1	10.8	8.9	7.3	5.9	4.7	5.0	5.7	6.4	9.5
B3_AH	13.6	14.7	14.7	11.6	9.8	7.5	6.1	5.5	6.4	6.5	7.8	11.0
B4_AH	11.1	13.6	13.4	10.4	7.7	6.2	4.2	3.6	4.1	4.4	5.5	8.7
B5_AH	10.6	14.1	14.1	10.5	7.4	5.9	4.3	3.6				
B6_AH	11.0	14.3	14.2	10.6	8.6	6.8	4.9	4.3	5.3	5.6	6.6	9.3
C1_AH	11.5	15.1	15.3	11.5	8.8	7.5	5.5	4.8				
C2_AH	11.1	14.7	14.8	10.9	7.8	6.2	4.1	3.0	4.2	4.6	5.7	8.9
C3_AH	11.3	14.7	14.8	11.2	10.0	9.6	7.2	5.6	7.3	6.6	7.8	10.0
C4_AH	11.7	14.7	14.7	11.4	8.6	9.1	6.5	6.5	7.5	7.9	8.5	10.1
C5_AH	11.8	14.8	14.8	11.2	8.3	8.6	7.9	7.2	8.6	7.8	6.9	9.1
C6_AH	11.8	14.7	14.7	11.5	9.8	10.3	10.2	10.5	10.2	10.0	10.2	10.9
D1_AH	10.7	13.6	13.3	10.7	7.8	6.8	5.1	4.9	5.4	5.6	6.3	8.3
D2_AH	11.2	14.8	14.4	11.1	9.2	7.5	5.1	4.6	4.9	5.8	6.4	9.7
D3_AH	12.2	14.8	14.8	11.8	10.9	10.4	8.8	7.5				
D4_AH	10.9	14.1	13.9	10.7	8.5	9.1	8.1	6.6	8.0	8.2	8.8	9.6
D5_AH	15.0	15.9	15.0	13.7	13.1	11.6	10.5	9.1	10.4	10.7	11.7	13.9
D6_AH	11.4	14.6	14.5	11.1	9.0	8.4	7.2	6.6	7.8	7.4	8.1	9.2
Mean	11.8	14.7	14.6	11.5	9.3	8.5	6.8	6.0	7.0	7.2	7.9	10.0
Min	10.6	13.6	13.3	10.4	7.4	5.9	4.1	3.0	4.1	4.4	5.5	8.3
Max	15.0	16.1	15.8	13.7	13.1	11.6	10.5	10.5	10.9	11.5	11.8	13.9
Mean_A	12.1	15.1	15.1	12.2	10.2	9.6	7.9	7.1	7.9	8.2	8.8	10.5
Mean_B	11.7	14.2	14.1	10.9	8.5	6.8	5.0	4.2	5.0	5.4	6.4	9.5
Mean_C	11.5	14.8	14.8	11.3	8.9	8.5	6.9	6.3	7.6	7.4	7.8	9.8
Mean_D	11.9	14.6	14.3	11.5	9.8	9.0	7.5	6.6	7.3	7.5	8.3	10.2

Table_ A 19:
Average Air Temperature. Relative Humidity and Absolute Humidity of Different Rooms in 6 Dwellings from June 2009 to August 2009 [Summer] and from December 2009 to February 2010 [Winter]

	Air temperature [°C]		Relative humidity [%]		Absolute humidity [g/kg]	
	Summer	Winter	Summer	Winter	Summer	Winter
Living	28.9	23.3	56.5	34.1	13.9	6.2
Bed	29.0	24.4	56.2	36.4	14.0	6.9
Children 1	29.4	23.7	54.3	33.4	13.8	6.3
Children	29.0	23.1	55.0	35.3	13.6	6.4
Min.	28.9	23.1	54.3	33.4	13.6	6.2
Max.	29.4	24.4	56.5	36.4	14.0	6.9
Mean	29.1	23.6	55.5	34.8	13.8	6.4

