THESIS ON CIVIL ENGINEERING F11

HYGROTHERMAL CRITERIA FOR DESIGN AND SIMULATION OF BUILDINGS

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Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any degree or examination.

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ABSTRACT

This study determined indoor and outdoor boundary conditions as design values for hygrothermal design and indoor climate and energy simulations. They include moisture reference year, test reference year, internal moisture excess, temperature factor, and long-term indoor temperature and humidity conditions. For these analyzes, data of the Estonian climate were retrieved from six weather stations, covering a 31-year period, from 1970 to 2000. Indoor climate was measured from 27 detached houses and 13 apartments in Estonia, and in 101 detached houses in Finland.

Two different hygrothermally critical years were chosen on the basis of the saturation deficit method and the mould index method. These years are to be used for design and assessment of the hygrothermal performance of the building envelope and they represent critical years for the risk of water vapour condensation and the risk of mould growth. Test Reference Year (TRY) was constructed for heating and cooling energy calculations and indoor climate simulations with slightly modified ISO15927-4:2005 standard method. The TRY contains months from a number of calendar years. For a simplified estimation of annual heating demand, the average number of heating degree-days was calculated from long-term data for six locations.

Long term measurements of indoor climate in measured dwellings were used to determine average and critical temperature and humidity conditions which were used also in moisture excess analysis. The average indoor temperature during winter was +21.6 °C and the average relative humidity 27 %. Despite this almost ideal winter temperatures, the variations in temperature was larger than expected to be produced by modern heating systems and well insulated envelopes. Large variations in temperature indicated that problems existed with temperature control of the heating systems. The average indoor temperature during summer seasons was +24.6 °C and relative humidity 52 %. However, the results showed an extensive period of high indoor temperatures during summer indicating that thermal comfort was not considered in the original design.

For the calculation of indoor humidity loads in the design of building envelopes, critical values of moisture excess were determined. The design curve on the 10 % critical level is +4 g/m^3 during the cold period (outdoor temperature $\leq$ +5 °C) and +1.5 g/m^3 during the warm period (outdoor temperature $\geq$ +15 °C) for detached houses and +6 g/m^3 during the cold period and +2.5 g/m^3 during the warm period for apartments. Between these levels, moisture excess decreases linearly.

The design values of the temperature factor were determined for Estonian houses and apartments to be used for building design and building inspections. In apartment buildings, temperature factor shall be ≥ 0.80 according to mould growth criterion and ≥ 0.70 according to surface condensation criterion. In detached houses, these values are lower, ≥ 0.65 and ≥ 0.55 respectively.

Keywords: Building physics, Moisture Reference Year, Test Reference Year, indoor climate, moisture excess, temperature factor

Kalamees, T. (2006) **Niiskus- ja soojuslikud kriteeriumid hoonete projekteerimiseks ja simulatsiooniks.** Doktoritöö, Tallinna Tehnikaülikool.

KOKKUVÕTE

Käesolevas töös on määratud sisemised ja välimised ääretingimused, niiskustehniline testaasta, energiaarvutuste testaasta, niiskuslisa, temperatuurifaktor ja keskmised ning kriitilised temperatuuri ja niiskuse tingimused, hoonete soojus- ja niiskustehnilisteks arvutusteks. Väliskliima osas on kasutatud kuue linna, Tallinna, Tartu, Pärnu, Kuressaare, Väike-Maarja ja Võru kliimaandmeid 31-aastaselt (1970-2000) perioodilt. Sisekliimatingimusi ja niiskuskoormusi analüüsitud 27 Eesti väikemajas ja 13 korteris ning 101 Soome väikemajas. Temperatuuri ja õhuniiskuse mõõtmised teostati kokku 138 magamistoas ja 96 elutoas ühe tunnise intervalliga ühe aasta jooksul.

Veeauru kondenseerumise ja hallituse tekke riski kontrollimiseks hoonete välispiiretes niiskustehniliste arvutuste abil on küllastusvajaku ja hallituse kasvu mudeli abil valitud kaks niiskustehniliselt kriitilist testaastat. Hoonete kütte ja jahutuse energiakulu arvutuseks on, natuke muudetud ISO 15927-4:2005 standardi abil, konstrueeritud testaasta (Test Reference Year, TRY), mis koosneb kaheteistkümnest tüüpilisest kuust, mis on valitud erinevatelt aastatelt. Lihtsamateks kütteenergia arvutusteks on välja toodud kuue linna 31 aasta ja kuude keskmised kraadpäevade arvud.

Elamute pikaajaliste sisekliima mõõtmiste tulemusi kasutati keskmiste ja kriitiliste soojus- ja niiskustingimuste ning niiskuslisa määramisel. Keskmine sisetemperatuur talvel oli +21.6 °C ja suhteline niiskus 27 %. Vaatamata kaasaegsetele küttesüsteemidele ja korralikule soojustusele oli peamiseks probleemiks talvel sisetemperatuuri kõikumine suures ulatuses, mis viitab küttesüsteemi juhtimise probleemidele. Keskmine sisetemperatuur suvel oli +24.6 °C ja suhteline niiskus RH 52 %. Mõõtmised näitasid kõrgeid suvised temperatuure, mis viitab, et soojusliku mugavusega nõuetega pole projekteerimisel arvestatud.

Niiskustehnilisteks arvutusteks kasutatava niiskuslisa oli väikemajades külmal perioodil (välistemperatuur $\leq +5°C$) +4 g/m^3 ja soojal perioodil (välistemperatuur $\geq +15°C$) +1.5 g/m^3. Korterite jaoks on kriitiline niiskuslisa külmal perioodil +6 g/m^3 ja soojal perioodil +2 g/m^3. Välistemperatuuri vahemikus +5°C…+15°C muutub niiskuslisa lineaarselt.

Külmasildade klassifitseerimiseks ja nende mõju hindamiseks on määratud temperatuuriindeksi kriitilised tasemed. Korterites peab hallituse tekke riski vältimiseks temperatuuriindeks olema ≥ 0.8 ja kondenseerumise vältimiseks olema ≥ 0.7. Väikemajades, kus niiskuskoormus on väiksem on vastavad väärtused ≥ 0.65 ja ≥ 0.55.

Märksõnad: ehitusfüüsika, niiskustehniline testaasta, energiaarvutuste testaasta, sisekliima, niiskuslisa, temperatuuriindeks

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Targo Kalamees

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is mainly on the basis of the data presented in the following publications on peer-reviewed journals:

I Kalamees, T., Vinha, J. (2004) Estonian Climate Analyzes for Selecting Moisture Reference Years for Hygrothermal Calculations. Journal of Thermal Envelope and Building Science 2004; 27 (3): 199-220.

II Kalamees, T., Kurnitski, J. (2006) Estonian test reference year for energy calculations. Proceedings of the Estonian Academy of Sciences. Engineering 2006; 12 (1): 40-58.

III Kalamees, T., Vinha, J., Kurnitski, J. (2006) Indoor Humidity Loads and Moisture Production in Lightweight Timber-frame Detached Houses. Journal of Building Physics 2006; 29 (3): 219-246.

IV Kalamees, T. (2006). Critical values for the temperature factor to assess thermal bridges. Proceedings of the Estonian Academy of Sciences. Engineering; 2006; 12 (3-1), 218–229.

V Kalamees, T. Indoor climate conditions and the performance of ventilation in Estonian lightweight detached houses. Indoor and Built Environment 2006; 15 (6).

VI Kalamees, T., Kurnitski, J., Vinha, J. The effects of ventilation system and building envelope on thermal comfort in Finnish lightweight houses during the summer. Submitted to Building and Environment (22.12.2005).

and on following conference publications:

VII Kalamees, T., Kurnitski, J., Vinha, J. (2004) Indoor Temperature, Humidity, and Moisture Production in Lightweight Timber-Framed Detached Houses. Proceeding of Performance of Exterior Envelopes of Whole Buildings IX conference 2004. December 5-10, Florida, USA, CD-ROM.

VIII Kalamees, T. (2006) Indoor hyrgothermal loads in Estonain dwellings. The 4th. European Conference on Energy Performance & Indoor Climate in Buildings. 20-22 November 2006, Lyon, France.

These publications are referred to in the text by their Roman numbers.

AUTHOR'S CONTRIBUTION

The author of the thesis is the main author in all the publications. In I the climate data were analyzed by the author, the principles of the selection method were basically developed by the co-author. In II climate data were analyzed by the author, results were discussed and conclusions were made by both authors. In III, VI and VII the author analyzed the measured data, results were discussed and conclusions were made together with co-authors who were also responsible for leading and development of the research project.

ACRONYMNS, ABBREVIATIONS AND NOTATIONS

AMeDAS	Automated Meteorological Data Acquisition System
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AVG	Average
CWEC	Canadian Weather Year for Energy Calculations
DBT	Dry-Bulb Temperature
DI	Drying Index
DPT	Dew-Point Temperature
DRY	Durability Reference Year
EMHI	Estonian Meteorological and Hydrological Institute
EPBD	European Union Energy Performance of Buildings Directive
FiSIAQ	Finnish Society of Indoor Air Quality and Climate
FS	Finkelstein-Schafer
GSR	Global Solar Radiation
HAM	Heat, Air, and Moisture
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
IWEC	International Weather for Energy Calculations
KS	Kolmogorov-Smirnov
MAX	Maximum
MDRY[1]	Moisture Durability Reference Year
MDRY[2]	Moisture Design Reference Year
MI	Moisture Index
MIN	Minimum
MRY	Moisture Reference Year
PAQ	Perceived Air Quality
PFT	Passive tracer gas (Per fluorocarbon) air infiltration measurement technique
PMV	Predicted Mean Vote
RH	Relative Humidity
TMM	Typical Meteorological Month
TMY	Typical Meteorological Year
TRY	Test Reference Year
WBT	Wet-Bulb Temperature
WI	Wetting Index
WSP	Wind Speed
WVP	Water Vapour Pressure
WYEC	Weather Year for Energy Calculations
WYEC2	Weather Year for Energy Calculations, second version

Cold period	Outdoor temperature $T_{\mathrm{out}} \leq +5$ °C
$F_{(p,y,m,i)}$	Cumulative distribution function of climatic parameter p within each calendar month m in year y;
Heating season	Outdoor temperature $T_{\mathrm{out}} \leq +15$ °C
m	month
p	Climatic parameter
P	Statistical significance according to Student-s T-test
pers.	person
S	Summer season
W	Winter season
Warm period	Outdoor temperature $T_{\mathrm{out}} \geq +15$ °C
y	year
$\Phi_{(p,m,i)}$	Cumulative distribution function of climatic parameter p within each calendar month m in all years in the data set

ach	air change per hour, 1/h
f_{Rsi}	temperature factor, -
G	moisture production, kg/day
M	mould index, -
q_{v}	air change rate, m^3/day
R	thermal resistance, $(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}$
RH	relative humidity, %
S_{Tin}	number of heating degree-days per year
T	temperature, °C
$\Delta\nu$	internal moisture excess (moisture supply), $\mathrm{g/m}^3$
$\Delta\nu_{\mathrm{sat.def}}$,	saturation deficit, $\mathrm{g/m}^3$
ν	humidity by volume, $\mathrm{g/m}^3$

$_{\mathrm{crit}}$	critical
$_{\mathrm{e}}$	external
$_{\mathrm{i}}$	internal
$_{\mathrm{in}}$	indoor
$_{\mathrm{out}}$	outdoor
$_{\mathrm{sat}}$	saturation
$_{\mathrm{si}}$	internal surface
$_{\mathrm{T}}$	total
$_{\mathrm{d}}$	day

1 INTRODUCTION

1.1 Background

Moisture problems have become a major cause of building damage. It is estimated (Ronald 1994, Bomberg and Brown 1993) that 75-80% of all the problems with building envelopes, to a certain extent, are caused by moisture. Haverinen (2002) has classified moisture damages. In her cross sectional analyzes of moisture findings in the Finnish housing stock she has reported that some 38 % of the detached houses and 25 % of the apartments have notable or significant moisture problems. The results of the study in 420 buildings in Sweden (Wessén et al. 2002) refer to moisture problems that resulted in vivid microbial growth, with microbial/chemical emissions of the building material and microbial metabolites, in 65% of the buildings. The presence of home dampness and/or moulds (that is damp spots, visible mould or mildew, water damage, and flooding) was reported by 38% in Canadian study (Dales et al. 1991). These estimates show that moisture problems are a serious issue and have a strong economic effect. In fact, repair of extensive problems is very expensive. According to estimates by Pirinen et al. (2005), expenses to repair microbiological damages causing health effects, are in the magnitude of 10000-40000 € per case.

A major result caused by moisture damages is health effects on the occupants. The evidence of a causal association between dampness and health effects is strong. However, the mechanisms are unknown, as shown in comprehensive reviews by Bornehag et al. (2001 and 2004). Common symptoms associated with moisture problems are respiratory symptoms, sensitization to house dust mites, asthmatic symptoms or emergency room visits due to asthma as well as tiredness and headaches. Causal association between dampness and health effects shows that avoidance and control of moisture problems should be an essential concern in public health issues.

Design process is one component to prevent moisture damages and to guarantee longer service life for buildings. The design process of the building envelope consists of several parts, including hygrothermal design. Hygrothermal design consists of selection and dimensioning of structures, detailed drawings and specifications of critical joints and details and other design documents and rules for operation and maintenance (Lehtinen 2000). In many cases, hygrothermal design is divided between other design components (architectural design, structural design, and HAVC design) and has not been established as a separate design area. To assess and predict the long-term hygrothermal performance of the building envelope, calculations or experimental investigations are needed. Because laboratory and field experiments are expensive and time-consuming, calculation and simulation methods are increasingly used to assess the hygrothermal behaviour of building components. During the last decades, computer programs for building simulation have been developed and changed from in-laboratory tools to advanced and commercially available simulation tools for personal computers, which are easy to use and include databases of building materials and climatic data.

In research, field simulation programs are successfully used to solve hygrothermal problems, for example, in crawl spaces (Kurnitski 2000, Airaksinen 2003), attics and roofs (Kalagasidis and Mattsson 2005, Salonvaara and Nieminen 2002), and churches (Häupl and Fechnerm 2003, Schellen et al. 2004), to work out typical building envelope solutions for certain climatic areas (Burch and Saunders 1995, Karagiozis 2002, Mukhopadhyaya et al. 2003), to analyze the hygrothermal performance of renovated building envelopes (internal thermal insulation, for example, Cerny et al. 2001, Häupl et al. 2003), etc. According to (Burke and Yverås 2004), the use of simulation tools in hygrothermal design in consulting companies is hindered because it is too expensive, too difficult to learn, too time-consuming to run the simulations, and time resources are insufficient. These could also be the reasons why, as a rule, hygrothermal dimensioning in consulting companies is limited to the calculation of U-value and moisture accumulation in structures due to water vapour diffusion on the basis of the Glaser-method (Lehtinen 2000). In consulting companies, hygrothermal simulation programs are used mainly in complicated renovation cases. In the design of new houses, the solutions already developed and standardized may be used. To design these standard solutions, hygrothermal design is necessary. As in the structural design, where simulation programs are widely used, simulation programs will probably come into everyday use also in hygrothermal design. As users of the simulation tools should know the calculation principles, limitations of the model and correct material properties, they should also be aware of the correct boundary conditions. Holm and Künzel (2001) point out that the influence of the exterior and interior climate conditions on the results of hygrothermal simulations is comparable (sometimes even higher) to the influence of the material property variation.

A lot work is done, but no finally standardized methodologies for dynamic moisture design and hygrothermal loads exist yet. Determining the loads for hygrothermal calculations is still an ongoing process. The same applies to the performance criteria, the definitions of which vary in standards and codes. In many cases, the methods of how boundary conditions are defined may strongly influence the results of hygrothermal simulations. Although boundary conditions are very important parameters, little attention has been paid to them. Frequently, constant values are given for variable values and durability calculations are made with average climatic data. For example, Kokko et al. (1999) suggest Finnish energy test-year 1979 to be used for hygrothermal calculations. In their studies, Kurnitski (2000) and Airaksinen (2003) used the weather data of the year 1998, which was considered a typical year in respect of temperature and humidity conditions. Regarding mould growth and humidity condensation, these years offered much milder hygrothermal conditions than Finnish moisture reference years (Vinha and Kalamees 2003). Many hygrothermal simulation programs consist of an outdoor climate database. Often these climatic data are also long-term average climatic data.

Similarly, to the outdoor climate, the indoor climate plays an important role in the hygrothermal conditions of the building envelope. Indoor humidity is the result of the rate of moisture production, air change rate and moisture exchange with hygroscopic materials inside the building. In most of the cases, the difference between the absolute humidity of indoor and outdoor air is sufficient information in the determation of indoor humidity level in hygrothermal design. In indoor climate analyzes, moisture production and air change rate are suitable input parameters. In the standardization level, it is unclear how to define indoor hygrothermal loads. In different standards, hygrothermal loads are defined differently and in different standard stages: EN ISO 13788:2001, prEN 15026:2006, ASHRAE Standard 160P 2004, DIN 4108-3 2001. Thus, a standardized methodology is required for design loads and criteria.

Due to the cold climate, buildings in Baltic and Nordic countries are normally designed according to the outdoor climate conditions in winter. Since now, outdoor climate conditions in summer have not usually been taken into account. However, recently after heat waves in 2003 and 2006, a discussion of summer thermal comfort has begun. In addition, the understanding about the quality of indoor environment has changed over the last decades. Due to rising living standards, requirements for thermal comfort and healthy indoor air have been raised. As air conditioning and special shadings for solar protection have become normal solutions in modern office buildings, these may become common in houses as well. In cold climate in winter, low outdoor humidity combined with overheating may result in indoor humidifying that would strongly increase humidity loads. Portative humidifiers used in bedrooms of sensitive people provide a lower effect, but it is still to be taken into account. The actual indoor temperature and humidity conditions and the performance of ventilation are important data for assessments of indoor climate and thermal comfort as well as for energy consumption. It is also to be taken into account in the hygrothermal performance as specifications in the indoor climate and ventilation codes and standards influence directly indoor hygrothermal loads. Indoor climate and ventilation specification together with occupant behaviour produce real indoor loads. As many factors affect indoor loads, probably the most reliable way to determine the relevant design values is to perform long-term field measurements in a representative sample of houses.

Typically, sizing of the heating systems as well as chillers are on the basis of steady state conditions. Dynamic building simulation has been increasingly used for accurate indoor climate, cooling load and energy consumption calculations as well for the simulation of active or passive solar energy systems. Dynamic indoor and energy simulation requires a standardized test reference year that would represent typical outdoor climate. For economical reasons test reference year is also suitable for air conditioning dimensioning in primarily heating climate.

1.2 Aims and content of the study

The main objectives of this thesis were to define indoor and outdoor boundary conditions for hygrothermal design as well as indoor climate and energy simulations.

Specific objectives were as follows:

- To determine the critical outdoor climatic conditions in Estonia, to assess the hygrothermal performance of the building envelope;
- To construct a Test Reference Year (TRY) for Estonia for indoor climate and heating and cooling energy calculations and simulations;
- To analyze long-term indoor temperature and humidity conditions in detached houses;
- To determine the typical and critical values of indoor hygrothermal load components in dwellings;
- To determine the criteria to be used for the building design and infrared thermography inspections to assess the thermal bridges.

The thesis consists of eight papers: six peer-reviewed journal papers and two conference publications (see page 10).

The outdoor climate (temperature and RH) for hygrothermal calculations in regard to vapour diffusion and moisture convection is analyzed in I. Climatic data were analyzed on the basis of six weather stations (Tallinn, Kuressaare, Pärnu, Tartu, Väike-Maarja, and Võru) over a 30-year period, from 1970 to 2000. Weather stations were chosen according to climatic areas and the building density of the towns. 10 %-level critical years for hygrothermal calculations, for two moisture performance criteria, the risks of water vapour condensation and mould growth, were determined.

The Estonian TRY was selected in II. The selection was on the basis of temperature, humidity, and global solar radiation and wind speed from the same six weather stations over a period of 31 years from 1970 to 2000. The constructed TRY contains typical months from a number of different years. The average number of heating degree-days was calculated from data from six locations for use in simple energy calculation methods. The TRY has many applications, including indoor climate and energy simulations, and energy performance certificate calculations and simulations that are demanded according to the European Union energy performance in buildings directive (EPBD 2002) as well as for the simulation of active or passive solar energy systems.

The indoor temperature and humidity conditions in detached houses are studied in V, VI, and VII. The indoor climate conditions were measured and analyzed mainly in lightweight timber-frame detached houses occupied by single-families in Estonia and in Finland during 2002-2005. The temperature and RH were continuously measured in 128 detached houses (125 bedrooms, 96 living rooms), and outdoors in each house at one–hour intervals over a one-year period. The temperature and humidity levels were analyzed in the subdivisions of houses, divided according to the HVAC systems and the envelope solutions. Additionally, the dependence between the indoor temperature and the outdoor temperature was determined suitable for use in the indoor temperature calculations, where the indoor temperature is not generated by the room model of the simulation program.

Indoor humidity loads in dwellings are studied in III, VII, and VIII. On the basis of temperature, RH measurements of the above-mentioned 128 detached houses and in 13 apartments, the moisture excess (difference between the absolute humidity of the indoor and outdoor air) was calculated for the hygrothermal design of the building envelope. Moisture excess levels and their dependence on outdoor temperature are given. Average moisture excess and moisture production values were calculated for the use of indoor climate simulations. The design curve of moisture excess validated is suitable for different types of hygrothermal analyzes of building envelopes, e.g. for steady state calculations and detailed dynamic simulations for cases with no humidification in dwellings. In Finnish houses, the design curve of moisture excess was given for the humidification case with a set point of 25 % indoor RH.

The design value for the temperature factor to assess thermal the bridges of the building envelope was selected in (IV). For this analyzes, data of the outdoor climate were retrieved from the six above-mentioned weather stations, covering a 31-year period, from 1970 to 2000. For the indoor boundary conditions, the critical values from field measurements in the studied dwellings were used. The critical values of the temperature factor were calculated for different indoor temperature and humidity conditions for two different criteria: to avoid surface condensation and mould growth.

2 FACTORS DETERMINING BOUNDARY CONDITIONS OF HYGROTHERMAL DESIGN AND BUILDING SIMULATION

2.1.1 Outdoor climate for hygrothermal calculations

Outdoor climate conditions are important parts of hygrothermal modelling. We need different climatic data for different purposes. For failure analyzes, the real climatic parameters are needed from failure locality and time. In new building design, critical climatic parameters should be applied to the whole service life of building. The main difference between energy reference years and moisture reference years is that the energy reference year is composed of the mean values of climate parameters for the locations under consideration. The moisture reference year should take into account the critical moisture load on the building envelope components to provide the required level of safety as regards moisture damage.

Determining the loads for hygrothermal calculations is still an ongoing process. The cooperative project Annex 24 on Heat, Air and Moisture (HAM) Transport, Task 2 Environmental Conditions (Sanders 1996) of the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems Programme has made recommendations on how to determine a Moisture Durability Reference Year (MDRY[1]) for hygrothermal calculations. IEA project Annex 41 on Whole Building HAM Response defines outdoor and indoor thermal and humidity loads and other parameters to be used in the HAM modelling of the whole building (Hens 2005). Similarly, the ASHRAE Standard Committee 160P, Design Criteria for Moisture Control in Buildings, is attempting to formulate appropriate humidity loads for moisture design analyzes (TenWolde and Walker 2001).

Building envelope should ideally endure the maximum hygrothermal loads that the building will experience during its service life. The IEA project Annex 24, Task 2 Environmental Conditions (Sanders 1996), has recommended that MDRY[1] for hygrothermal calculations is 1 in 10 years. A 10 % level criterion means that the defined hygrothermal conditions should not be exceeded more than 10 % of the time. In other words, these should not occur more frequently than once every ten years. In terms of moisture load, nine years in ten are less severe and may be considered in-service or typical years which building envelopes should be expected to cope with without difficulty.

In the framework of the IEA project Annex 24, different proposals were made to determine outdoor climate for hygrothermal calculations. Mohamed and Hens (1992) proposed a methodology for selecting a reference year on the basis of the monthly mean outdoor temperature. According to their proposal, it was first needed to define the statistical relevance and then couple the different meteorological parameters by regression. Independent variables in these single regression analyzes were monthly mean temperature, RH and solar gain. Regression between temperature and RH covered a rather broad field, with nonetheless one clear constant was used, where the monthly mean RH decreased with increasing monthly mean temperature. Regression between temperature and solar radiation was analyzed in two steps: first, the regression line "duration of direct sunshine"-"solar gains" was defined and second, the regression line outdoor temperature-solar gain was calculated.

Rode (1993) proposed a monthly-based and hourly-based methodology to select reference years for moisture calculations. On the monthly-based reference year, for every month in the-long term period, the mean values of dry bulb temperature (DBT), RH and global solar radiation (GSR) on the horizontal surface were calculated by traversing the hourly data. Rode did not attempt to make linear regressions of RH and GSR as functions of outdoor air temperature that would cover the whole year, but for every month name, a linear regression was generated between the above set of parameters. The hourly-based reference year from long-term data was calculated with the MATCH (Pedersen 1990) simulation program. Rode studied the light-weight flat roof with a hygroscopic layer (wood) on the inside of the mineral wool insulation; a light-weight wall with wood, wood wool cement and rendering on the outside of the mineral wool insulation (facing either north or south) and a light-weight metal wall without hygroscopic materials insulated with mineral wool (either north or south). None of the constructions had vapour retarded. The indoor climate varied in temperature from +21 °C (heating season) to +23 °C (in the warmest summer months). Indoor humidity was defined by moisture excess which varied between +3 g/m^3 in the heating season and +2 g/m^3 in the peak summer months. The aim was to establish one of the years to be the "worst year" judged on the moisture conditions. A secondary aim was to show whether the different constructions have the same "worst year". Rode suggested the actual hourly weather data from 1966 to be used as an example of a worse case-year for moisture conditions in all types of constructions exposed to Danish outdoor climate.

Geving (1997A) evaluated and improved the Rode method to determine the Moisture Design Reference Year (MDRY^2). Geving used six constructions: in addition to Rode's components, a compact flat roof with concrete at the inside, a timber frame wall with high initial moisture content, and a concrete wall insulated at the inside. Two evaluation criteria: the maximum monthly average moisture content of the hygroscopic layer just outside the insulation during the last year of the simulation period and the average total moisture content of the whole construction in the final year of the simulation period were used. The year that produced the result closest to the 10 % level was selected to be the 10 % year (MDRY^2).

Harderup (1994) used the Π-factor method to find the Durability Reference Year (DRY) for Sweden. The Π-factor is defined as the difference between humidity at saturation at the external surface at outdoor air temperature and outdoor absolute humidity of the air. When the Π-factor is small, there is a relatively high potential for interstitial condensation within a construction. The humidity at saturation of the outdoor air was calculated in two different ways: first, the radiation from the sun was ignored and second, the diffuse sun radiation was taken into account. For a north-facing wall, only half the intensity of the total incoming diffuse sun radiation on a horizontal surface was considered. Harderup studied two periods: from January to March and the whole year. Finally, Harderup calculated the statistical distribution of the Π-factor, for all months of the years and selected 12 months that determined the 10 % percentile concerning the condensation rate.

The final method in the IEA project Annex 24 to determine the outdoor climate for hygrothermal calculations, Durability Reference Year (DRY), is on the basis of the construction-dependent method. The Glaser method (Glaser 1959) or hygrothermal simulation program should calculate net accumulation of condensation for each year for five constructions (north and south facing walls with an impermeable facade, north and south facing lightweight walls, and flat roof) with constant indoor temperature +21 °C and indoor humidity calculated on the basis of the third climate class (Sanders 1996). On the basis of the 10 % level of annual interstitial condensation, the DRY was selected or constructed.

Lstiburek et al. (2002) used the procedure developed in the IEA project Annex 24 to construct two weather years that coincide with the 10 % percentile coldest and warmest years with corresponding hygrothermal loads for Minneapolis. The influence of rain loads was included in the analyzes to determine the hygrothermal loads.

Cornick and Dalgliesh (2003) and Cornik et al. (2003) used the Moisture Index (MI) approach to characterize climates for building envelope design. The MI comprises the wetting index (WI) and the drying index (DI). The WI describes the availability of water or the source part of the water budget. The WI was chosen to be the annual rainfall for the year in question. The DI describes the sink part of the water budget. The DI is a simple function of drying that related to evaporation was the difference between the humidity ratio at saturation and the humidity ratio present in the ambient air. The hypothesis was that the higher the value of the MI the more severe is the moisture loading. Years that have the same MI despite having different WI and DI, have a similar potential for moisture loading.

2.2 Outdoor climate for indoor climate and energy simulations

Indoor climate and energy simulation programs are widely used to calculate the accurate indoor climate and energy performance, to simulate active or passive solar energy systems, to compare design alternatives and optimize HVAC system performance calculations, etc. Simulation tools can provide a better understanding of the performance of HVAC systems and the interaction between the HVAC systems and the whole building. These calculations require a standardized reference year for each country.

An overview of the Design Reference Years and Test Reference Years in Europe, Turkey and Israel was given by Lund (2001). The report contains a short description of the selection methods of the reference years and locations (latitude, longitude, altitude) of the places where the reference years are available for 24 European countries. In the following, the main types of TRYs are described.

Keeble (1990) has classified three types of hourly weather data for use in building energy simulation:

- Multi-year datasets: they are the fundamentals and include a substantial amount of information for a number of years;
- Typical years: a typical or reference year is a single year of hourly data selected to represent the range of weather patterns that would typically be found in a multi-year dataset. The definition of a typical year depends on its satisfying a set of statistical tests relating it to the parent multi-year dataset;
- Representative days: they are hourly data for some average days developed to represent typical climatic conditions. Representative days are economical for small-scale analyzes and are often found in simplified simulation and design tools.

A reference year for energy calculations should represent mean values of main climate parameters that are as close as possible to long-time mean values. Lund (1991) has suggested three main requirements for a reference year:

- True frequencies, i.e. as near as possible to true mean values over a longer period, e.g. a month, and a natural distribution of higher and lower values for single days;
- True sequences, i.e. the weather situations must have a duration and must follow each other similarly to frequently-recorded courses for the location;
- True correlation between different parameters, i.e. temperature, solar radiation, cloud cover, and wind.

Over the past 30 years, several weather data sets have been designed for use in building energy simulations. In the following paragraphs, the most common selection methods are described.

The principle for determining the ASHRAE Test Reference Year (ASHRAE TRY) (NCDC 1976) is to eliminate those years that contain months with extremely high or low monthly mean dry-bulb air temperatures (DBT) until only one year, the ASHRAE TRY, remains. The months are arranged in order of importance for energy comparisons. For example, the hottest July and the coldest January are assumed the most important; the coolest October and the warmest April are considered as the most unimportant. Depending on climate regions, this order may change. The first step in the selection process is to mark all 24 extreme months according to the rankings. If two or more years remain without any marked months, elimination will be repeated with the next-to-hottest July, the next-to-coldest January, and so on, until one year is left without being marked. The ASHRAE TRY is an actual historic year.

The Typical Meteorological Year (TMY) (Hall et al. 1978, NCC 1981) consists of twelve Typical Meteorological Months (TMM) selected from a multi-year weather database. The selection of a TMM is on the basis of the statistical analyzes and evaluation of four weather parameters: global solar radiation (GSR), DBT, dew-point air temperature (DPT), and wind speed (WSP). A set of nine parameters is included in the selection: daily maximum, daily minimum, and daily mean DBT and DPT, daily maximum and daily mean WSP, and daily total solar radiation GSR. A nonparametric method, known as the Finkelstein-Schafer (FS) statistic (Finkelstein and Schafer 1971), is used to determine the candidate months by comparing the yearly cumulative distribution to long-term distributions. Climatic parameters are weighted in terms of relative importance from 1/24 to 12/24. The authors of the method gave the highest weighting to solar radiation, as it was intended for use primarily in assessing solar energy conversion systems and buildings. In the final selection, it is the intention that the selected month has a small FS statistic value, small deviation, and typical run structure. The TMY data contain months from a number of different years.

The basic method used to select the Weather Year for Energy Calculations (WYEC) is to determine the individual month with the average DBT closest to the long-term monthly average; there are no abnormalities and the DBT is within 0.1 °C of the long-term monthly average (Crow 1980). If the chosen month is outside the 0.1 °C limit, then another year’s month, close to the mean but below it, is chosen and days from this month are substituted into the chosen month until its average DBT is within 0.1 °C of the long-term average. The WYEC data contain months from a number of different years. The selected month may include climatic data from another year’s month. The WYEC data set format was reorganized by Stoffel and Rymes (1998) who developed the WYEC2 data format.

Selection processes in International Weather for Energy Calculations (IWEC) (Thevenard and Brunger 2002) and the Canadian Weather Year for Energy Calculations (CWEC) (Numerical Logics (1999) are similar to those in the TMY, but weighting factors differ.

The ISO 15927-4:2005 method is based closely on the Danish selection method (Skartveit et al. 1994). DBT, GSR, and air humidity were taken as the primary parameters for selecting the best month to form the reference year. The selection process tries to find the mean values of individual parameters, frequency distribution of individual parameters, and correlations between the different variables within each month as close as possible to the corresponding calendar month of the long-term data. This selection procedure was used in this study and is described in more detail in Chapter 3.3.

In addition to these most common standardized selection methods, some countries have developed their own methods, which are modifications of common methods or completely new methods. The Finnish energy test-year (Tammelin and Erkiö 1987) is an actual historical year (1979) that was selected mainly on the basis of monthly mean temperatures and global radiation levels. In the first selection round, the method discarded those years for which monthly average temperatures for whole years and/or single months differed from long-term (1968-1983) average data. From the remaining 3-5 years, the selected test-year took into account average DBT, GSR, and the interaction of DBT and GSR. Additionally, the number of heating degree-days and daily and hourly variation of DBT and GSR were taken into account.

Lam et al. (1996) developed TMY for Hong Kong. Apart from the FS statistic, the nonparametric test statistic, Kolmogorov-Smirnov (KS) statistic (Massey 1951), was also used for the analyzes. While the FS statistic is on the basis of the average deviation of the cumulative distribution frequency, the KS statistic is on the basis of the maximum deviation.

In Japan, the Automated Meteorological Data Acquisition System (AMeDAS) is the most dense array system for weather data acquisition. Expanded AMeDAS weather data for building energy calculation have been developed by Akasaka et al. (2000). The candidate month and typical month are selected from weather data by using a multi-step filtering process. Each month's mean temperature is compared with the multi-year average for the specific month. When the values have a deviation within the standard deviation of multi-year data, values identified by the years are considered as candidates for the specific month at that stage. A similar process was performed for global solar radiation, humidity ratio, precipitation, and wind speed. FS statistics were then used to indicate the deviation of daily averages of the same weather data parameters. In the calculation of the weighting factors, the effects of temperature, humidity ratio, and horizontal global irradiation on the heating loads of the building were considered.

2.3 Indoor climate conditions in detached houses

Occupant density and behaviour as well as ventilation and indoor climate specifications influence the indoor temperature and humidity conditions. Therefore, specifications in indoor climate and ventilation standards and codes will influence indoor boundary conditions for hygrothermal design and building simulation.

Indoor temperature is the most important factor in the assessment of moderate indoor thermal comfort. Recommended indoor operative temperature for living spaces of residential buildings with the highest indoor climate category is +21 °C during winter season and +25.5 °C during summer season (prEN 15251:2005). At light, primarily sedentary activity (<1.2 met), the neutral temperature (predicted mean vote (PMV) = 0) is for summer (clothing ~0.5 clo) +24.5 °C and for winter (clothing ~1.0 clo) +22.0 °C (ISO EN 7730). A room temperature above +22 °C has been associated with increased symptoms of the sick building syndrome (Jaakkola et al. 1989). Temperature and humidity have also a significant impact on perceived air quality (PAQ). The acceptability of air is linearly related to the enthalpy and decreases with increasing air temperature and humidity (Fang et al.

1998). High indoor temperatures influence also energy consumption. Field measurements of Finnish detached houses (Vinha et al. 2005) validated a simple rule that 1 °C rise of the average indoor air temperature during winter period will increase the average consumption by 5 %.

Absolute humidity and RH are important parameters for hygrothermal design and indoor climate, respectively. In a cold climate, a low outdoor humidity level during winter season combined with overheating may decrease the indoor RH to unacceptably low levels that may provoke numerous health symptoms, such as dryness, primarily of the eyes, as well as of the nasal cavity, mucous, and skin. To achieve the suggested indoor RH may require indoor air to be humidified that may set a serious hygrothermal load to the building envelope. Indoor humidity may be too high at a low ventilation or/and a high moisture production rate. This may cause both serious moisture problems for the building envelope and indoor climate problems due to the growth of micro-organisms and house dust mites.

Sterling et al. (1985) suggested that the optimum conditions to minimize the risks to human heath would occur in the narrow range of RH, between 40 % and 60 % at normal room temperatures. Other studies suggest somewhat lower RH-values due to material emissions, odours, PAQ, and mould growth. Fanger (1971) has reported that the RH values should not be below *RH* 20 %, because complaints about dry mucous membranes may often be caused by the irritants in the air rather than by the dry air. Wyon et al. (2002) have shown that 5-hour exposures to low humidity conditions at +22 °C (*RH* 15 % and *RH* 5 %) have a negative effect on the tear film quality that does not occur above the level of *RH* 25 %. Another limitation for the low RH is the control of static electricity. RH above 40 % or 55 % when under floor heating is used will prevent most shocks (Brundrett, 1977). Paasi et al. (2002) studied the surface resistivity and charge decay times for several materials as a function of relative humidity in the range of *RH* 5–70 %. The results show that special care is needed in the electrostatic discharge management if RH below 20 %…30 % is anticipated. However, humidification is not common in Baltic and Nordic countries, it is a matter of discussion if the envelopes should be designed for humidification, as sensitive people use humidifiers. If humidification is decided to be installed, prEN 15251 (2005) suggests set points RH 20, 30 or 40 %, depending on the indoor climate category.

There is sufficient evidence of an association between exposure to a damp indoor environment and upper respiratory tract symptoms: nasal congestion, sneezing, runny or itchy nose, and throat irritation (IOM 2004), as well as worsened perceived air quality (Fang et al. 1998). Bornehag et al. (2001 and 2004) have found in their review that "dampness" in buildings appears to increase the risk for a number of health effects, mainly respiratory symptoms (cough, wheeze and asthma), but also other health effects, such as unspecific symptoms like tiredness and headaches. Even the ultimate lower RH for germination of fungi is found to be in the range of *RH* 62 %…65 %, fungal growth experiments on common building and finishing materials indicate that susceptible surfaces can be kept free of fungal growth if the RH is maintained below *RH* 80 % (Adan 1994). According to Viitanen and Ritschkoff (1991), there is no growth of mould fungi below the *RH* 75 % within a temperature range of +5 °C to +40 °C. Based on an extensive analysis of published data and on laboratory experiments, Rowan et al (1999) recommend maintaining RH below 75% to limit fungal growth in buildings. On the basis of a literature review and their experience gained from damage studies and materials testing, Johansson et al. (2005) described the critical moisture level. Critical moisture conditions for microbiological growth of materials that are clean are between *RH* 75 % and 90 % (Table 2.1). Contaminated or soiled materials will lower the critical moisture level to 75-80% RH.