Table_ A 20:
Thermal Bridge Calculation in Building A

Detail No.	Detail	Thermal bridge calculation		
Section 1 (to balco-ny)				
		Ψ -value: 0.25 W/(mK)	Length: 21.2 (m)	Heat loss: 5.34 W/(K)
Section 2 (to side wall)				
		Ψ -value: 0.45 W/(mK)	Length: 8.06 (m)	Heat loss: 3.63 W/(K)
Detail 1				
		Ψ -value: 0.05 W/(mK)	Length: 5.4 (m)	Heat loss: 0.27 W/(K)
Detail 2				

<table>
<tr><td></td><td></td><td>Ψ -value:
0.32 W/(mK)</td><td>Length:
2.7 (m)</td><td>Heat loss:
0.86 W/(K)</td></tr>
<tr><td rowspan="2">Detail 3</td><td rowspan="2">
</td><td colspan="3"></td></tr>
<tr><td>Ψ -value:
-0.13
W/(mK)</td><td>Length:
5.4 (m)</td><td>Heat loss:
0.70 W/(K)</td></tr>
<tr><td rowspan="2">Detail 4</td><td rowspan="2">
</td><td colspan="3"></td></tr>
<tr><td>Ψ -value:
0.40 W/(mK)</td><td>Length:
5.4 (m)</td><td>Heat loss:
2.13 W/(K)</td></tr>
<tr><td rowspan="2">Detail 5</td><td rowspan="2"></td><td colspan="3"></td></tr>
<tr><td>Ψ -value:
0.58 W/(mK)</td><td>Length:
2.7 (m)</td><td>Heat loss:
1.57 W/(K)</td></tr>
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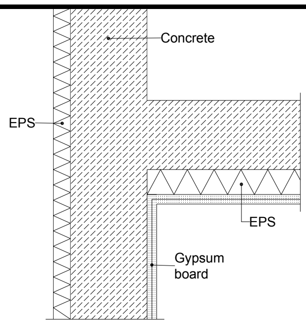
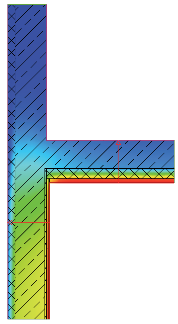
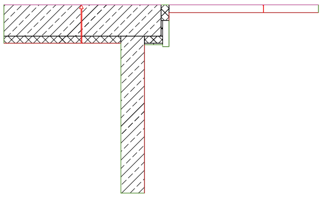
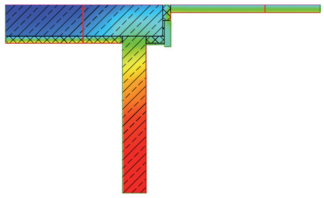
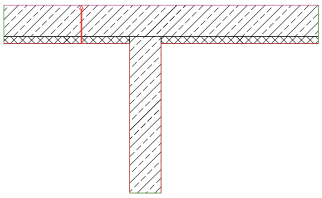
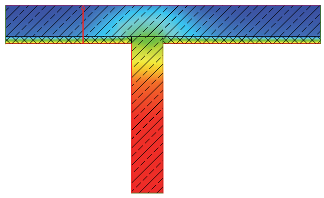
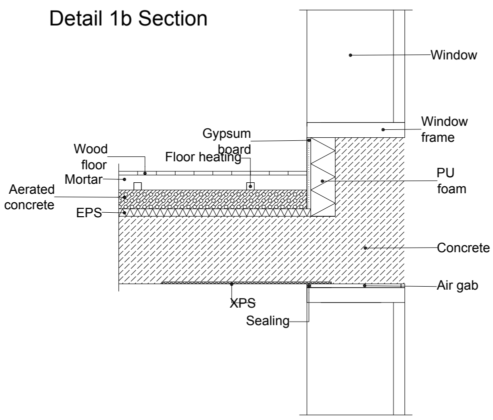
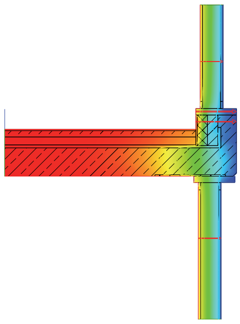
Detail	Drawing	Thermal simulation	Ψ-value	Length	Heat loss
Detail 6			Ψ -value: 0.01 W/(mK)	Length: 5.4 (m)	Heat loss: 0.054 W/(K)
Detail 7			Ψ -value: 0.53 W/(mK)	Length: 2.7 (m)	Heat loss: 1.43 W/(K)
Detail 8			Ψ -value: 0.87 W/(mK)	Length: 2.7 (m)	Heat loss: 2.35 W/(K)
Current state					
Detail Section			Ψ -value: 0.37 W/(mK)	Length: (m)	Heat loss: W/(K)

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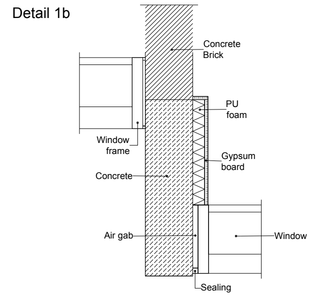
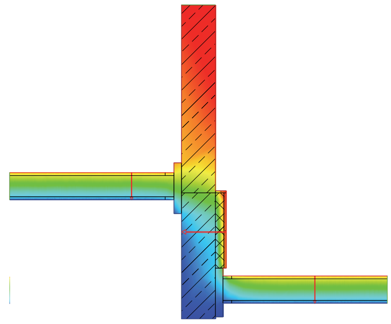
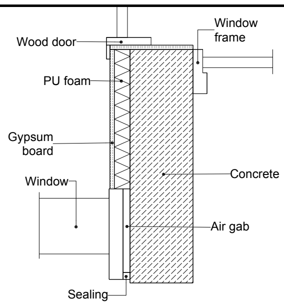
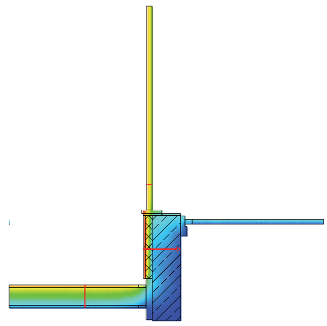
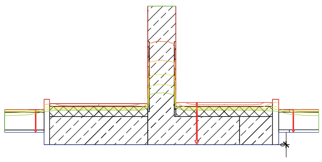
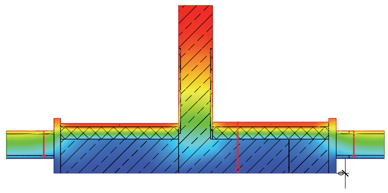
<tr><td rowspan="2">Detail 1b</td><td rowspan="2">
</td><td colspan="3"></td></tr>
<tr><td>Ψ -value:
0.67 W/(mK)</td><td>Length:
2.7 (m)</td><td>Heat loss:
2.35 W/(K)</td></tr>
<tr><td rowspan="2">Detail 2b</td><td rowspan="2">
</td><td colspan="3"></td></tr>
<tr><td>Ψ -value:
-0.23 W/(mK)</td><td>Length:
2.7 (m)</td><td>Heat loss:
2.35 W/(K)</td></tr>
<tr><td>Detail 3b</td><td></td><td colspan="3"></td></tr>
<tr><td></td><td></td><td>Ψ -value:
0.81 W/(mK)</td><td>Length:
2.7 (m)</td><td>Heat loss:
W/(K)</td></tr>
</table>

Table A 21:
Frequency of Indoor Operative Temperature Depending on Weekly Running Outdoor Air Temperature (row: weekly running outdoor temperature; column: indoor operative temperature; grey: 90 % acceptance area according to EN 15251)

	25 °C	26 °C	27 °C	28 °C	29 °C	30 °C	32 °C
Tout 22 °C	3	1	0	0	0	0	0
Tout 23 °C	0	4	13	4	0	0	0
Tout 24 °C	0	1	1	2	2	2	0
Tout 25 °C	0	1	10	10	7	2	1
Tout 26 °C	0	0	1	0	2	3	0
All	3	7	25	16	11	7	1