Table 2.1 Critical moisture levels for different groups of materials (Johansson et al. 2005)

Material group	*RH*
Wood and wood based materials	75-80 %
Paper on plasterboard	80-85%
Mineral insulation materials	90-95 %
Extruded and expanded polystyrene	90-95 %
Concrete	90-95 %

Hart (1998) and Korsgaard (1983) found larger house-dust-mite populations, when the absolute indoor air humidity is above 7 g/kg (*RH* 45 % at +20 °C). Arlian et al. (1999) observed effective restriction of dust mite growth and the production of allergen associated with the maintenance of mean daily RH below 50%, even when RH rises above 50% for 2 to 8 hours daily. To completely prevent population growth of dust mite, RH must be maintained below 35 % for at least 22 hours per day when the daily RH is 75 % or 85 % for the remainder of the day.

For both indoor climate assessment and determination of hygrothermal design loads, long-term field measurements in dwellings can be used. In the cross-sectional study of the Finnish housing stock between November 1988 and April 1989 Ruotsalainen et al. (1992) reported that the average temperature in the bedrooms was approximately 22 °C (range 18 °C…27 °C), slightly but significantly higher in the apartment than in the houses. In half of the dwellings, the mean temperature was between +21 °C and +23 °C. The RH ranged from 21 % to 65 %. In 60 % of the dwellings, the mean RH was between 30 % and 40 %. The air change rate was between 0.2 ach and 0.7 ach in the majority of the dwellings. The average air change rate in detached houses was 0.45 ach. Inspections and measurements in over 1100 residential buildings during winter 1991-1992 in Sweden (Norlén and Andersson 1993) showed that indoor temperature was on average +20.9 °C in single-family houses and +22.2 °C in multi-family buildings and had increased by 0.5 °C during the last decade. More than one-third of all the apartments in multi-family buildings had the RH lower than 30 %, and in one-fifth of the single-family houses, the RH during the winter season was over 45 %. In four out of five single-family houses and in about half the apartments in multi-family buildings, ventilation did not came up to the that time normative value: 0.35 l/(s·m^2). Ventilation was the poorest in dwellings with passive stack ventilation. According to measurements by Gustavsson et al. (2004) conducted in 390 dwellings (83 % were detached houses) in Sweden over the period from October 2001 to April 2002 (for a week in each home), the mean temperature was +20.9 °C. The air change rate in all the dwellings was 0.37 1/h and in detached houses, it was 0.36 l/h. Only about 20 % of detached houses and about 40 % of multi-family houses had a ventilation degree that fulfilled the 0.5 ach. Jenssen et al. (2002) measured 32 dwellings of different types in Norway from November 2000 until March 2002. The mean values of temperatures in bedrooms and living rooms were +23.5±4.3 °C and +21.4±2.3 °C, respectively. The mean values of the RH in bedrooms and living rooms were 40.0±8.4 % and 28.7±6.0 %, respectively. Janssens and Vandepitte (2006) and Vandepitte (2006) measured 39 various types of dwellings (18 social houses, 17 private single family houses of moderate size and 4 single family houses with a swimming pool) all over Belgium (60% built in the 1980's, and 40% built after 1990) over the period from December 2002 to April 2005. The average indoor temperature was during winter period +18.1±1.9 °C and during summer period +24.5±2 °C. The temperature in bedrooms was particularly low. At outside temperatures of 0 °C, the daily mean bedroom temperature was smaller than +16 °C in 50% of the houses and even smaller than +12 °C in 5 % of the houses. The measurements also revealed uncomfortably hot conditions in part of the bedrooms during summer. In current study, long-term data from Estonian and Finnish dwellings are reported.

2.4 Indoor humidity loads

In a cold climate, indoor humidity by volume normally exceeds the outdoors value. If the envelopes are protected from driving rain, the major humidity load to the building envelope is usually the outgoing moisture flows due to air exfiltration or vapour diffusion through the building envelope. After the construction process, the drying out of construction time moisture, especially in the case of massive and hygroscopic constructions, may also be a notable moisture source. To design building envelopes for the humidity load during the service period, it is necessary to know the critical values of the difference between indoor and outdoor humidity by volume (referred to as moisture excess in this thesis and papers IV and VIII according to the prEN ISO 13788:2001, and moisture supply in papers III and VII according to the EN ISO 13788:1997). Moisture excess is also referred to in the literature as the moisture, humidity or vapour increase or –increment, the moisture balance or the moisture addition.

In most studies that have analyzed indoor hygrothermal loads, the indoor climatic data are measured for a particular short period, while outdoor climatic data are retrieved from a meteorological station. To assess sufficient critical loads during different seasons, measurements over a year are necessary. To show the possible influence of ventilation systems and envelope assemblies, these different variables should be ascertained by measurements. When the outdoor climatic data are retrieved from meteorological stations, the possible differences in the microclimate around the building might not be taken into account. The overview of the indoor humidity load studies is given in Table 2.2.

Table 2.2 The overview of the indoor humidity load studies

Reference	Measurement time	Rooms and country measured	Average moisture excess
Van der Kooi and Knorr (1973)	February to August 1967, average measuring time was 6 h	One office building and five small dwellings in the Netherlands	from +2 to +3 g/m^3
Hens (1992)	1974 and 1992, in winter and summer (3 weeks to 6 months periods)	Living rooms, kitchens, bedrooms, and bathrooms in about fifty social housing units in Belgium	Winter ~+5 g/m^3 in day zones (living rooms and kitchens) and ~+2 g/m^3 in night zones (bedrooms)
Tolstoy (1993)	Winter 1991–1992	1500 dwelling units in more than 1100 buildings in Sweden	Single-family houses +3.6±0.1 g/m^3 (from +2 to +5 g/m^3).
Rodriguez et al. (2000)	1995 and 1999.	Domestic dwellings in Spain	+1.8 g/m^3 (from +0.3 to +3.1 g/m^3)
Jenssen et al. (2002)	November 2000 to March 2002 7-day period in each dwelling from	32 dwellings of different types in Norway: detached single-family houses, terraced houses with 1–5 apartments, semi-detached 2 and 4 family houses, and apartment buildings	Bedrooms: +1.3±0.8 g/m^3 Living rooms +1.9±0.8 g/m^3
Gustavsson et al. (2004)	October 2001 to April 2002, a week per house	Living rooms and children's bedrooms in 390 dwellings in Sweden	+2.3 g/m^3 (from 0 to +6 g/m^3)
Rose and Francisco (2004)	November 2001 to April 2002	Bedrooms, family rooms, and basements in 15 buildings (31 dwellings) in the USA	+2.2 g/m^3
Janssens and Vandepitte (2006), Vandepitte (2006)	December 2002 to April 2005.	18 social houses, 17 private single family houses of moderate size and 4 single family houses with a swimming pool	Living rooms: +2.3 g/m^3 (<+5°C), +0.3 g/m^3 (>+15°C); Bedrooms: +2.1 g/m^3 (<+5°C), +0.4 g/m^3 (>+15°C).

In hygrothermal simulations, indoor hygrothermal loads are defined differently. Burch and Saunders (1995) made a computer analyzes of wall constructions for the Moisture Control Handbook. The indoor temperature was assumed to be +21 °C and indoor RH of 35 % and 50 %. Hourly outdoor climatic data were obtained from ASHRAE WYEC weather data. Burch et al. (1997) analyzed moisture and heat transfer in the roof cavities. During the heating period, constant indoor temperature +20 °C was used. The indoor RH was permitted to vary and was calculated from a moisture balance of the whole building with effective leakage area and the indoor moisture production rate, 10.9 kg/m^3, serving as inputs. During the summer, the set-point temperature +24 °C and *RH* 56 % was used. Krus (1998) made hygrothermal calculations to analyze the influence of the water-repellent surfaces on the drying of the natural stone materials. Indoor climate was determined with a sinus function with a RH of 50±10 % for the medium humidity load with its maximum on the 15th of August. The indoor temperature varied from +20 °C with its maximum on the 3 rd of June. In outdoor climate calculations, a year that represented typical conditions was used. Geving (1997B) presented a general systematic method for the hygrothermal analyzes of building constructions by the use of simulation models. The indoor air temperature was set as a constant value at +21 °C, while the moisture excess was assumed to be normally distributed: AVG=3.3 g/m^3 and standard deviation=1.0 g/m^3. Rode and Rasmussen (1999) analyzed the hygrothermal behaviour of envelope assemblies with alternative insulation materials with the Danish reference year and constant indoor temperature +21 °C and moisture excess +3.0 g/m^3. Levin and Gudmundsson (2000) made simulations to analyze moisture conditions in walls with an air barrier but open to moisture diffusion with moisture excess +2 and +4 g/m^3. Beaulieu et al. (2002) made simulations to develop the guidelines for moisture management strategies applicable to low-rise wood-frame exterior wall systems in North America at constant indoor temperature +22 °C and *RH* 25 % (when mean monthly outdoor temperature was lower than +11 °C) to summer values of +25 °C, *RH* 55 % for the warmer months.

In addition, standards handle indoor hygrothermal loads differently. On the basis of buildings in Western Europe, EN ISO 13788 (2001) standard sets five humidity classes: very low (storage), low (offices, shops), medium (dwellings with low occupancy), high (dwellings with high occupancy, sports halls, kitchens, canteens, buildings heated with gas), very high (special buildings, e.g. laundry, brewery, swimming pool). For the monthly mean outdoor temperature below ±0 °C, moisture and vapour excess rises at 2 g/m^3 and 270 Pa step from 0 to 8 g/m^3 and 0 to 1080 Pa. At temperatures above +20 °C, no difference in moisture excess exists between indoor climate classes. Between outdoor temperatures ±0 °C…+20 °C, linear interpolation should be made to determine the moisture- or vapour excess. In the standard proposal (TC 89 WI 29.3 2002), mainly the same principle is presented to determine internal humidity loads. Only during the warm period (T_{out}>+20 °C), there is a constant vapour excess +100Pa in all climate classes. In the latest version of this standard (prEN 15026:2006), indoor humidity is not provided any more by vapour or moisture excess. A simplified approach is given to determine the indoor temperature and humidity for heated buildings (only dwellings and offices). The indoor temperature and RH depend directly on the daily mean outdoor temperature. Indoor temperature is +20 °C, when the outdoor temperature is below +10 °C and indoor temperature is +25 °C, when the outdoor temperature is above +20 °C. Between outdoor temperatures +10 °C and +20 °C, indoor temperature increases linearly from +25 °C to +20 °C. RH is given for two humidity levels: normal occupancy and high occupancy. Indoor RH is 30 %, when the outdoor temperature is below -10 °C and indoor RH is 60 %, when the outdoor temperature is above +20 °C in normal occupancy cases. In high occupancy cases, the indoor RH is 10 % higher. Künzel et al. (2003) referred to a similar principle from Künzel (1997), where measurements were between outdoor temperature -11 °C and +26 °C from 10 houses. The working draft of the new ASHRAE SPC 160P (2004) standard gives also a simplified method to determine indoor design parameters from the daily mean outdoor temperature. Indoor temperature is +21.1 °C, when outdoor temperature is below +18.3 °C and indoor temperature is +23.9 °C, when outdoor temperature is above +21.1 °C. Between outdoor temperature +18.3 °C and +21.1 °C, indoor temperature increases linearly from +21.1 °C to +23.9 °C. Indoor RH is 40 %, when outdoor temperature is below -10 °C and indoor RH is 70 %, when outdoor temperature is above +20 °C. The German standard DIN 4108-3 (2001) specifies climatic parameters for the so-called Glaser calculations (Glaser 1959) for the condensation period: temperature -10 °C, *RH* 80 % and indoor climatic parameters: +20 °C and *RH* 50%. This corresponds to the moisture excess Δv +6.7 g/m^3.

These references show clearly differences in the definition of indoor climate for hygrothermal simulations. It is evident that the use of different boundary conditions will also influence the results.

2.5 Critical values for the temperature factor to assess thermal bridges

Almost all building envelopes have thermal bridges - locations where the thermal resistance of the assembly is locally lower. Thermal bridges are caused mainly by geometrical or structural reasons. In cold climates, the assessment of thermal bridges is important for many reasons. Thermal bridges may lead to surface condensation, mould growth, and staining of surfaces. Due to lower temperatures on the thermal bridge, higher RH occurs. While surface condensation starts at the *RH* 100%, the limit value for RH in respect of mould growth is above *RH* 75% to 90% depending on the groups of materials, as shown in Table 2.1. Thermal bridges lead to an increase of heat losses. An increase in the thermal insulation level will increase the relative significance of the thermal bridges in the energy consumption of buildings. If there exist large poorly insulated or uninsulated areas of the envelopes, the surfaces will be cold in the winter and may cause thermal comfort problems due to cold draughts or radiation (in particular, asymmetric radiation).

To accomplish the building design process and the inspection of the thermal bridges with infrared thermography in real buildings, knowledge of the critical level of the thermal conductance of the thermal bridge is required. The IEA project Annex 14 (Hens 1990) has proposed to use the temperature factor method to assess the thermal bridges. It is the responsibility of each individual country to establish the design values of the temperature factor. The principle of the temperature factor is attached also to the EN ISO 13788:2001 standard. The temperature factor at the internal surface ($f_{\mathrm{R.si}}$, -) shows the relation of the total thermal resistance of the building envelope (R_{T}, (m^2·K)/W) to the thermal resistance of the building envelope without the internal surface resistance (R_{si}, (m^2·K)/W) and it depends on the internal (T_{i}, °C) and the external (T_{e}, °C) air temperature and on the temperature on the internal surface of the building envelope (T_{si}, °C), see Eq. 2.1. The temperature factor is also referred to in the literature as the temperature ratio, temperature index, or condensation resistance factor.

$$\frac{R_T - R_{si}}{R_T} = f_{\mathrm{Rsi}} = \frac{T_{si} - T_e}{T_i - T_e} \qquad (2.1)$$

In many countries, limit values or guidelines are set for the temperature factor. These limit values are reviewed in Table 2.3

Table 2.3 Limit values for the temperature factor values

Country	Reference	Temperature factor	Limiting criteria
Belgium	BBRI 1984	≥ 0.7 (normal dwellings)	avoiding condensation
Finland	Asumisterveysohje 2003	≥ 0.61 (thermal bridge) ≥ 0.65 (thermal bridge)	health hazard building law min. req.
France	Berthier 1980	> 0.52 (Δv 2.5…5g/m^3)	avoiding condensation
Germany	DIN 4108-2:2001	> 0.7 (T_{in}+20°C, RH_{in} 50 %, T_{out} -5 °C)	avoiding mould growth
Netherlands	NEN 2778:1991	≥ 0.65 (new residential buildings, new hotels)	
	Adan 1994	>0.73	fungal growth
Sweden	Thorsell 2002	≥0.63 (dwellings) ≥0.80 (high occupancy)	mould growth
Switzerland	SIA-180:1999	≥ 0.75	
Poland	Wouters et al. 2003	0.769…0.811 (dwellings)	
Portugal	Wouters et al. 2003	0.642…0.826 (medium internal humidity class)	
United Kingdom	BRE IP 17/01	≥ 0.75 (residential buildings) ≥ 0.8 (kitchens)	mould growth surface condensation

3 METHODS

3.1 Outdoor climate used in this study

The main climatic boundary divides the territory of Estonia into two climatic areas (Kirde 1939 and 1943, Raik 1967, Karing 1992): the coastal area, which is directly influenced by the sea, and the inland area. The western island region, the West Estonian region, and the northern coastal region make up the coastal area. The North Estonian region and South Estonian region compose the inland area. The principal territorial differences in climate are due to the adjacent Baltic Sea. The boundary line between the two main climatic areas is shown in Figure 3.1.

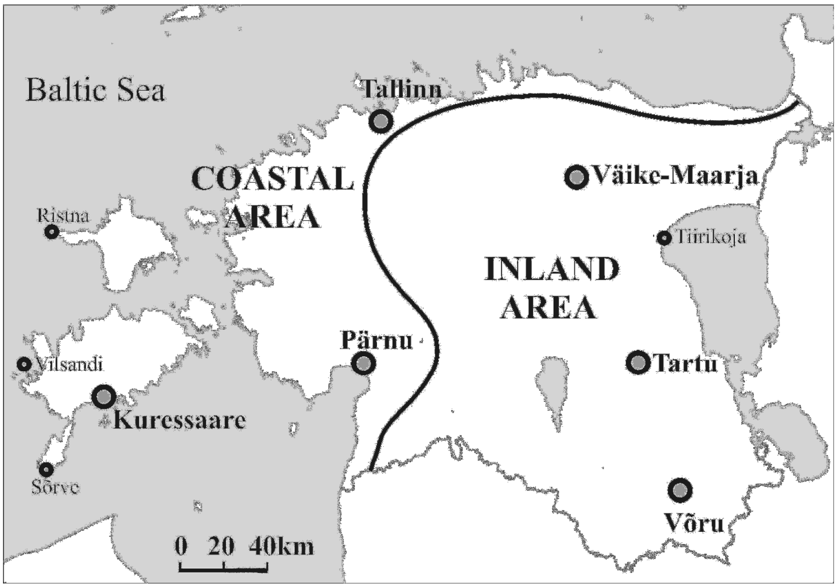

Figure 3.1 Climatic areas of the territory of Estonia. Meteorological stations whose data were used in the analyzes of this study are indicated by large dots

Six meteorological stations, three from both climatic areas, were selected for the analyzes. They were chosen according to climatic areas and the building density of the towns. Tallinn, Kuressaare, and Pärnu represent the coastal area and Tartu, Väike-Maarja, and Võru the inland area. Tallinn and Tartu have the highest rate of occupancy and building density in Estonia. Kuressaare represents the western island region and Pärnu the West Estonian region in the coastal area. Väike-Maarja represents Northeast Estonia and Võru represents the South Estonian highland region.

The World Meteorological Organization regards a thirty-year period sufficient to eliminate year-to-year variations. In this study, temperature, RH, and wind data at three-hour steps and global solar radiation at one-hour steps over the period from

1970 to 2000 were used. The Estonian Meteorological and Hydrological Institute (EMHI, http://www.emhi.ee) provided all climatic data. Locations of the meteorological stations are shown in Table 3.1.

Table 3.1 Locations of meteorological stations

Meteorological station	Longitude	Latitude	Altitude
Tallinn 1970-04.1980	N 59°25’	E 24°48’	39 m
Tallinn 05.1980-2000	N 59°23’54’’	E 24°36’15’’	33 m
Kuressaare	N 58°13’53’’	E 22°30’18’’	3 m
Pärnu	N 58°22’53’’	E 24°30’12’’	3 m
Tartu 1970-1997	N 58°18’	E 26°44’	62 m
Tõravere 1998-2000	N 58°15’50’’	E 26°27’42’’	70 m
Väike-Maarja	N 59°08’27’’	E 26°13’52’’	120 m
Võru	N 57°50’46’’	E 27°01’10’’	82 m

There were some deficiencies in the climatic data. For instance, no data were available in Kuressaare during a 34-month period at 00 and 03 hour for temperature and RH and in Pärnu during a seven-month period at 00, 03, and 06 temperature and RH data. In these cases, linear interpolation was used to substitute missed data. No temperature and RH data were available in Võru during a two-month period. In this case, the 30 year-period was used instead of the 31-year period for data of June and August.

In Tartu, episodic measurements of solar radiation were carried out already in the early 20th century and in the 1930s. Complete measurements of solar radiation in the Tartu-Tõravere meteorological station began in 1965. The direct normal radiation and diffuse radiation (one minute averages and daily totals) are measured directly, from where global radiation is calculated (Russak and Kallis 2003).

3.2 Methods to select outdoor climate for hygrothermal calculations

Critical years for hygrothermal calculations were chosen in regard to risk of water vapour condensation and risk of mould growth. Critical years were selected independently of the construction response, using air temperature and RH data. A 10 % critical level was used to select the outdoor climate for hygrothermal calculations. Using this definition, only 10 % of years would be defined as critical, whereas the remaining 90% of years would fall below the defined threshold or criterion chosen for selecting the critical year.

Critical years do not correspond exactly to calendar years, but more critical periods for hygrothermal analyzes usually occur in autumn, winter, and spring. Therefore, a moisture reference year beginning in July and ending at the end of June is selected because in the studied climate the risks for water vapour condensation and mould growth are minimal in summer and start to increase thereafter.