A.2 Annex_ Figure

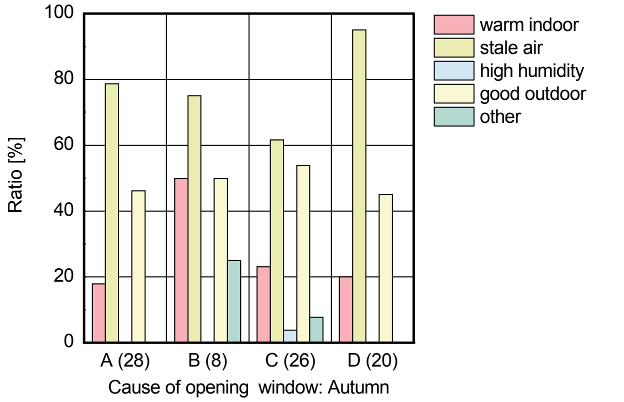


Figure_ A 1:
Cause for Opening a Window in Autumn

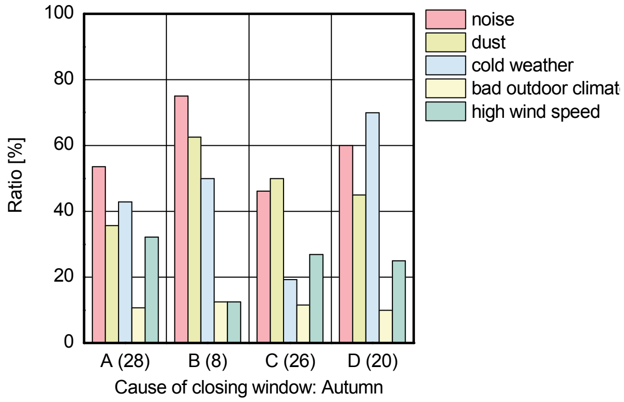


Figure_ A 2:
Cause for Closing a Window in Autumn

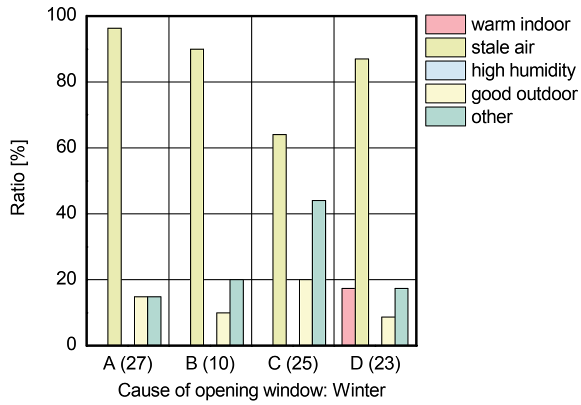


Figure_ A 3:
Cause for Opening a Window in Winter

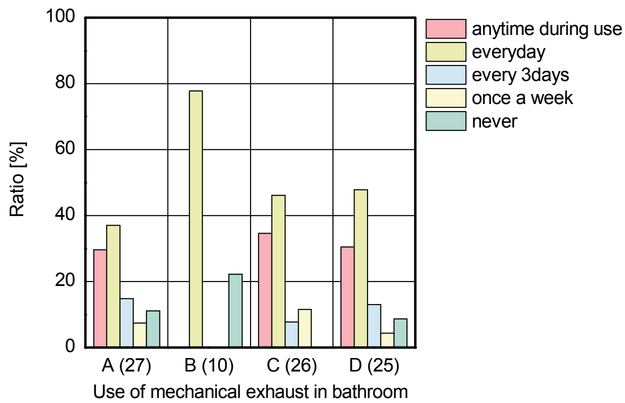


Figure_ A 4:
Use of Mechanical Exhaust in Kitchen

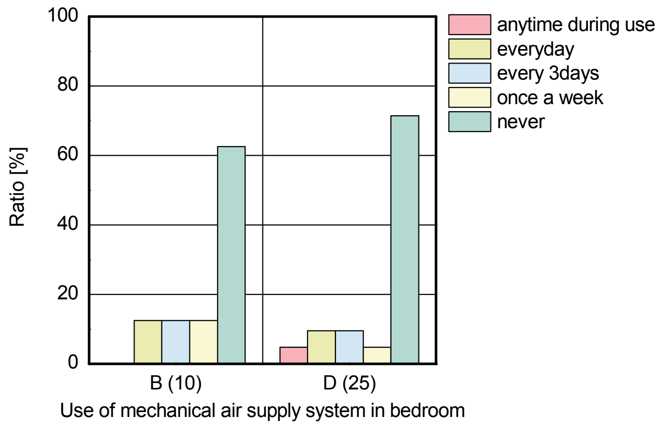
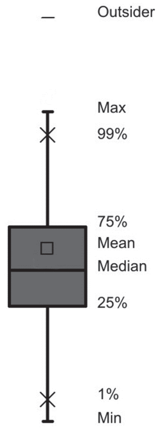


Figure_ A 5:
Use of Mechanical Air Supply System in Bedroom



Outsider	Outside of 1.5*IQR (interquartile range (Box)).
Max:	Largest value (maximum) except outsider.
3. Quartile:	Cuts off lowest 75 % of data
Mean:	is the sum of all of the list divided by the number of items in the list).
Median:	The number separating the higher half of a sample from the lower half
1. Quartile:	cuts off lowest 25 % of data.
Min:	Smallest value (minimum) except outsider.

Figure_ A 6:
Explanations of Box Plots.