The critical year for the risk of water vapour condensation analyzes has been selected on the basis of the saturation deficit, $\Delta v_{sat.def}$, [g/m^3]. The background of this method is similar to the Π-factor method described in Chapter 2.1.1. The saturation deficit is defined as the difference between the absolute humidity by volume at saturation, v_{sat} [g/m^3], of the outdoor air, having a temperature T_{out} [° C] and absolute humidity by volume of the outdoor air v_{out} [g/m^3] over a given time period (see Eq. 3.1).

$$\Delta v_{sat.def} = \frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} (v_{sat}(T_{out}) - v_{out}) dt = \overline{v_{sat}(T_{out}) - v_{out}} \tag{3.1}$$

The saturation deficit describes also the drying potential of building envelope to outdoor air. When it is small, the potential for a wet assembly to dry out is low. When it is larger, the potential of the building envelope to dry out is higher. The average value of saturation deficit was calculated for winter months, December, January, and February that is the most critical period for moisture condensation in Estonia. As Figure 3.2 shows, the saturation deficit is at its lowest level during these months.

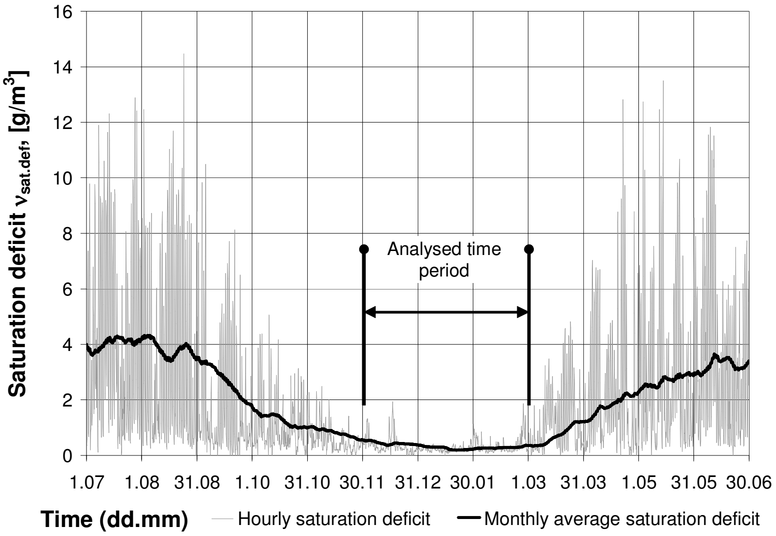

Figure 3.2 Saturation deficit values for the year: Väike-Maarja 1995-96

The mathematical model of mould growth (Hukka and Viitanen 1999) was used to select the critical year for risk of mould growth. In this study, daily average temperature and RH data were used for calculating the mould index *M*. The wood species was pine and original surface quality was kiln-dried. This is the typical construction wood material in Estonia that also yields the highest mould index value. The favourable temperature range for mould growth is ±0 °C…+50 °C, and the critical RH required for initiation of mould growth is a function of temperature and can be described by a polynomial function (Hukka and Viitanen 1999), Eq. 3.2 and Figure 3.3. Mould growth is indexed on the visual appearance of the growing surface, Table 3.2. The explanation, how the mould index *M* is calculated is described in more detail in paper I.

$$RH_{\mathrm{crit}} = \begin{cases} -0.00267\,T^3 + 0.160\,T^2 - 3.13\,T + 100 & ,when\ T \le 20\,^\circ C \\ 80\% & ,when\ T > 20\,^\circ C \end{cases} \qquad (3.2)$$

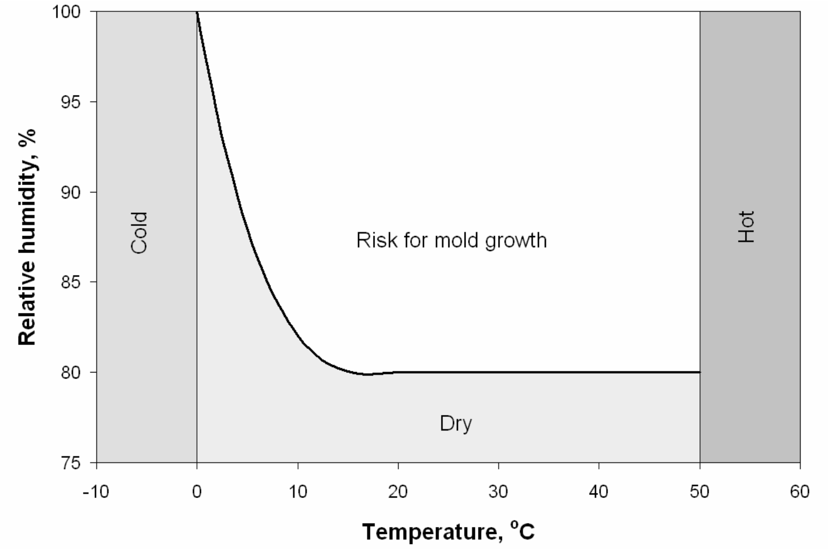

Figure 3.3 Conditions favourable for the initiation of mould growth on a wooden (spruce and pine) material as a mathematical model (Eq. 3.2)

Table 3.2 Indexes to describe mould growth rate

Index *M*, -	Mould growth rate
0	No growth, spores not activated;
1	Minor growth detected only by microscopy, initial stages of hyphae growth;
2	Moderate growth detected by microscopy (coverage of hyphae more than 10 %-25% of the analyzed surface);
3	Some growth detected visually, new spores produced;
4	Clear visually detected growth (visually detected coverage more than 10 % of the analyzed surface);
5	Plenty of visually detected growth (visually detected coverage more than 50% of the analyzed surface);
6	Very heavy and tight growth (visually detected coverage more than 100% of the analyzed surface).

To cope with present lack of knowledge of mould model behaviour during the freezing period, the maximum value of the mould index was taken from the period before the continuous freezing period started and possible higher values of the mould index during spring were not taken into account. To reduce the effect of fast daily temperature and humidity variations, 24 h. time step was chosen for input data to the mould growth model.

For each year, the lowest average saturation deficit during the winter period (for critical year of the risk of water vapour condensation) and the highest mould index (for critical year of mould growth risk) were calculated. From this data (each year was represented by one value), the 10 % critical years (90 % or 10 % level from cumulative distribution function) were selected for both selection criteria.

3.3 Methods to select outdoor climate for energy analyzes

In this study, the ISO 15927-4:2005 method was used to construct the test reference year (TRY). The primary selection was made on the basis of DBT, GSR, and water vapour pressure (WVP). The wind speed (WSP) was used for secondary selection. As GSR data were obtained only from Tartu (not measured at other selected stations), the months to the TRY were selected from this meteorological station. To guarantee that the selected TRY covers the whole Estonian climate as completely as possible, temperature and humidity from all six meteorological stations over 31 years are represented in the reference long-term data.

For each climatic parameter p, daily mean values were calculated. For each calendar month, the cumulative distribution function $\Phi_{(p,m,i)}$ of daily means throughout all the years in the data set was calculated. For each year of the data set, the cumulative distribution function $F_{(p,y,m,i)}$ of the daily means within each calendar month was calculated. For each calendar month, the FS statistic (Finkelstein-Schafer 1971) $FS_{(p,y,m)}$ for each year of the data set was calculated:

$$FS_{(p,y,m)} = \sum_{i=1}^{n} \left| F_{(p,y,m,i)} - \Phi_{(p,m,i)} \right| \text{, where} \tag{3.3}$$

$FS_{(p,y,m)}$	is the Finkelstein-Schafer statistic for parameter p in month m in year y;
$F_{(p,y,m,i)}$	is the cumulative distribution function of daily mean values for a month m in year y;
$\Phi_{(p,m,i)}$	is the cumulative distribution function of daily mean values for the same month m taken through all the years of the data set considered.

The monthly average FS statistic values of each climate parameter (DBT, GSR, WVP) were summed up and the same months of all the years were ranked in order of increasing size of FS statistic. From each calendar month, three candidate months with the lowest total ranking were selected. The monthly deviation of the wind speed (WSP) of the three months was compared with the corresponding multi-year mean of calendar months. The month with the lowest deviation in WSP was selected as the best month for inclusion in the TRY.

For a simplified estimation of heating energy, the average number of heating degree-days was calculated from long-term data for six locations. The duration of the heating season was not taken into account, i.e. the calculation was not stopped when the outdoor temperature rose above +12 °C in spring or was higher than +10 °C in autumn, as is the case with some old heating degree-day calculation methods. It was taken into account that modern heating systems are available on demand and long heating season breaks are not common any more in a cold climate. The number of heating degree-days per year, S_{Tin}, was calculated as the sum of the differences between the indoor temperature and the daily average outdoor temperature; see Eq. 3.4.

$$S_{T_{in}} = \sum_{i=1}^{n} (T_{in} - T_{d,out})^{+} \text{ , where} \tag{3.4}$$

T_{in}	is the indoor temperature;
$T_{\mathrm{d,out}}$	is the daily average outdoor temperature of the day i;
$^{+}$	indicates that only positive values are summed;
n	is the total number of days in the year.

3.4 Measurements in dwellings

To study the indoor climate and hygrothermal loads in dwellings, the field measurements were carried out in 128 lightweight timber-frame detached houses occupied by single–families in Estonia (mainly close to Tallinn region) and in Finland (mainly close to Tampere and Helsinki region). The houses were randomly selected from the databases of the manufacturing and construction companies. The houses were relatively new, built, on average, four years prior to the measurements. The studied houses had three different types of ventilation systems: passive stack ventilation (referred to as natural ventilation in this study), mechanical exhaust ventilation and the mechanical supply and exhaust ventilation (referred to as balanced ventilation in this study). In all of the studied rooms, windows were available for airing purposes.

To study the hygrothermal loads in dwellings with higher occupancy, measurements were carried out in a small control group: in 13 apartments. All the apartments were supplied with the natural ventilation (passive stack ventilation and window airing) in all apartments.

Table 3.3 shows the main characteristic of the studied dwellings.

Table 3.3 Main characteristic data of the measured dwellings

	Estonian detached houses, n=27	Finnish detached houses, n=101	Estonian apartments, n=13
Measurement period	April 2003 … July 2005	July 2002 … June 2004	Dec. 2005… April 2006
Floor area	135 m^2	153 m^2	55 m^2
Volume	344 m^3	386 m^3	136 m^3
Occupancy	46 m^2/person	43 m^2/person	17 m^2/person
Envelope air leakage rate at 50 Pa	4.2 $m^3/(h \cdot m^2)$ 4.9 1/h	4.0 $m^3/(h \cdot m^2)$ 3.9 1/h	6.7 1/h
Ventilation rate	0.41 ach 13 $l/(s \cdot pers.)$, 0.28 $l/(s \cdot m^2)$	0.38 ach 13 $l/(s \cdot pers.)$, 0.26 $l/(s \cdot m^2)$	

The values of temperature and RH were measured with data loggers at one–hour intervals from inside and outside the building over a one-year period (in apartments over a four-month period). The indoor loggers were located on separating walls in bedrooms and living rooms. The outdoor loggers were located on the north façade, protected from direct solar radiation and driving rain. The measured temperature range of the data logger (Delta Ohm HD226) in the Estonian study was between -30 °C...+80 °C with an accuracy of ±0.3 °C…±0.4 °C, while the RH measurement range was between 5 %…98 % with an accuracy of *RH* ±2.5 %. In the Finnish study, the measured temperature range of the data logger (Comark N2003) was between -20 °C…+60 °C with an accuracy of ± 0.5 °C, while the RH measurement range was between 0 %...97 % with an accuracy of *RH* ±3 %. If we consider an accuracy of the temperature measurements ±0.35 °C and an accuracy of the RH measurements ±2.5 % average indoor climate conditions we obtain the maximum error from ±0.5 g/m^3 (at -25 °C) to ±1.6 g/m^3 (at +25 °C). The accuracy of the loggers was checked before and after both measurement years. As in the Finnish study after the second measurement year, the measuring accuracy of almost all outdoor data loggers was below the acceptable level, for the second measurement year, the outdoor climate was retrieved from the nearest weather station.

The exhaust air flow rates were measured with anemometers SwemaFlow 233 (in Estonia) and AirFlow LCA 6000 VA (in Finland). The supply air flow rates were measured with an anemometer (SwemaFlow 233 + foldable capture) and a manometer (TSI Micromanometer).

In the Finnish study, in addition to instantaneous measurements in 74 houses, the air change rates were measured using a homogenous constant emission (passive) method (Nordtest, 1997).

Small perfluorocarbon tracer gas (PFT) samplers were distributed in the house (7-13 samplers pre house depending on house volume and number of rooms). The tracer gas was continuously released at a constant rate to the room air. Passive diffusion samplers were placed in each room to sample tracer gas at steady state room air concentration. Measurement period in each house lasted three weeks.

After the sampling period, the samplers were capped and sent by mail to the laboratory for analysis. The inaccuracy of the PFT-method is approximately ±15…20%.

The air leakage of each house and apartment was measured with the standardized (EN 13829:2000) fan pressurization method, using Minneapolis Blower Door Model 4 equipment with an automated performance testing system (flow range at 50 Pa 25 m^3/h – 7800 m^3/h, accuracy ±3 %). Depending on the purpose, air tightness measurements were taken under three different conditions. To determine the air leakage of the building envelope, depressurizing and pressurizing tests were conducted. All the exterior openings: windows and doors were closed; ventilation ducts and chimneys were sealed. Measurements were made at 10 Pa pressure difference step from 0 Pa to 60 Pa. To estimate the natural infiltration rate in Estonian houses with natural ventilation and in houses with mechanical exhaust ventilation, a third series of tests were conducted. These tests were made with normally opened passive fresh air inlets, opened window airings and sealed ventilation exhaust ducts under negative indoor pressure conditions. To compare different buildings, the air flow rate at the pressure difference 50 Pa was divided by the internal volume of the building (result n_{50} value) or by the external envelope area (resulting air leakage rate at 50 Pa).

A questionnaire was completed for each house and apartment, where the building characteristics, used building materials, type of HVAC systems and its use, occupants' habits, typical complaints and symptoms related to indoor air quality, etc. were interviewed from occupants acting as contact persons of the study. For purposes of comparison, similar questionnaires were used in Estonian and in Finnish studies.

3.4.1 Assessment of indoor climate and indoor humidity loads

Assessment of indoor climate was done according to the Estonian standard of the indoor climate (EVS 839:2003) and to the Finnish classification of the indoor climate (FiSIAQ 2001). Both references set the target values for three categories: A, B, C in EVS 839:2003 and S1, S2, S3 in FiSIAQ 2001. For the indoor climate studies, the lowest and average categories were chosen to compare the results. Table 3.4 shows the target values for the indoor temperature and RH.

The Estonian indoor climate standard does not set any limits for indoor temperature level during summer in category C, when the outdoor temperature is higher than +22 °C. In categories A and B, indoor temperature may exceed limit values by +5 °C if the outdoor temperature is higher than +22 °C. If the outdoor temperature during winter is below the rated temperature, the indoor temperature may also be below the normative value.

Finnish indoor climate classification sets the upper limit for the indoor temperature during summer in category S3 +35 °C when the outdoor temperature is above +15 °C. Room temperature may temporarily deviate from the designed temperatures for a maximum of seven days of the designed weather conditions. As categories S2 and S3 do not specify RH values, the range from 20 % to 60 % was used as a criterion for the acceptable RH.

Table 3.4 Target values for the indoor temperature and RH

	Estonia (EVS 839:2003)		Finland (FiSIAQ 2001)	
	Summer	Winter	Summer	Winter
	Temperature, °C			
A and S1	24-25	21-23	23-24	21-22
B and S2	23-26	20-24	23-26	20-22
C and S3	22-27	19-25	22-27	20-23
	RH, %			
A and S1	30-70	25-45	-	25-45
B and S2	30-70	25-45	-	-
C and S3	30-70	25-45	-	-

The values of the moisture excess Δv (the difference between the indoor and outdoor air's absolute humidity, Eq. 3.5) were calculated on the basis of the measured results of the indoor and outdoor temperatures and RH. Absolute humidity values were averaged for weekly average values.

$$\Delta \nu = \nu_i - \nu_e , \tag{3.5}$$

where $\Delta \nu$ indicates the moisture excess [g/m^3], ν_i humidity by volume of the indoor air [g/m^3] and ν_e humidity by volume of the outdoor air [g/m^3].

On the basis of the dependence of moisture excess on the outdoor temperature, frequency distributions of moisture excess during the cold period ($T_{out} \leq 5$ °C) were analyzed separately from other data ($T_{out} > 5$ °C). To analyze the dependence of the moisture excess on the outdoor temperature and to determine the critical moisture excess values, the data from each room were sorted according to the outdoor air temperature, using a 1 °C step of the outdoor temperature. From these sorted values, 10 % critical levels were calculated. On the basis of moisture excess and indoor temperature dependence on the outdoor temperature, the critical moisture excess levels are given for the cold period ($T_{out} \leq 5$ °C) and on the basis of the dependence of the indoor temperature on the outdoor temperature, the critical moisture excess levels are presented for the warm period ($T_{out} \geq 15$ °C).

On the basis of the air change rate during winter and the moisture excess during the cold period, the daily average moisture production G, [kg/day] was estimated in detached houses, Eq. (3.6):

$$G = q_v \cdot \Delta v, \tag{3.6}$$

where Δv indicates the moisture excess [kg/m^3], and q_v stands for the air change rate [m^3/day].

Moisture production was calculated from the measured air change rate during winter. The actual air change rates during summer were not known, because these depend on the use of window airing and infiltration. As the ventilation air change rate was measured for the whole building, the moisture excess values were the average values of the results of bedroom and living room measurements.

3.4.2 Method to determine critical values for the temperature factor for thermal bridge analyzes

To determine the critical value of the temperature factor for thermal bridge analyzes, the outdoor climate was retrieved from six weather stations (Tallinn, Kuressaare, Pärnu, Tartu, Väike-Maarja, and Võru), covering a 31-year period, from 1970 to 2000. The critical temperature factor value was calculated for two internal moisture excess levels with two indoor temperature models, Figure 3.4. The average temperature model with moisture excess on a 10 % higher critical level corresponded best to the measured indoor RH values on a 10 % higher critical level (Figure 4.18). Temperature on a 10 % lower level was 2 °C lower than the average temperature. As there were many rooms where the average temperature was on average 2 °C lower than the average temperature of all the houses, the critical temperature factor analyzes was done also with the indoor temperature on a 10 % lower critical level. Moisture excess model: +4 g/m^3 during the cold period, +1.5 g/m^3 during the warm period represents a humidity load in houses with low occupancy. The moisture excess model: +6 g/m^3 during the cold period and +2.5 g/m^3 during the warm period was chosen to represent a higher living density in apartments. As suggested in EN ISO 13788:2001, the values of the moisture excess were multiplied by 1.1.

The values of the critical temperature factor f_{Rsi} were selected according to the mould growth and surface condensation criterion. For each location, each year and each month, the maximum temperature factors were calculated (daily average values for surface condensation criteria and monthly average values for mould growth criteria). This means that for the temperature factor values below the critical temperature factor value, mould growth or surface condensation will not occur in 90 % of the cases. It means that 10 % of the monthly maximum values would be defined as critical, whereas the remaining 90 % of the monthly maximum values would fall below the critical temperature factor value.

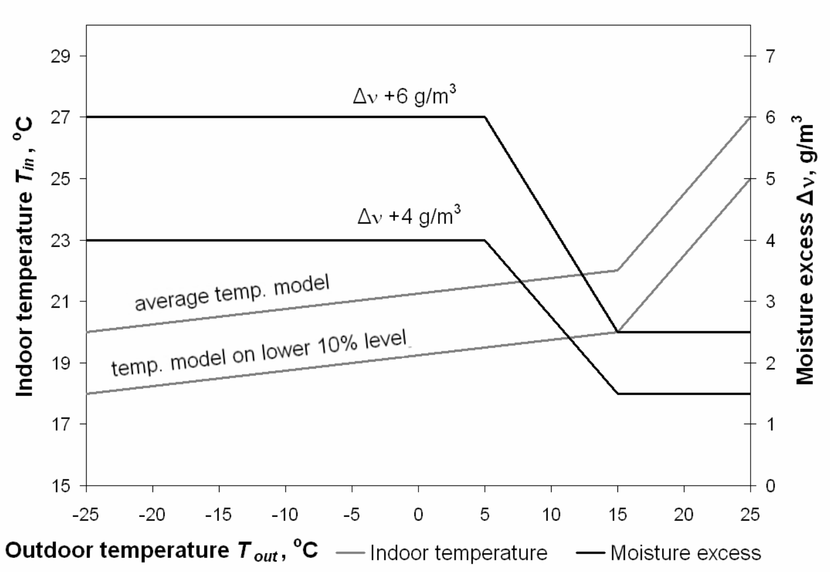

Figure 3.4 The indoor climate models used to determine the critical value of the temperature factor

In the selection according to the mould growth criterion, the average monthly absolute indoor humidity was calculated from the outdoor temperature and humidity, using the above-mentioned dependences between the outdoor temperature and the internal moisture excess models (Figure 3.4). With the maximum acceptable RH at the thermal envelope surface RH_{si} 80 %, the maximum acceptable absolute humidity was calculated, followed by the calculation of the minimum acceptable surface temperature. Using this minimum acceptable surface temperature, the outdoor temperature, and the indoor temperature, the minimum temperature factor was calculated according to Eq. 2.1. The calculation procedure employed for selecting the critical temperature factor to avoid surface condensation, was the same, only the daily average climate values and the maximum acceptable RH at the thermal envelopes surface RH_{si} 100 % were used. For each location, each year and each month, the maximum temperature factor was calculated. From this data (each month was represented by one temperature factor value), the higher 10 % critical level was calculated. The determined design values of the temperature factor were rounded to the upper 0.00 or 0.05 value.

4 RESULTS

4.1 Outdoor climate for hygrothermal calculations

Critical years for hygrothermal calculations were chosen in I. The risks of water vapour condensation and mould growth were chosen for criterions. The critical year for the risk of water vapour condensation analyzes was selected on the basis of the saturation deficit during winter months. The mathematical model of mould growth was used to select the critical year for the risk of mould growth. Selected years are mainly for the hygrothermal performance assessment of vapour diffusion and moisture convection in building envelopes.

Figure 4.1 shows average values of the saturation deficit over the winter months and Figure 4.2 presents annual maximum mould index values in different stations over a 30-year period from 1970 to 2000. We can see deviation between the years of the same location and also deviation between locations during the same year. It means that if hygrothermal calculations or field measurements are made on the basis of some arbitrary year, climatic data should be compared with the reference year and this should be taken into account when interpreting the results.

A 10 % critical level (10 % and 90 % level from the cumulative distribution function) was used to select the year for hygrothermal calculations. The distribution of the cumulative percentage of saturation deficit values is shown in Figure 4.3. Väike-Maarja had the coldest winters and the highest RH. This symbiosis resulted in the lowest saturation deficit during the winter period. The maritime climate in Kuressaare resulted in the highest saturation deficit during the winter period. Distributions of the cumulative percentages of mould index values are shown in Figure 4.4. Võru and Tartu that are located in the inland area and Pärnu show lower values, on average, but the curve for Võru also rises at lower percentage values. Tallinn, Kuressaare in the coastal area, and Väike-Maarja show higher mould index values on average.

The 10 % percentile critical year for the risk of water vapour condensation is in Väike-Maarja from July 1995 to June 1996. The same year from Jyväskylä was selected also for the Finnish critical year for the risk of water vapour condensation (Vinha and Kalamees 2003). The 10 % percentile critical year for the risk of mould growth is in Väike-Maarja from July 1989 to June 1990 (maximum mould index M=2.3). The monthly average data of temperature and RH of these critical years for the hygrothermal calculation are shown in Figure 4.5 and in Table 4.1. The winter of the critical year for the risk of water vapour condensation is much colder and longer than the critical year for the risk of mould growth (average temperature of winter months -9.3 °C versus -2.1 °C). The period from August to end of November in the critical year for the risk of mould growth is more humid than in the critical year for the risk of water vapour condensation (monthly average *RH* 88 % versus *RH* 84 %, rainfall 308 mm versus 278mm).

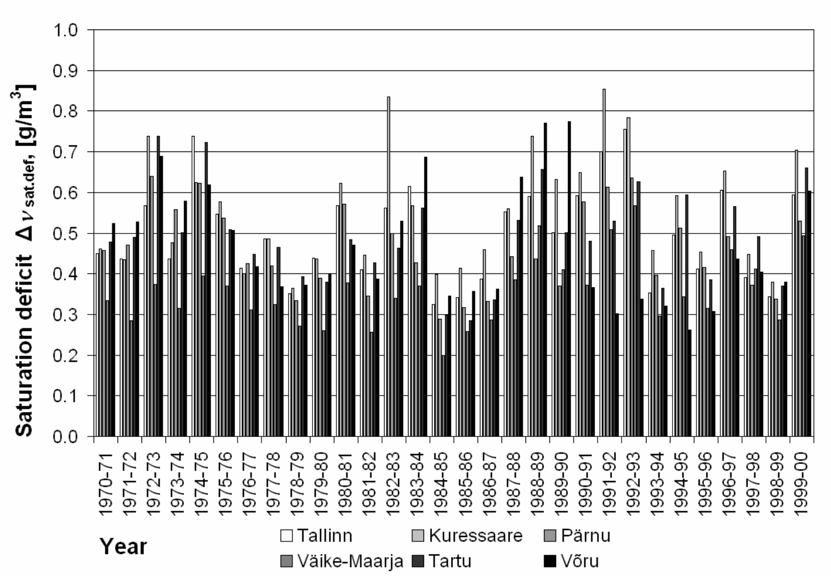

Figure 4.1 Average saturation deficit values in winter months of the analyzed period: from 1970 to 2000

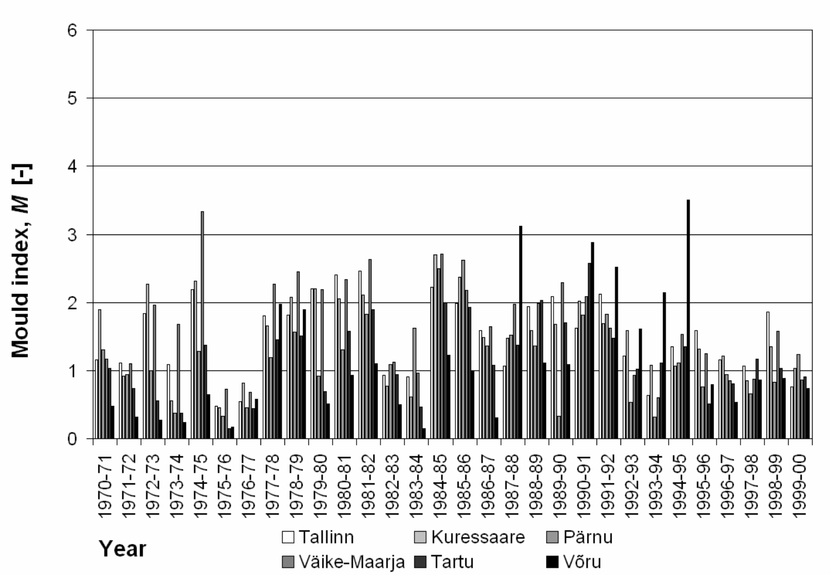

Figure 4.2 Annual maximum mould index values of the analyzed period: from 1970 to 2000

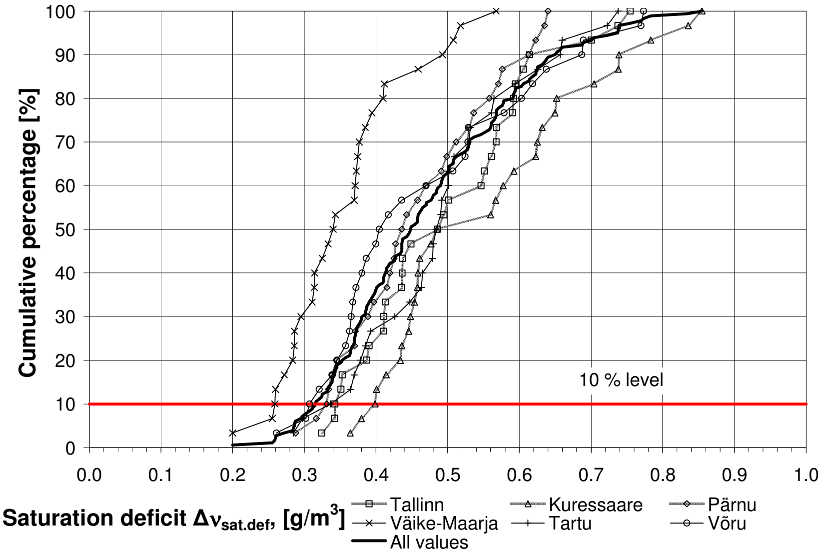

Figure 4.3 Cumulative percentage of saturation deficit of winter month averages in the analyzed period: from 1970 to 2000

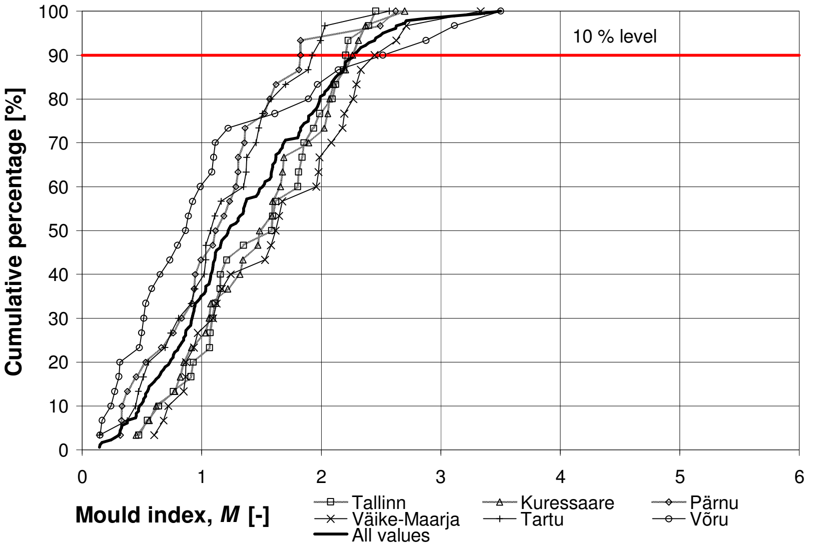

Figure 4.4 Cumulative percentage of mould indexes in the analyzed period: from 1970 to 2000

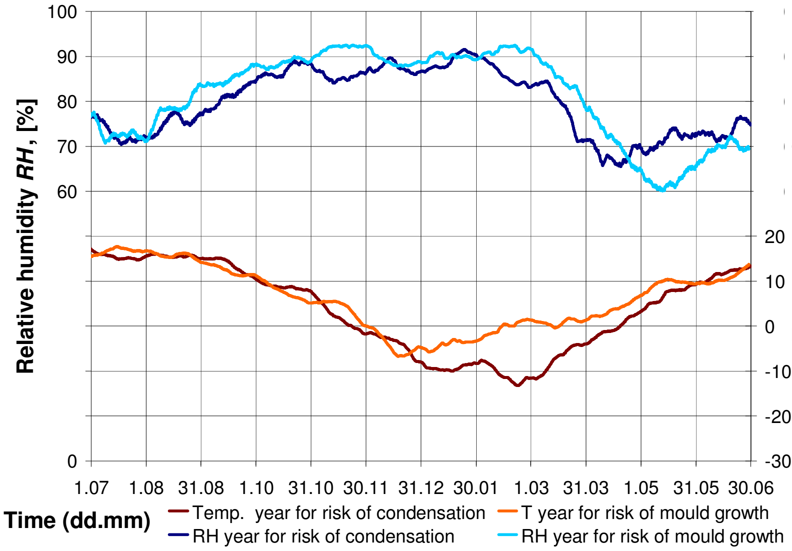

Figure 4.5 Monthly running average temperature and RH data of the critical year for the risk of water vapour condensation: Väike-Maarja 1995-96 (darker lines) and the critical year for the risk of mould growth: Väike-Maarja 1989-90 (lighter lines)

Table 4.1 Monthly running average climatic data of the critical year for the risk of water vapour condensation: Väike-Maarja 1995-96 and the critical year for the risk of mould growth: Väike-Maarja 1989-90

Month	Air temperature (monthly avg.) °C		Relative humidity (monthly avg.) %		Wind speed (monthly avg.) m/s		Rainfall intensity (monthly sum.) mm	
	1995-1996	1989-1990	1995-1996	1989-1990	1995-1996	1989-1990	1995-1996	1989-1990
Jul	+15.4	+16.7	72	71	4	3	68	83
Aug	+15.1	+14.2	77	84	3	4	81	125
Sep	+10.4	+11.2	85	89	3	3	54	41
Oct	+7.6	+5.2	88	89	4	4	80	87
Nov	-1.8	0.0	86	92	4	5	62	55
Dec	-7.9	-4.7	87	89	3	5	28	40
Jan	-8.3	-3.1	90	90	3	5	8	62
Feb	-11.8	+1.4	83	91	4	6	28	94
Mar	-3.9	+1.4	72	79	3	5	12	63
Apr	+3.4	+6.9	69	65	3	4	25	11
May	+9.4	+9.5	73	65	4	4	73	31
Jun	+13.3	+13.8	75	70	3	3	43	31
Avg.	+3.5	+6.0	80	81	4	4	562	772

4.2 Outdoor climate for indoor climate and energy simulations

In indoor climate and energy simulations, outdoor temperature, humidity and solar radiation play the most important role. For natural ventilation and infiltration simulations, also wind speed and directions are important. The Estonian TRY is selected in II. As indoor climate and energy simulations are made with typical outdoor data, the TRY selected represents maximum possible long-term average outdoor climate and consists of typical months from a number of different years.

The primary selection of typical months was made on the basis of temperature, global solar radiation, and water vapour pressure, using 31-year data from all six weather stations (6×31-year). Years were ranked according to the FS statistic value for each month. In Tables 4.2-4.4, five years with the lowest FS statistic value are shown. Bold numbers show three months with the lowest FS statistic value, when monthly average FS statistic values of temperature, humidity, and solar radiation were summed up.

In the final selection of the month of the TRY, wind speed (WSP) was involved. WSP of three months (the lowest total rankings are shown by bold numbers in Tables 4.2-4.4) was compared with the WSP data from the corresponding multi-year calendar month. The month with the lowest deviation in WSP was selected as the best month for inclusion in the TRY. Table 4.5 shows the main climatic parameters of the month selected for the TRY and the average data over a 31-year period from the six meteorological stations (wind and radiation data are only from Tartu). Figure 4.6 shows the monthly average temperature and RH data for the TRY (each month is from a different year; see Table 4.5).

Table 4.2 Temperature selections for the TRY

Rank	Selected years											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Long-term data: six meteorological stations, 31 years											
1.	**1988**	1987	1994	**1995**	**1985**	1981	**1982**	1975	1981	1999	**1990**	**1979**
2.	1999	**1988**	1993	1982	**1977**	**1974**	**1970**	**1971**	**1982**	1981	1976	**1980**
3.	**1994**	**1973**	**1973**	1971	**1982**	1998	1971	**1990**	**1998**	**1990**	1972	**1983**
4.	1984	**1991**	1978	1977	1976	2000	1981	1995	1997	**1983**	**1989**	1993
5.	2000	1972	1972	**1993**	1987	1984	1995	1999	1980	1987	1974	1994

Table 4.3 Humidity selections for the TRY

Rank	Selected years											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Long-term data: six meteorological stations, 31 years											
1.	**1988**	1987	1993	**1970**	1987	**1974**	**1982**	1989	1983	**1983**	**1989**	**1980**
2.	1999	1972	**1973**	**1995**	**1977**	1991	1999	1979	1980	1977	**1990**	**1983**
3.	**2000**	**1973**	**1999**	1975	**1985**	**1983**	1986	1970	1970	1999	1972	**1979**
4.	1994	**1991**	1994	1972	1989	1997	1990	2000	**1991**	**1990**	1976	1999
5.	1984	**1988**	1977	1977	1990	**1984**	**1991**	**1971**	**1998**	1982	**1999**	1991

Table 4.4 Solar radiation selections for the TRY

Rank	Selected years											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Long-term data: Tartu, 31 years											
1.	**1997**	**1988**	**2000**	1986	**1985**	2000	1987	1972	1976	2000	**1989**	1977
2.	1992	1993	**1973**	1991	1999	1973	1976	1976	**1982**	1978	1994	1981
3.	1977	1982	1986	1982	1981	1978	1992	**1982**	**1991**	1993	1983	1974
4.	1995	1977	1977	176	1974	1977	**1982**	1991	1977	**1991**	1996	1975
5.	**1994**	**1991**	**1999**	1978	2000	1971	1980	**1990**	1983	1984	**1999**	1970

Table 4.5 (I) Monthly average (AVG), daily minimum (MIN) and daily maximum (MAX) values of the climatic parameters for the Estonian TRY and average data over a 31-year period (1970-2000)

Month	Year	Air dry bulb temperature (monthly avg.) °C						Relative humidity (monthly avg.) %						Wind speed (monthly avg.) m/s					
		TRY			1970-2000			TRY			1970-2000			TRY			1970-2000		
		AVG	MIN	MAX	**AVG**	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX
Jan	1994	**-3.0**	-14.3	+3.2	**-4.5**	-34.4	+6.1	**90**	80	98	**87**	39	100	**5**	2	8	**4**	0	12
Feb	1991	**-5.2**	-12.5	+3.8	**-5.1**	-29.1	+8.7	**89**	79	97	**85**	42	100	**4**	1	8	**4**	0	11
Mar	1973	**-0.1**	-10.9	+8.5	**-1.4**	-20.7	+11.6	**76**	58	93	**81**	30	100	**4**	1	8	**4**	0	11
Apr	1970	**+4.0**	-0.8	+12.9	**+4.2**	-7.8	+20.3	**77**	50	94	**75**	38	100	**4**	1	7	**4**	1	10
May	1977	**+11.2**	+5.4	+19.3	**+10.6**	-0.2	+23.7	**70**	46	98	**68**	32	99	**4**	1	7	**3**	1	9
Jun	1984	**+14.1**	+8.5	+18.5	**+14.9**	+3.6	+26.1	**73**	56	90	**73**	37	99	**3**	2	5	**3**	1	9
Jul	1991	**+17.2**	+13.9	+21.0	**+16.9**	+9.1	+26.1	**77**	67	91	**76**	47	99	**3**	1	6	**3**	0	9
Aug	1990	**+15.7**	+11.6	+22.0	**+15.8**	+7.1	+25.6	**81**	57	97	**79**	47	99	**3**	1	6	**3**	0	10
Sep	1982	**+10.8**	+4.2	+16.2	**+10.8**	-0.3	+24.2	**82**	70	96	**83**	44	100	**4**	1	7	**3**	0	10
Oct	1990	**+5.8**	+0.5	+11.0	**+6.0**	-7.8	+17.0	**87**	64	99	**85**	43	100	**4**	1	9	**4**	0	10
Nov	1989	**-0.1**	-11.6	+7.7	**+0.9**	-19.2	+10.8	**91**	81	97	**88**	42	100	**4**	1	9	**4**	1	10
Dec	1979	**-2.5**	-11.9	+7.4	**-2.6**	-36.2	+8.3	**86**	61	96	**89**	46	100	**5**	2	8	**4**	0	11
Avg		**+5.7**			**+5.6**			**81**			**81**			**4**			**4**		

Table 4.5 (II)Monthly average/sum (AVG/SUM), daily minimum (MIN) and daily maximum (MAX) values of the climatic parameters for the Estonian TRY and average data over a 31-year period (1970-2000)