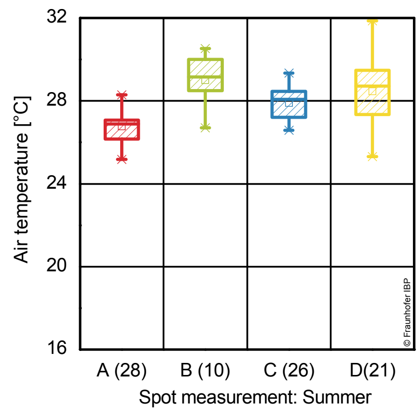


Figure_ A 7:
Box-Plot of Indoor Air Temperature in Summer

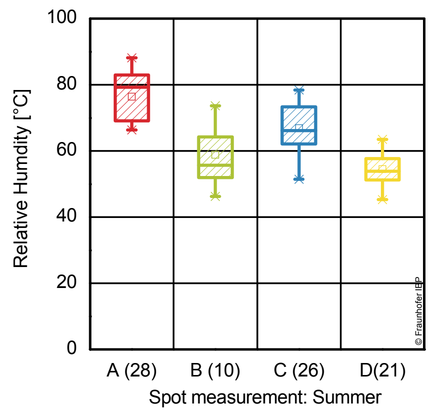


Figure_ A 8:
Box-Plot of Indoor Relative Humidity in Summer

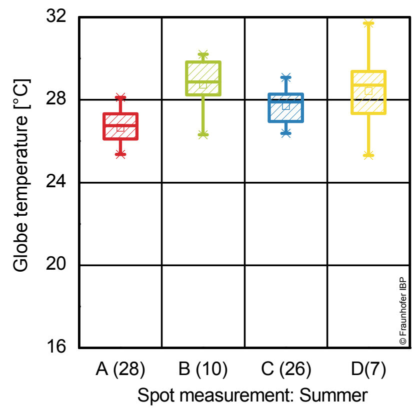


Figure_ A 9:
Box-Plot of Global Temperature in Summer

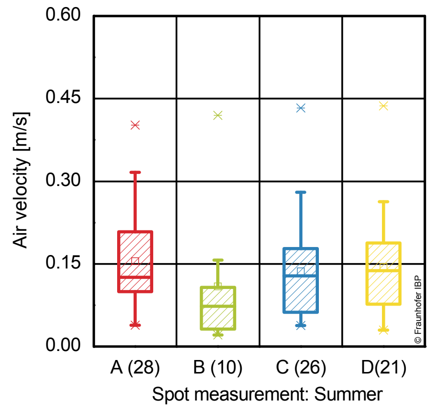


Figure_ A 10:
Box-Plot of Air Velocity in Summer

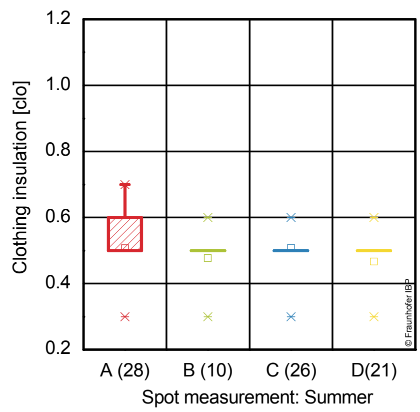


Figure_ A 11:
Box-Plot of Clothing Insulation Value in Summer

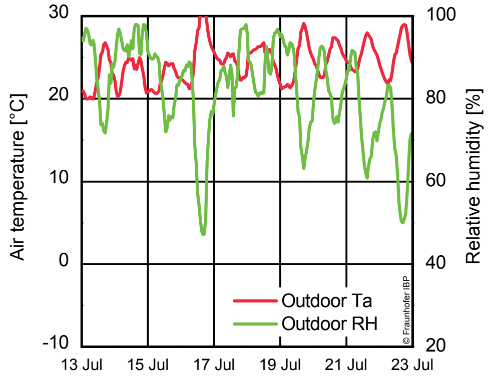


Figure_ A 12:
Outdoor Climate During the Summer Spot Measurement

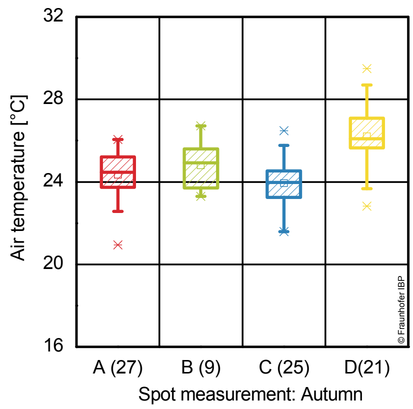


Figure_ A 13:
Box-Plot of Indoor Air Temperature in Autumn

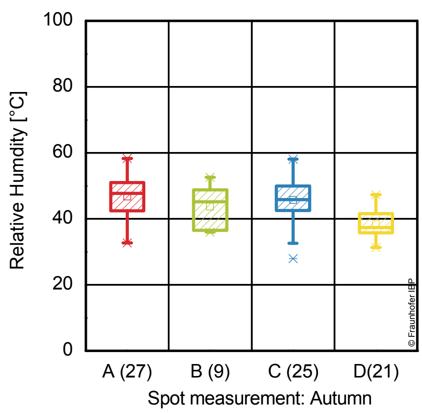


Figure_ A 14:
Box-Plot of Indoor Relative Humidity in Autumn

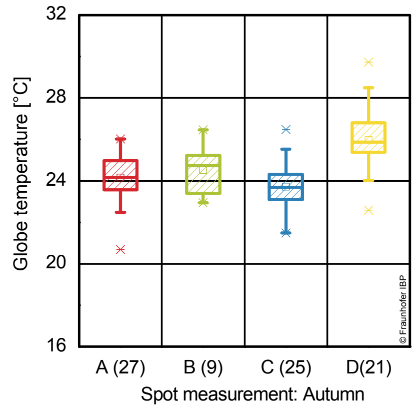


Figure_ A 15:
Box-Plot of Global Temperature in Autumn

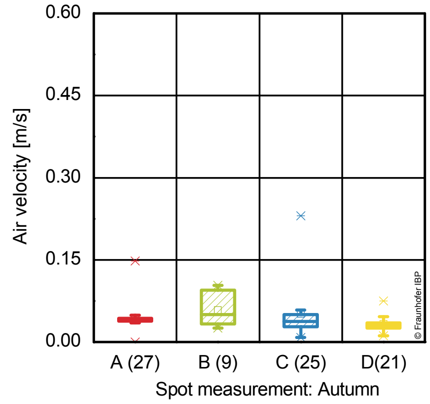


Figure_ A 16:
Box-Plot of Air Velocity in Autumn

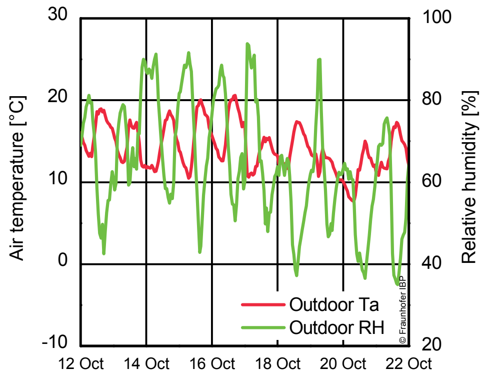


Figure_ A 17:
Outdoor Air Temperature and Relative Humidity During the Measurement in Autumn