Month	Year	Direct norm. radiation (monthly sum.) MJ/m^2						Diff. radiation on hor. surf. (monthly sum.) MJ/m^2						Enthalpy (monthly avg.) kJ/kg					
		TRY			1970-2000			TRY			1970-2000			TRY			1970-2000		
		SUM	MIN	MAX	SUM	MIN	MAX	SUM	MIN	MAX	SUM	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX
Jan	1994	**35.0**	0.0	8.66	**61.3**	0.0	18.2	**39.2**	0.60	2.51	**36.2**	0.16	2.77	**4.0**	-12	14	**1.8**	-34	20
Feb	1991	**93.4**	0.0	14.9	**126.2**	0.0	27.1	**82.0**	1.26	5.15	**78.3**	0.61	5.82	**0.7**	-10	16	**0.8**	-29	25
Mar	1973	**308.1**	0.0	29.0	**265.6**	0.0	34.4	**144.2**	2.39	7.34	**151.9**	1.07	9.55	**7.3**	-9	20	**5.7**	-20	24
Apr	1970	**254.4**	0.0	35.7	**346.9**	0.0	38.1	**190.2**	2.39	9.38	**203.7**	1.21	13.9	**14**	6	32	**14**	-5	41
May	1977	**493.3**	0.0	38.7	**538.2**	0.0	44.8	**269.6**	4.01	12.4	**262.2**	2.30	14.7	**26**	14	44	**24**	6	57
Jun	1984	**497.8**	1.42	43.7	**544.3**	0.0	48.5	**306.1**	4.98	14.3	**281.5**	2.64	15.4	**33**	18	45	**34**	12	70
Jul	1991	**606.1**	0.0	41.9	**520.3**	0.0	47.6	**290.8**	5.11	13.4	**283.6**	1.92	14.6	**41**	31	49	**40**	23	62
Aug	1990	**453.6**	0.0	39.1	**423.4**	0.0	40.0	**229.7**	2.79	11.6	**230.9**	1.00	13.0	**38**	28	47	**38**	19	60
Sep	1982	**259.0**	0.0	30.5	**267.8**	0.0	38.2	**161.3**	2.27	9.40	**148.8**	1.12	9.40	**28**	16	38	**28**	7	53
Oct	1990	**143.8**	0.0	19.7	**164.4**	0.0	28.5	**82.9**	0.70	5.03	**82.9**	0.26	7.24	**19**	7	30	**19**	-4	44
Nov	1989	**68.2**	0.0	15.0	**58.4**	0.0	19.9	**37.0**	0.42	2.30	**36.1**	0.13	3.27	**9**	-9	23	**10**	-18	28
Dec	1979	**49.7**	0.0	10.5	**39.6**	0.0	12.3	**20.8**	0.09	1.07	**23.5**	0.09	1.74	**5**	-9	22	**4.7**	-36	23
Avg		**271.9**			**279.7**			**154.5**			**152.2**			**19**			**18**		

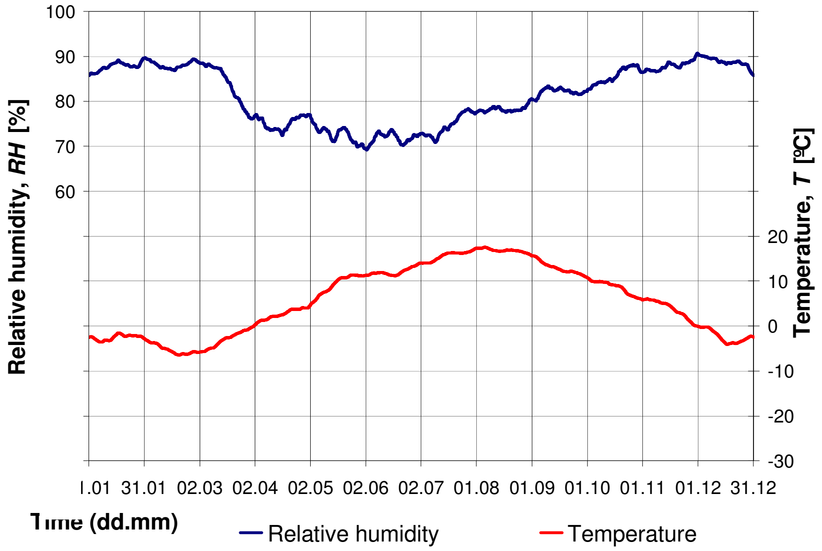

Figure 4.6 Monthly running average temperature and RH data of the TRY

After the selection of the twelve calendar months for the TRY, the months should be joined together. The first and the last eight hours of each month should be adjusted by smoothing them with a cubic splined curve. The adjustment also includes the last eight hours of December and the first eight hours of January, so that the TRY can be used repeatedly in simulations. Because wind direction and wind velocity change considerably during each day, these climatic elements are not smoothed. Neither is solar radiation, which is zero at midnight, not smoothed.

The annual average numbers of heating degree-days (S_{Tin}) for some indoor temperatures are shown in Table 4.6. 31-year average data and the selected TRY are given as well. The monthly average numbers of heating degree-days at indoor temperature +21° C and average outdoor temperatures are shown in Table 4.7.

Table 4.6 The annual average number of heating degree-days S_{Tin} for some indoor temperatures T_{in}

Meteorological	S_{Tin}							
station	$S_{15°\mathrm{C}}$	$S_{16°\mathrm{C}}$	$S_{17°\mathrm{C}}$	$S_{18°\mathrm{C}}$	$S_{19°\mathrm{C}}$	$S_{20°\mathrm{C}}$	$S_{21°\mathrm{C}}$	$S_{22°\mathrm{C}}$
Tallinn	3604	3918	4249	4589	4940	5294	5656	6016
Kuressaare	3316	3625	3950	4288	4635	4990	5349	5711
Pärnu	3472	3760	4075	4404	4745	5093	5448	5808
Tartu	3700	3998	4330	4653	5009	5349	5718	6067
Väike-Maarja	3936	4256	4588	4929	5279	5634	5994	6357
Võru	3620	3920	4234	4561	4898	5243	5609	5952
31-year average	3608	3913	4238	4571	4917	5267	5629	5985
TRY	3528	3804	4160	4470	4850	5177	5568	5903

Table 4.7 The monthly average number of heating degree-days, $S_{21°C}$ and outdoor temperatures T_{out} [° C]

	Meteorological station															
	Tallinn		Kures-saare		Pärnu		Tartu		Väike-Maarja		Võru		31-year average		TRY	
	$S_{21°C}$	T_{out}	$S_{21°C}$	T_{out}	$S_{21°C}$	T_{out}	$S_{21°C}$	T_{out}	$S_{21°C}$	T_{out}	$S_{21°C}$	T_{out}	$S_{21°C}$	T_{out}	$S_{21°C}$	T_{out}
Jan	776	-4.0	725	-2.4	775	-4.0	817	-5.9	832	-5.3	815	-5.3	790	-4.5	743	-3.0
Feb	728	-4.8	693	-3.6	724	-4.7	754	-6.4	772	-5.7	746	-5.4	736	-5.1	732	-5.2
Mar	692	-1.3	681	-1.0	684	-1.1	697	-2.4	724	-1.5	682	-1.0	693	-1.4	654	-0.1
Apr	517	+3.8	523	+3.6	503	+4.2	489	+3.5	525	+4.7	474	+5.2	505	+4.2	511	+4.0
May	349	+9.7	342	+10.0	308	+11.1	310	+10.0	341	+11.0	294	+11.5	324	+10.6	304	+11.2
Jun	200	+14.4	195	+14.5	169	+15.5	178	+14.3	202	+15.1	165	+15.6	185	+14.9	206	+14.1
Jul	140	+16.6	132	+16.8	112	+17.5	131	+16.2	152	+16.9	120	+17.3	131	+16.9	117	+17.2
Aug	169	+15.6	145	+16.4	140	+16.5	167	+14.9	191	+15.6	157	+15.9	162	+15.8	165	+15.7
Sep	309	+10.7	272	+11.9	284	+11.6	317	+9.7	339	+10.4	308	+10.7	305	+10.8	306	+10.8
Oct	463	+6.1	430	+7.3	446	+6.6	479	+4.8	502	+5.6	471	+5.8	465	+6.0	471	+5.8
Nov	597	+1.1	546	+2.8	586	+1.5	623	-0.4	643	+0.2	620	+0.3	602	+0.9	632	-0.1
Dec	715	-2.1	665	-0.4	716	-2.1	757	-3.9	773	-3.4	756	-3.4	730	-2.6	727	-2.5
Annual avg.	5656	+5.5	5349	+6.3	5448	+6.0	5718	+4.5	5994	+5.3	5609	+5.6	5629	+5.6	5568	+5.7

4.3 Indoor temperature and humidity conditions in dwellings

Indoor temperature and RH conditions are analyzed in V, VI, VII to study the indoor climate in the measured dwellings that are basis for the determination of indoor hygrothemal loads.

4.3.1 Outdoor climate during the measurements

Temperature and RH measurements were carried out during 2002-2005 in Estonia and in Finland. In detached houses, measurements lasted for one year in each house. There was a one–month pause of measurements during summer when the data loggers were placed in new houses. Measurements in apartments lasted for four month. The average monthly outdoor temperature and RH during the two measurement years in detached houses are shown in Table 4.8.

Table 4.8 Average monthly outdoor temperature and RH during the measurement period in Estonia and in Finland

Estonia	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May
Temperature, °C												
2003–04	+14.2	+20.9	+17.2	+12.9	+5.5	+4.3	+1.4	-5.3	-2.5	+0.8	+5.7	+11.1
2004–05	+13.3	+16.3	+16.9	+12.6	+6.4	+1.2	+0.8	-0.5	-4.8	-5.7	+3.7	+9.4
RH, %												
2003–04	75	79	81	85	89	98	94	95	93	91	69	72
2004–05	76	78	79	87	85	86	92	92	86	74	71	69

Finland	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June
Temperature, °C												
2002-03	+19.9	+19.3	+10.9	+0.3	-3.1	-8.7	-10.2	-5.8	-1.1	+2.8	+10.4	+13.3
2003-04	+20.5	+16.1	+11.6	+3.5	+0.8	-1.0	-7.0	-5.0	-1.4	+4.6	+10.2	+12.6
RH, %												
2002-03	74	71	78	84	96	95	94	95	83	71	72	69
2003-04	74	76	80	87	95	90	90	88	86	60	64	66

4.3.2 Indoor temperature and humidity conditions during the summer seasons

Indoor temperature and humidity conditions were analyzed separately during the summer and the winter season in two measurement years. Analyzes of the all data resulted in the indoor temperature model and moisture excess curves.

In Estonia, the analyzed summer season lasted for three summer months: during the first measurement year, between 01.06…31.08.2003 and during the second measurement year, between 01.07…31.08.2004 and 01.06…30.06.2005. In Finland, the analyzed summer season was during the first measurement year, between 01.07…10.09.2002 and during the second measurement year, between 04.07…25.08.2003. The beginning of the analyzing period was chosen when measurements in all the houses were started and the end was taken when outdoor temperatures began to decrease.

Average values of the temperature, RH and humidity by volume during summer seasons divided into subdivisions according to the ventilation systems are shown in Table 4.9 (Estonian houses) and in Table 4.10 (Finnish houses). Average values and the distributions of indoor climate values between other subdivisions are described in detail in papers V, VI and VII and in reports (Vinha et al. 2005 and Kalamees 2005).

Table 4.9 Average values of the temperature (T), RH and the humidity by volume (ν) and their standard deviations during summer seasons in Estonian detached houses

	Summer season: 01.06.03…31.08.03						Summer season: 01.07.04…31.08.04 01.06.05…30.06.05					
	12 houses, 22 rooms						15 houses, 17 rooms					
	T	δT	RH	δRH	ν	$\delta\nu$	T	δT	RH	δRH	ν	$\delta\nu$
	°C		%		g/m^3		°C		%		g/m^3	
Natural vent.	+22.9	0.3	62^{A}	6	12.7^{C}	1.2	+23.4	1.9	54	6	12.2	0.6
Exhaust vent.	+23.3	1.6	56^{B}	9	11.6^{D}	1.0	+23.5	1.0	55	2	10.8	0.7
Balanced vent.	+24.2	1.2	$49^{A,B}$	2	$10.8^{C,D}$	0.4	+23.8	1.4	51	7	10.9	1.3
All data	+23.4	1.4	56	8	11.6	1.1	+23.6	1.4	53	5	11.0	0.9

$^{A; B; C, D}$ The difference is significant, $P < 0.05$

Table 4.10 Average values of the temperature (T), RH and the humidity by volume (ν) and their standard deviations during summer seasons in Finnish detached houses

	Summer season: 01.07.02…10.09.02						Summer season:07.07.03…25.08.03					
	46 houses, 78 rooms						50 houses, 97 rooms					
	T	δT	RH	δRH	ν	$\delta\nu$	T	δT	RH	δRH	ν	$\delta\nu$
	°C		%		g/m^3		°C		%		g/m^3	
Natural vent.	+24.2	1.0	52	5	11.4	0.5	+24.4	1.2	53	4	11.8	0.5
Exhaust vent.	+24.7	0.8	50	6	11.3	0.4	+24.8	1.1	51	6	11.7	1.1
Balanced vent.	+24.6	1.0	51	5	11.4	0.4	+25.0	1.1	51	3	11.9	0.5
All data	+24.6	0.9	51	3	11.3	0.4	+24.9	1.1	51	4	11.8	0.7

The average indoor temperature during the summer seasons in Estonian detached houses was +23.5 °C (min. average being +21.0 °C and max. average +25.7 °C) and the average indoor RH was 55 % (min. average being 43 % and max. average 72 %). The average indoor temperature during the summer seasons in Finnish detached houses was +24.8 °C (min. average being +22.2 °C and max. average +28.5 °C) and the average indoor RH was 51 % (min. average being 34 % and max. average 60 %). All the temperature and humidity measurement results in measured detached houses during summer seasons are also shown in Figure 4.7, Figure 4.8, and Figure 4.9.

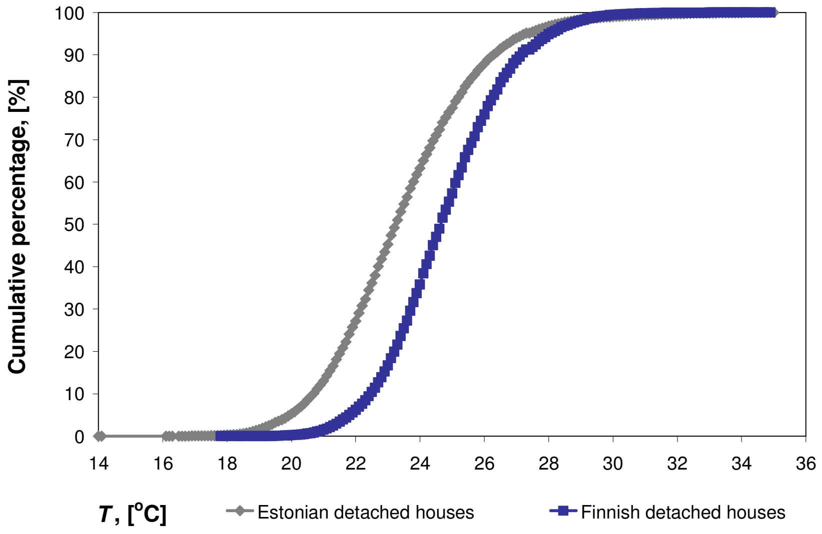

Figure 4.7 Distribution of the hourly indoor temperatures during two summer seasons in Estonian (39 rooms) and Finnish (175 rooms) detached houses

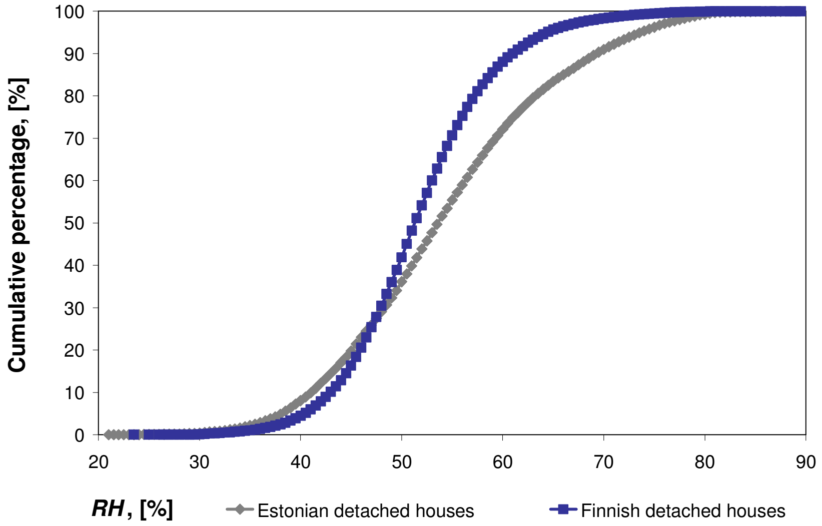

Figure 4.8 Distribution of the hourly indoor RH during two summer seasons in Estonian (39 rooms) and Finnish (175 rooms) detached houses

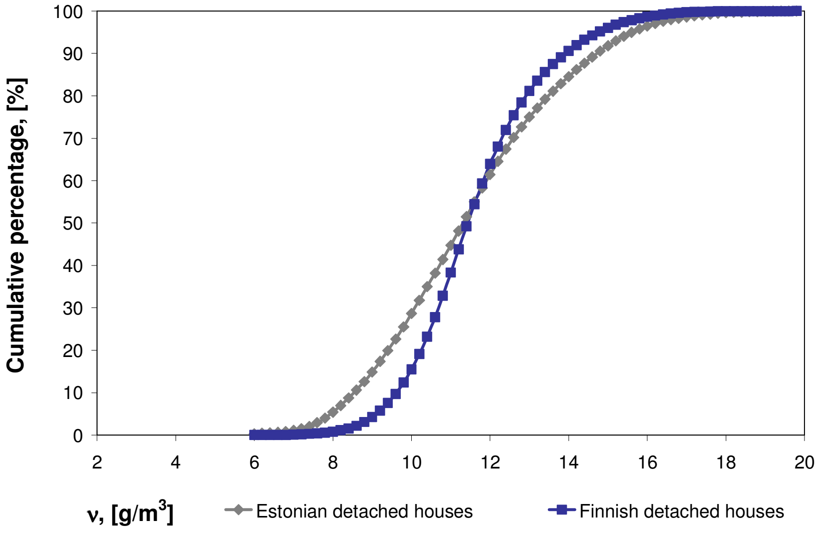

Figure 4.9 Distribution of the hourly indoor humidity by volume during two summer seasons in Estonian (39 rooms) and Finnish (175 rooms) detached houses

In the Estonian study during summer, only 13 % of the rooms (with 5 % excess) met the requirements of the temperature in indoor climate category C. During winter, only 18 % of rooms met the requirements of the temperature in indoor climate category B and the requirements of indoor climate category C were met by 45 % of the rooms (with 5 % excess).

4.3.3 Indoor temperature and humidity conditions during the winter seasons

The winter season analyzed in the measured houses lasted for three winter months: from the beginning of December to the end of February. Average values of the temperature, RH and humidity by volume during winter seasons in subdivisions according to the ventilation systems are shown in Table 4.11 (Estonian detached houses and apartments) and Table 4.12 (Finnish detached houses). Average values and the distributions of indoor climate values in detached houses between other subdivisions are described in detail in papers V, VI and VII and in reports (Vinha et al. 2005 and Kalamees 2005).

Table 4.11 Average values of the temperature (T), RH and the humidity by volume (v) and their standard deviations during winter seasons in Estonian detached houses and apartments

	Winter season: 01.12.03…29.02.04 12 house, 22 rooms			Winter season: 01.12.04…28.02.05 15 house, 17 rooms			Winter season: 01.12.05…28.02.06 13 apartments, 13 rooms		
	T, °C	RH, %	ν, g/m^3	T, °C	RH, %	ν, g/m^3	T, °C	RH, %	ν, g/m^3
	δT	δRH	δν	δT	δRH	δν	δT	δRH	δν
Natural vent.	+20.7	32	5.7	+20.7	34^{A}	6.1^{B}	20.8	36	6.6
	1.1	6	0.8	3.3	7	0.8	1.8	8	1.3
Exhaust vent.	+21.5	32	5.9	+21.5	28^{A}	5.3^{B}			
	1.6	8	1.1	1.6	3	0.2			
Balanced vent.	+21.6	29	5.5	+21.2	34	6.3			
	1.9	3	1.0	1.4	9	1.6			
All data	+21.4	31	5.7	+21.1	32	5.9	20.8	36	6.6
	1.6	6	1.0	2.2	7	1.0	1.8	8	1.3

$^{A; B}$ The difference is significant, $P < 0.05$

Table 4.12 Average values of the temperature (T), RH and the humidity by volume (v) and their standard deviations during winter seasons in Finnish detached houses

	Winter season: 01.12.02…28.02.03 44 house, 78 rooms						Winter season: 01.12.03…29.02.04 50 house, 98 rooms					
	T	δT	RH	δRH	ν	δν	T	δT	RH	δRH	ν	δν
	°C		%		g/m^3		°C		%		g/m^3	
Natural vent.	+20.8	1.6	26	10	4.7	1.4	+21.4	1.6	28	3	5.1	0.6
Exhaust vent.	+22.0	1.4	23	6	4.5	1.2	+21.3	1.5	31^{A}	6	5.8	1.1
Balanced vent.	+21.7	1.4	23	4	4.3	0.6	+21.8	1.3	28^{A}	5	5.4	0.8
All data	+21.7	1.4	23	5	4.4	0.9	+21.6	1.4	29	5	5.5	0.9

^{A} The difference is significant, $P < 0.05$

The average indoor temperature during these winter seasons from all Estonian detached houses was +21.3 °C (min. average being +17.1 °C and max. average +26.1 °C) and the average indoor RH was 32 % (min. average being 23 % and max. average 48 %). The average indoor temperature during the winter seasons in Estonian apartments was +20.8 °C (min. average being +16.9 °C and max. average +23.2 °C) and the average indoor RH was 36 % (min. average being 28 % and max. average 56 %). The average indoor temperature during the winter seasons in Finnish detached houses was +21.6 °C (min. average being +16.9 °C and max. average +26.5 °C) and the average indoor RH was 26 % (min. average being 14 % and max. average 47 %). All the temperature and RH measurement results in the measured dwellings during winter seasons are shown in Figure 4.10, Figure 4.11, and Figure 4.12.

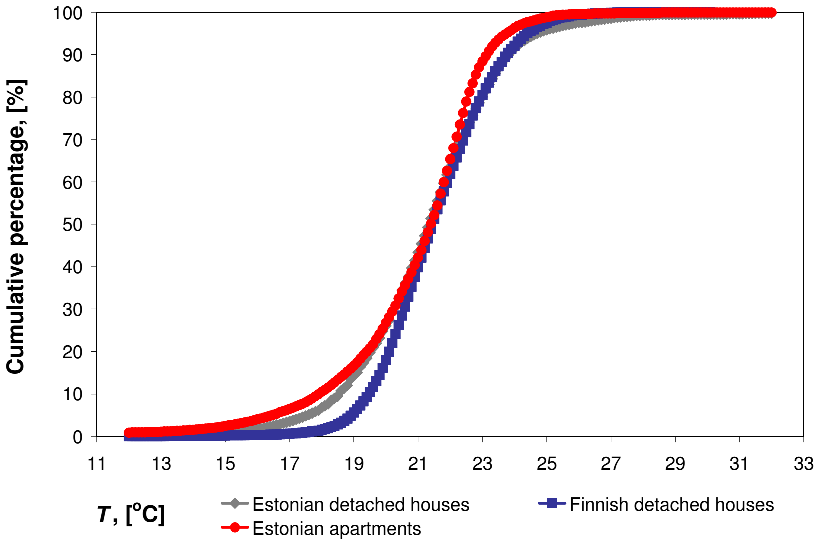

Figure 4.10 Distribution of the hourly indoor temperatures during winter seasons in Estonian (39 rooms in houses and 13 rooms in apartments) and Finnish (177 rooms) dwellings

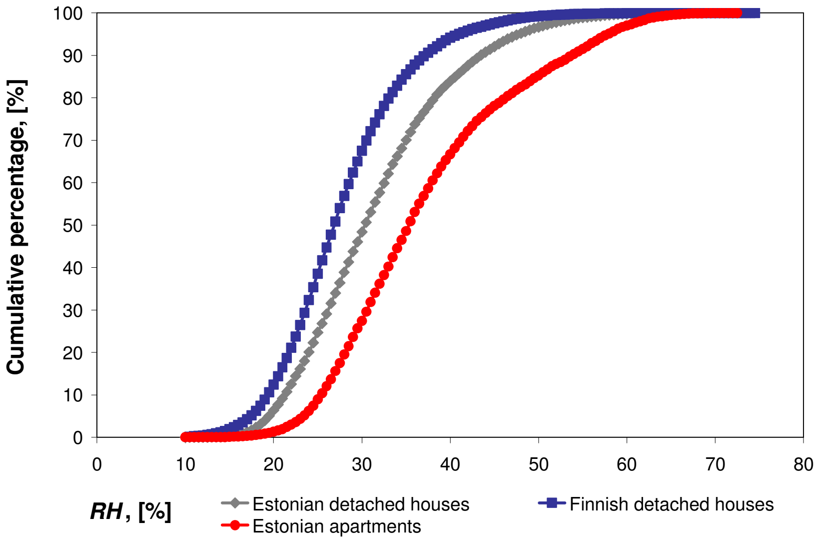

Figure 4.11 Distribution of the hourly indoor RH during winter seasons in Estonian (39 rooms in houses and 13 rooms in apartments) and Finnish (177 rooms) dwellings

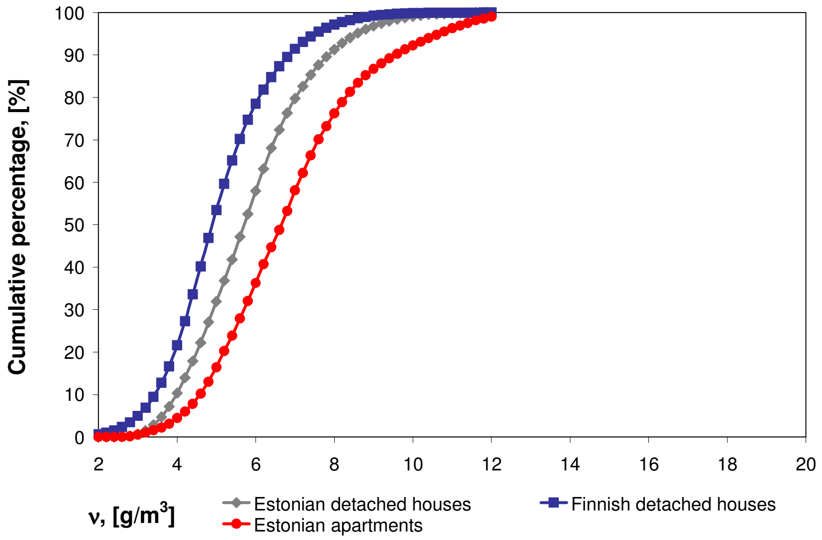

Figure 4.12 Distribution of the hourly indoor humidity by volume during winter seasons in Estonian (39 rooms in houses and 13 rooms in apartments) and Finnish (177 rooms) dwellings

In the Finnish study, during the first summer 19 % of the rooms and during the second summer only 2 % of the rooms remained below the higher limit of the indoor climate category S2. Thermal requirements of the indoor climate category S3 fulfilled 53 % of rooms during the first summer and 63 % of rooms during the second summer. During winter, the thermal requirements of the indoor climate category S3 fulfilled 2 % of rooms during the first winter and 4 % of rooms during the second winter.

4.3.4 Indoor temperature dependence on the outdoor temperature

Thermal comfort standards determine indoor conditions in buildings for winter (heating) and summer (cooling) seasons. The boundary line between these two seasons is not always well defined. For hygorthermal design, indoor temperature data should be more realistic, not just containing two temperature levels. In the following, the dependence of the indoor temperature on the outdoor temperature is analyzed, to determine a rough indoor temperature model for predicting indoor temperature directly from the mean outdoor temperature.

From each room at each average daily outdoor air temperature, all average daily indoor temperature values were selected. From all the indoor temperatures at the corresponding outdoor temperature, the average value was calculated, presented in Figure 4.13. Measurements in this study showed a dependence between the indoor temperature and the outdoor temperature. There is a turning point at +15 °C daily average outdoor temperature. Over +15 °C of average daily outdoor temperature, the slope of the indoor temperature is larger. Over +15 °C of average daily outdoor temperature, the indoor temperature reaching over +21…22 °C and heating is not necessary any more. These are two main factors, which may be interpreted that a heating season would change to the summer season at this +15 °C of average daily outdoor temperature in Estonian and Finnish dwellings.

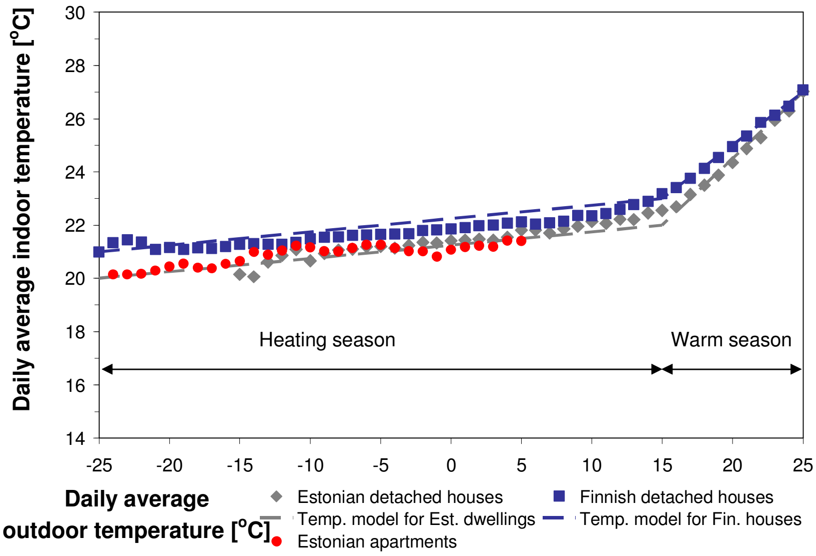

Figure 4.13 Dependence of average daily indoor temperature on the average daily outdoor temperature

The indoor temperature model proposed in the following is on the basis of the trend line of these curves. The average indoor temperature curve in Estonian detached houses rises from +20 °C (at T_{out} -25 °C) to +22 °C (at T_{out} +15 °C) in the heating season, reaching +27 °C (at T_{out} +25 °C) during summer. The indoor temperature model in Finnish detached houses is 1° C higher during the heating season. These indoor temperature models can be used in the indoor temperature calculations, where the indoor temperature is not generated by the room model of the simulation program.

4.4 Indoor humidity loads

Indoor humidity loads in dwellings are studied in III, VII and VIII. The moisture excess approach suits for calculations of the indoor humidity values with hygrothermal programs where the indoor climate is given by temperature and relative or absolute humidity values. In simulation programs intended for the whole building, where the room model calculates the indoor climate conditions, moisture production should be used as an input parameter. If moisture transfer in the structures is not simulated in those simulation programs, the daily moisture production profile should include also the possible smoothing effect of moisture buffering.

4.4.1 Internal moisture excess and moisture production

From each measured room moisture excess values were averaged over the cold period ($T_{\text{out}} \leq +5$ °C) and over the remaining time ($T_{\text{out}} > +5$ °C). Figure 4.14 shows the distribution of moisture excess in Estonian and in Finnish dwellings over the cold period and over the remaining time. The average value of weekly average moisture excess values from different rooms over the cold period in Estonian detached houses was +1.5 g/m^3 and over the remaining time +0.2 g/m^3 and in Finnish detached houses +1.8 g/m^3 and during the remaining time +0.5 g/m^3. In Estonian apartments during the cold period, the average value of the weekly average moisture excess was +3.2 g/m^3.

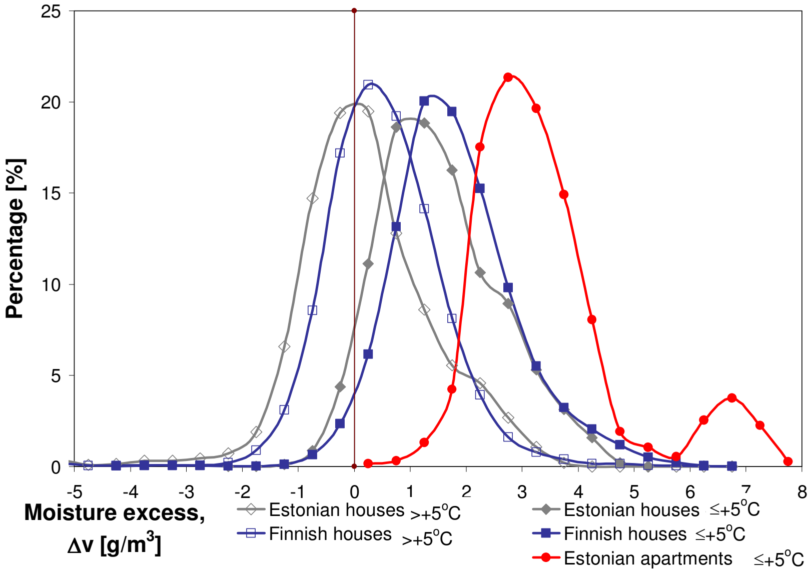

Figure 4.14 Distribution of the moisture excess values during the cold period ($T_{\text{out}} \leq +5$ °C) and during the rest of time ($T_{\text{out}} > +5$ °C)

The average values of moisture excess were compared between different subdivisions, see Table 4.13. In Estonian detached houses during the period when $T_{\text{out}} > +5$ °C, the moisture excess was significantly lower in houses with balanced ventilation compared to houses with exhaust ($P<0.02$) and natural ventilation ($P<0.04$). In Finnish detached houses, the moisture excess during the cold period was significantly lower in rooms with balanced ventilation compared to rooms with natural ($P<0.05$) and mechanical exhaust ventilation ($P<0.05$). During the rest of the time ($T_{\text{out}} > +5$ °C), balanced ventilation showed a markedly lower moisture excess ($P<0.003$) than natural ventilation.

Table 4.13 Average values of weekly average moisture excess during the cold period ($T_{out} \leq +5$ °C) and during the remaining time ($T_{out} > +5$ °C)

	Estonian detached houses		Finnish detached houses	
	$T_{out} \leq +5$ C	$T_{out} > +5$ °C	$T_{out} \leq +5$ °C	$T_{out} > +5$ °C
	AVG	AVG	AVG	AVG
Bedrooms	+1.6	+0.3	+1.9	+0.5
Living rooms	+1.4	+0.2	+1.7	+0.4
Natural ventilation	+1.6	+0.8*	+2.1*	+0.9**
Exhaust ventilation	+1.4	+0.2*	+2.0*	+0.5
Balanced ventilation	+1.6	-0.1*,*	+1.7*,*	+0.4**
≤3 occupants	+1.4	+0.2	+1.7	+0.4
>3 occupants	+1.6	+0.3	+1.8	+0.5

Significant difference: * $P < 0.05$;** $P < 0.01$;

To analyze the influence of different moisture excess components on the humidity load in Estonian detached houses, the houses with lower (<+1 g/m^3) and higher (>+2 g/m^3) average moisture excess during the cold period were compared. Detached houses with higher average moisture excess are characterized with higher occupancy (39 m^2 vs. 52 m^2 floor area per occupant), lower ventilation rate (8 l/(s·pers.) vs. 12 l/(s·pers.)) and significantly higher (P<0.02) air tightness of the building envelope (3.5 m^3/hm^2 vs. 7.4 m^3/hm^2). Similarly, in the Finnish study, houses with average moisture excess during the cold period >+3 g/m^3 and <+1.5 g/m^3 were compared. Houses with higher moisture excess had significantly lower (P<0.00003) air change rate (0.25 vs. 0.4 ach in average) and had significantly higher (P<0.01) air tightness of the building envelope (n_{50}=2.4 vs. n_{50}=4.0 ach at 50 Pa). The questionnaire conducted in the houses with higher moisture excess showed the following: markedly less window airing (P<0.02), more houseplants (P=0.05) and higher occupancy (41 m^2 vs. 51 m^2 floor area per occupant).

Figure 4.15 shows the maximum moisture excess from the studied dwellings on the higher 10 % critical level. In detached houses, the design curve of the moisture excess on the higher 10 % critical level during the cold period is close to +4 g/m^3, during the warm period +1.5 g/m^3. In apartments, the design curve of the moisture excess on the higher 10 % critical level during the cold period is close to +6 g/m^3. The proposed moisture excess design curve is on the basis of the trend line of these curves.

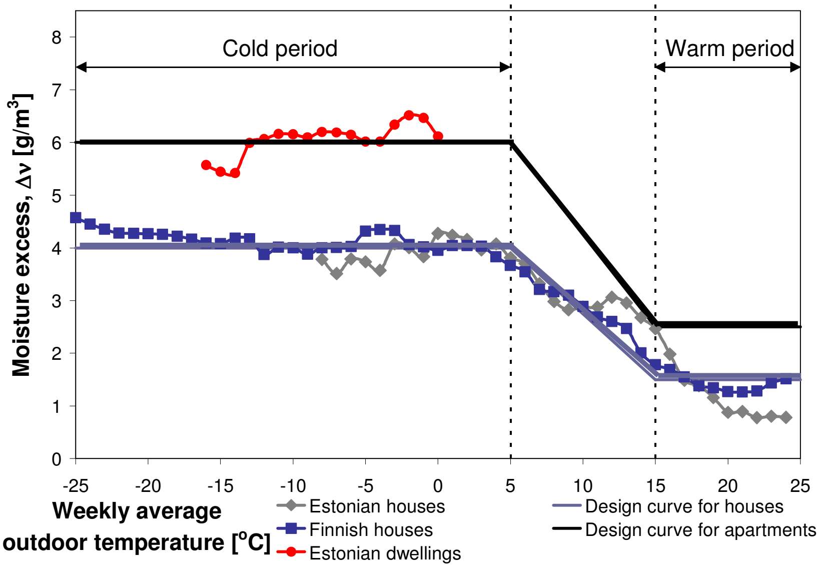

Figure 4.15 Moisture excess on the higher 10 % critical level and the design curve of moisture excess

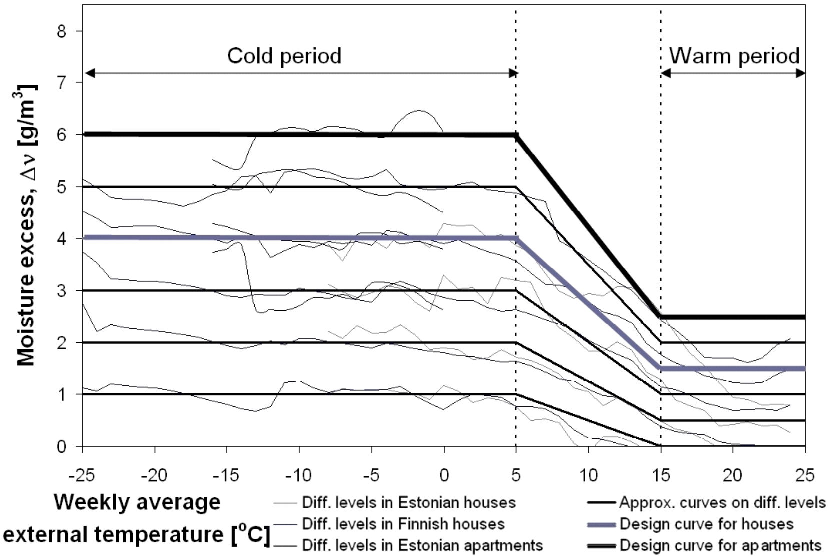

Figure 4.16 Simplified moisture excess curves on different humidity load levels

To do hygrothermal calculations and sensitivity analyzes under different hygrothermal loads, it is necessary to know the distribution of different moisture excess levels in the whole outdoor temperature range. To analyze the moisture excess performance through the full range of moisture production, different curves were calculated from the maximum moisture excess curves of each room, sorting the curves such that during the cold period, the average values of moisture excess would be as follows: +1 g/m^3, +2 g/m^3, +3 g/m^3, +4 g/m^3, +5 g/m^3, and +6 g/m^3. Different moisture excess levels and approximation curves from these levels that show the moisture performance of houses through the full range of moisture production are shown in Figure 4.16. These curves show that if the moisture excess changes by 1 g/m^3 during the cold period, it does by about 0.5 g/m^3 during the warm period. Similar performance was shown already in the first year measurement results in the Finnish study (Vinha et al. 2004). This performance means that in apartments with moisture excess of +6 g/m^3 during the cold period, the design curve of moisture excess during the warm period could be +2.5 g/m^3.