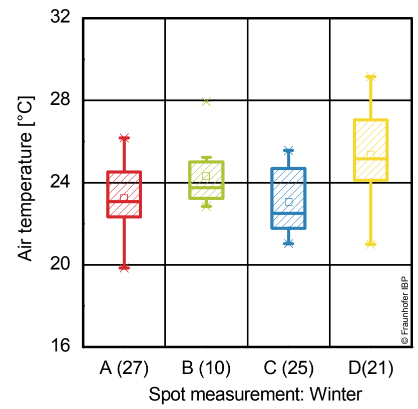


Figure_ A 18:
Box-Plot of Indoor Air Temperature in Winter

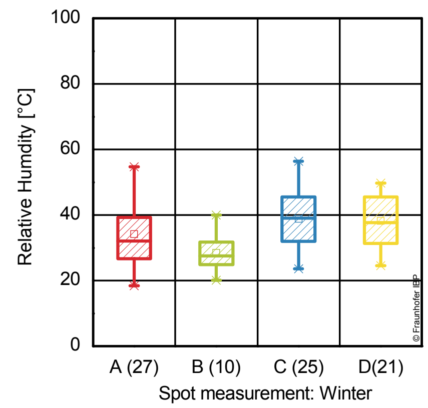


Figure_ A 19:
Box-Plot of Relative Humidity in Winter

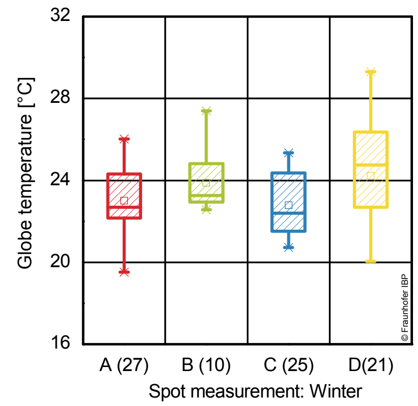


Figure_ A 20:
Box-Plot of Global Temperature in Winter

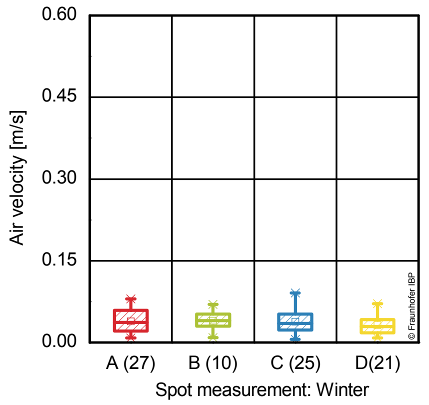


Figure_ A 21:
Box-Plot of Air Velocity in Winter

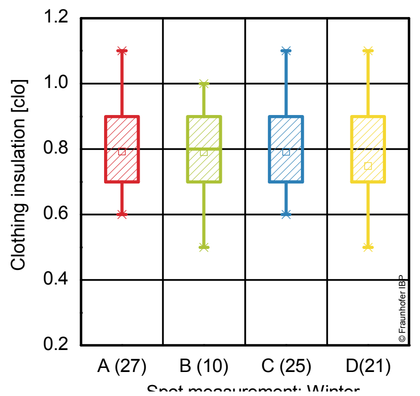


Figure_ A 22:
Box-Plot of Clothing Insulation Value in Winter

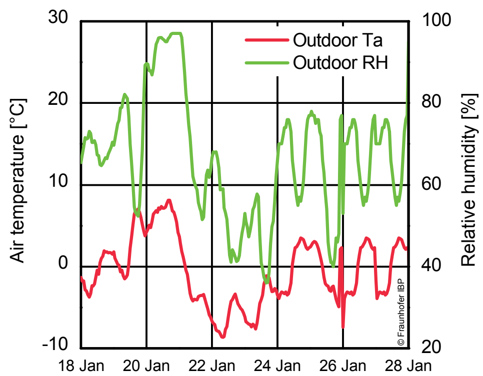


Figure_ A 23:
Outdoor Air Temperature and Relative Humidity During the Measurement in Winter

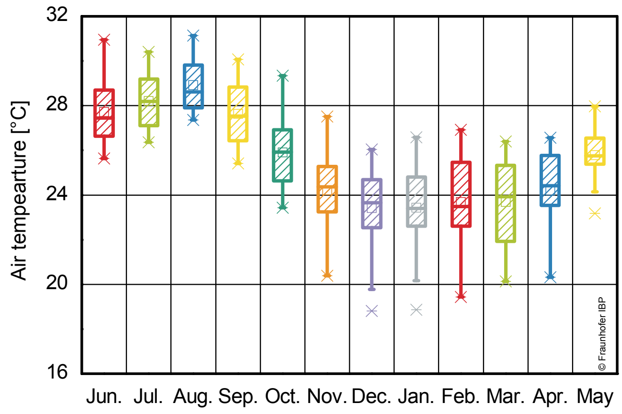


Figure_ A 24:
Box-Plot of Average Air Temperature in the Living Room in 24 Dwellings from June 2009 to May 2010 (n=24 from Jun. 2009 to Jan. 2010 and n=21 from Feb. 2010 to May 2010)

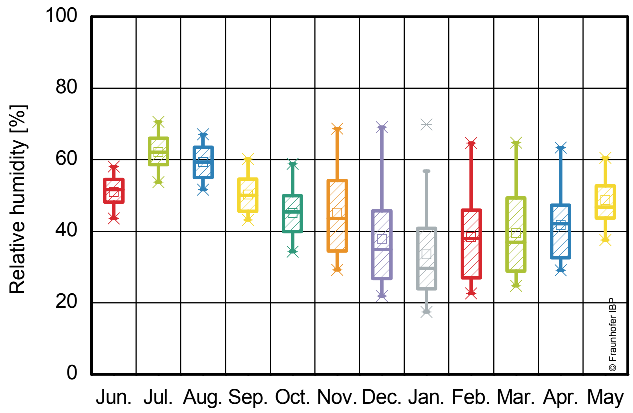


Figure_ A 25:
Box-Plot of Average Relative Humidity in the Living Room in 24 Dwellings from June 2009 to May 2010 (n=24 from Jun. 2009 to Jan. 2010 and n=21 from Feb. 2010 to May 2010)

FORSCHUNGSERGEBNISSE AUS DER BAUPHYSIK BAND 16

Recently, the political and social interest in energy-efficient residential buildings in South Korea, as well as the required technical measures for such practice has grown rapidly. However, experience in the field of energy-efficient buildings in Germany has indicated that not all proven measures for energy efficiency have achieved the expected energy savings in practice. "Incorrect" user behaviour has been repeatedly mentioned as a cause of such failure. Sometimes certain measures caused a thermally uncomfortable indoor environment or even mould growth, which results in user complaints. Therefore, a holistic approach taking the indoor climate, energy efficiency and user behaviour into consideration becomes more and more important.

The objective of this thesis is to analyse the current situation of representative South Korean high-rise residential buildings and to offer recommendations based on the holistic, multi-faceted approach considering thermal comfort, energy efficiency and user behaviour. For this purpose, measurements and questionnaire are conducted. This study shows that "incorrect" user behaviour can be physically explained and could be avoided. The user and the environment should be considered carefully prior to the implementation of a specific measure.

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