The air change rate has a direct influence on the indoor humidity loads. The effect of the air change rate on the maximum and average moisture excess in Finnish detached houses during the cold period is shown in Figure 4.17. This dependence is on the basis of the actual air change rate measurements in each house with the PFT technique during the winter season.

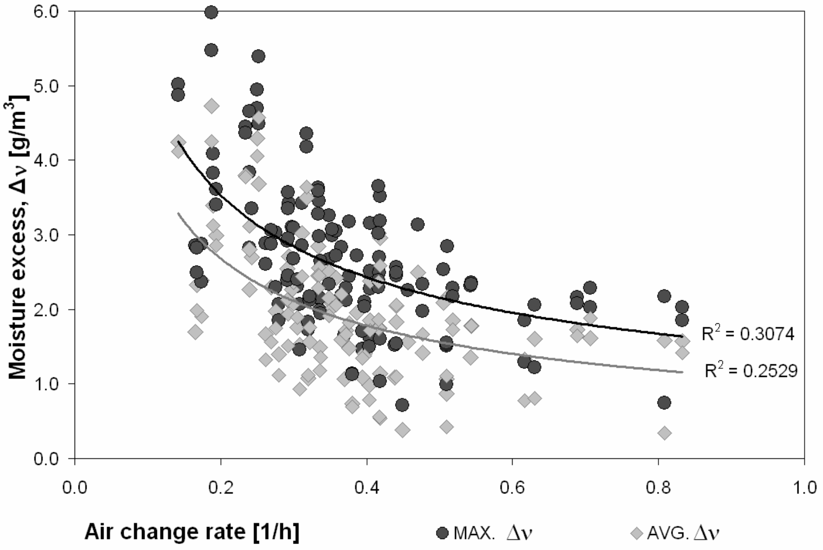

Figure 4.17 Effect of the air change rate on the maximum (MAX) and average (AVG) moisture excess during the cold period

On the basis of the air change rate and the moisture excess, the daily average moisture production rates from each house were estimated (Eq. 3.6).

Table 4.14 Moisture production in the studied detached houses

	Estonian detached houses	Finnish detached houses
Daily average moisture production	5.4 kg/day/house 1.6 kg/day/person	5.9 kg/day/house 1.9 kg/day/person
Average value from the daily maximum moisture production values	13.0 kg/day/house 4.1 kg/day/person	12.7 kg/day/house 4.0 kg/day/person

4.4.2 Performance of the indoor hygrothermal load model

In the following, it will be tested how to achieve realistic indoor humidity conditions by using the design curve of moisture excess all the year round. As the moisture excess approach is a robust simplified approach, thus, it should be checked that the model would not calculate too low or too high RH values. Correct RH values, in addition to absolute humidity values, are especially important for mould growth calculations in the internal part of the envelope.

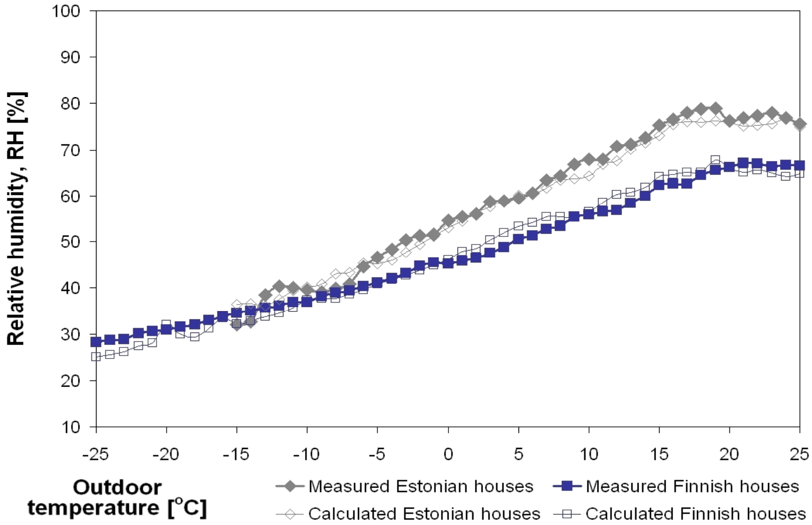

Figure 4.18 The comparison of measured and calculated daily average indoor RH on higher 10 % level

In Figure 4.18, the measured daily average indoor RH in detached houses on the higher 10 % level is shown by the curve with filled squares and rhombs (selected from measurement results similarly to the dependence of moisture excess and indoor temperature on the outdoor temperature). The corresponding calculated values are shown by the no filled squared and rhombed curve. This is calculated with the use of the design curve of moisture excess in detached houses (moisture excess on the higher 10 % level, Figure 4.15), the average temperature curve (Figure 4.13) and the daily average outdoor climate during two measurement years. Calculated RH values are sorted according to the outdoor air temperature from where the 10 % critical level was calculated (curve with no filled squares and rhombs). As indoor temperature models and outdoor climate were different in two (Estonian and Finnish) studies, also the performance of indoor RH dependency on outdoor temperature is different. Nevertheless, in both studies, the measured and the calculated indoor RH show a good agreement, which allows the dependence of the indoor temperature and the moisture excess on the outdoor temperature to be used in calculations of indoor RH values as boundary conditions for hygrothermal simulation.

4.5 Critical values for the temperature factor to assess thermal bridges

In Estonia, there exist no official requirements or guidelines for the critical temperature factor values. In many decrees, acts and standards (RT I 1999, 9, 138; RT I 2002, 47, 297; EVS 837-1:2003; EVS 839:2003), requirements are set to avoid moisture damages, surface condensation and mould growth. In IV, a special climate analyzes was conducted to determine the design value for the temperature factor for Estonian dwellings. The aim was to accomplish the building design process and the inspection of the thermal bridges with infrared thermography in real buildings. The outdoor climate was retrieved from six weather stations, covering a 31-year period, from 1970 to 2000. The critical temperature factor values were selected for two different internal moisture excesses, two different indoor temperature models, and two different selection criteria (mould growth and surface condensation). Figure 4.19 and Figure 4.20 show the influence of the indoor temperature and the moisture excess (marked value during the cold period) models on the temperature factor limit values to avoid mould growth and surface condensation. In these curves, a 10 % higher critical level was calculated from the six locations during the 31-year period. The determined critical value for the temperature factor was selected from the highest value of the curve of average temperature model.

In dwellings with a moisture excess during the cold period +6 g/m^3, during the warm period +2.5 g/m^3 (commonly apartments: high occupancy and/or low ventilation), the spot temperature factor on the thermal bridges should be according to the mould growth criterion ($RH_{si} \geq 80$ %) $f_{Rsi} \geq 0.80$. According to surface condensation, the limit value for the temperature factor is $f_{Rsi} \geq 0.70$. In dwellings with a moisture excess during the cold period +4 g/m^3, during the warm period +1.5 g/m^3 (commonly detached houses: low occupancy and normal ventilation), the spot temperature factor on the thermal bridges should be according to the mould growth criterion $f_{Rsi} \geq 0.65$ and for the surface condensation criterion, the limit value is $f_{Rsi} \geq 0.55$, respectively. In the most critical cases (high indoor humidity conditions, low room temperature), mould growth is possible even in well-insulated surfaces, see Figure 4.19. It proves the important role of ventilation and heating in the regulation of the humidity levels in rooms with high moisture production. The temperature factor $f_{\mathrm{Rsi}} \geq 0.70$ is a suitable value to avoid surface condensation also in the case of a lower temperature model.

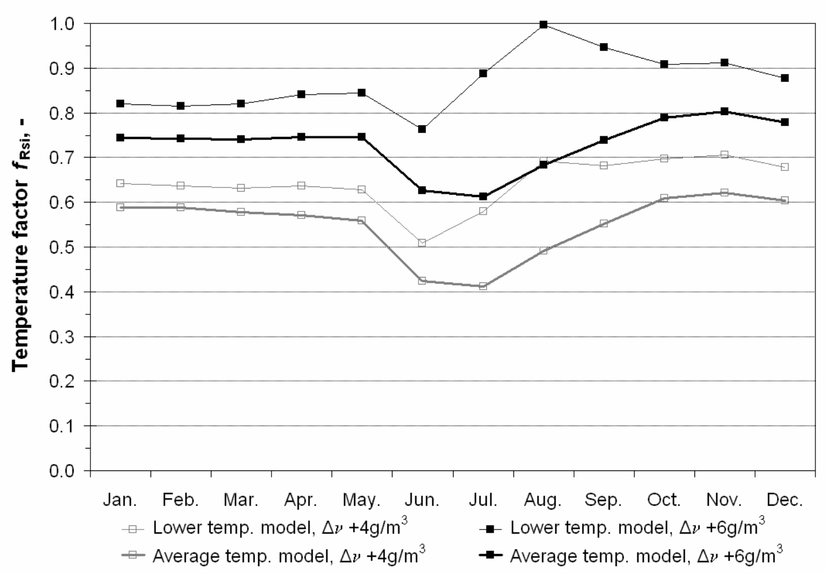

Figure 4.19 Influence of the indoor temperature and the moisture excess on the temperature factor calculated according to the mould growth criterion

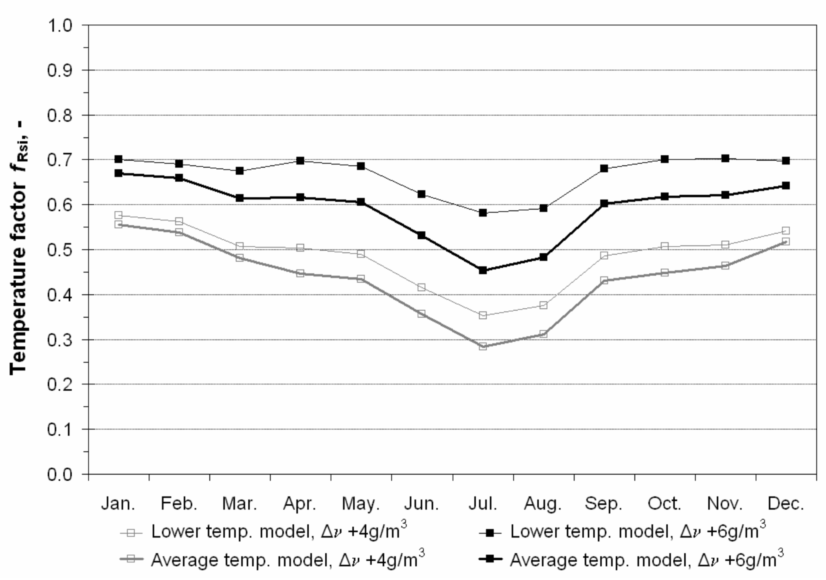

Figure 4.20 Influence of the indoor temperature and the moisture excess on the temperature factor calculated according to the condensation criterion

In the following, the limit values for indoor RH in relation to surface condensation and mould growth criteria are calculated. The aim was to find the highest level of indoor RH neither with surface condensation nor with mould growth. At each outdoor temperature, the highest indoor RH was calculated by using the temperature factor f_{Rsi} 0.80 and the highest RH at the internal surface of the building envelope RH_{si} 80% (mould growth criterion) and f_{Rsi} 0.70 and RH_{si} 100% (condensation criterion). For lower indoor humidity conditions, the highest indoor RH was calculated using the temperature factor f_{Rsi} 0.65 and the highest RH at the internal surface of the building envelope RH_{si} 80% (mould growth criterion) or f_{Rsi} 0.55 and RH_{si} 100% (condensation criterion). Indoor temperature and indoor water vapour pressure at saturation were calculated using the dependences between the outdoor temperature and the average indoor temperature. Using the critical temperature factor, critical indoor surface temperature was calculated. The maximum level of indoor water vapour pressure at the indoor surface of the building envelope was calculated from the critical indoor surface temperature for the condensation and mould growth criterion. The relation between the maximum level of indoor water vapour pressure at the indoor surface of the building envelope and indoor water vapour pressure at saturation show the highest level of indoor RH either surface condensation or mould growth do not occur. Figure 4.21 shows the limiting curves for the indoor RH for the average indoor temperature model (Figure 4.13). Design values of the temperature factor for a lower humidity load level do not cover standardized (EVS 839:2003) indoor RH values. Therefore, these lower values of the temperature factor are allowed to be used only if the lower indoor humidity conditions are clearly defined and argued.

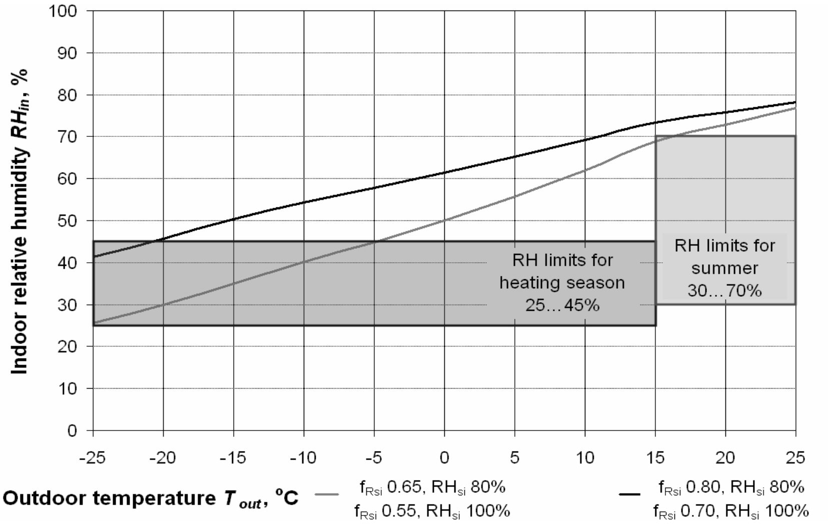

Figure 4.21 Limiting curves for indoor RH to avoid mould growth and surface condensation according to the determined temperature factor values

5 DISCUSSION

5.1 Outdoor climate for hygrothermal calculations

Outdoor temperature and RH were used to calculate the risk of mould growth and water vapour condensation in the current study. Depending on the combinations and properties of building envelope materials and the indoor hygrothermal conditions, the temperature and RH conditions within the envelope may be different in most critical points. This may lead to a different order of the years for the reference year selection. Djebbar et al. (2001) have pointed out that Moisture Reference Year (MRY) should be location- rather than construction-specific. In general, this is true, although with some reservations. The behaviour of different construction types differs under the same weather load. Wind-driven rain and solar radiation have a different impact on a brick wall and a log or wall with a ventilation gap and exterior boarding. For highly air-permeable walls, moisture convection may be more dangerous than moisture diffusion or capillary movement. For airtight walls with a ventilation gap and exterior boarding, commonly, diffusion is the main moisture movement mechanism. Therefore, the construction specific approach would lead to many MRY-s and for avoiding that MRY should be criterion-specific. In principle, one moisture reference year is insufficient, thus, more than one is needed to control the influence of different heat and moisture movement processes or their combined effects as well as to control different moisture performance criteria. The MRY determined in this study is most critical for the moisture diffusion. Even the selection method did not consider the influence of air flow through the construction, if the air pressure difference is added separately, it is possible to calculate also moisture convection cases. If the air pressure difference is calculated by wind data, it may not be the 10 % critical level year any more.

The most critical period for moisture condensation in Estonia climate is winter. Therefore in selecting the critical year in respect of the risk of water vapour condensation, the average value of saturation deficit in the winter period (December, January, February) was used. If design criteria allows some condensation and we expect that the moisture will dry out during the spring period, spring months must also be included in the selection analyzes. If the entire year moisture balance is considered, a summer and autumn periods must be included to make the right decision. To control the problems with summertime condensation, which may be worsened by high solar radiation after a rainfall or after a cold and humid spring, this time period must also be analyzed and rain and solar radiation data taken into account. To analyze the possible damage of brick walls due to freezing and thawing cycles, special climatic data are also needed. Driving rain and its effect on the envelope are not analyzed in this study.

Critical years do not correspond exactly to calendar years, they begin from July and end in late June. Such a period is selected because the risks for water vapour condensation and mould growth are minimal in summer and start to increase thereafter. To analyze the drying out of construction moisture, a more critical period sets in from humid autumn.

Saturation deficits and mould indexes were calculated ignoring solar, sky and ground radiation, rain and wind data, and building envelope properties. These simplifications were made because the aim at this stage was to select years independently of construction-specific details. Considering building- specific details would require, for example, absorptivity and emissivity of different building surfaces as well as the slope and orientation of specific envelopes to be determined. This would produce a number of individual reference years specific to the envelope type and orientation. Hagentoft and Harderup (1994) have analyzed the influence of solar radiation on the reference year selection. Hygrothermal calculations of three sample constructions showed that the effect of the shortwave radiation was quite small, and it was smallest for the worst year than for a normal year. Hagentoft and Harderup suggested that the effect of the solar radiation could be neglected when looking for a "bad" year as a moisture reference year.

5.2 Outdoor climate for energy analyzes

The TRY was selected from the Tartu meteorological station, because it was the only station where were radiation data were directly measured. There are methods (Averkiev 1961, Nimiya et al. 1997, Olseth and Skartveit 1993) available to assess solar radiation on the basis of cloud and sunshine duration. Nevertheless, the results of these empirical equations are approximate and provide rough estimations of solar radiation (Russak and Kallis 2003). Therefore, using these approximate methods to calculate solar radiation may result in a greater margin of error than using the TRY solar data from Tartu for the whole of Estonia. The use of Tartu solar data brought out the idea to expand the TRY-method so that one TRY can be used in all locations in Estonia. The ISO 15927-4:2005 method was modified so that temperature and humidity from all six meteorological stations over 31 years were represented in the reference long-term data. This modification method is useful, when the climate differences are relatively small, justifying the use of one TRY for a compact country.

Temperature, as the main climate parameter for heating energy demand during the heating season, and humidity data were used from all six weather stations. Heating degree-day analyzes shows that the deviation between these meteorological stations and the average of all data is almost the same as the deviation during different years at one meteorological station and that these deviations are below ±9 %. Thus, it is reasonable to use one TRY for all locations in Estonia.

Different weighting factors for the main climatic parameters have been used in different reference year studies. Weighting factors for climate parameters were not used in this study, i.e. all parameters have the same weight. Naturally, each climatic parameter has a different influence on energy demand. However, one could not directly say that one main parameter, e.g. temperature, is more important than humidity or solar radiation. Humidity does not affect heat demand, however, it affects cooling coil capacity a lot deal. Temperature and solar radiation affect both heating and cooling demand. Additionally, the influence of these climate parameters also depends on the building type and the use of the climatic data. For example, the influence of solar radiation on cooling and heat demand varies with different building types: an office building with a glass facade that is completely exposed has a higher demand than a detached house with a relatively small glazed area and solar protection from the neighbourhood. It is not reasonable for the TRY to be building-specific; the same TRY should be a good compromise for all cases. However, it is recommended that the effect of relevant weighting factors should be the subject of further studies.

5.3 Internal moisture excess and moisture production

According to statistics, the average living area per occupant in new detached houses is in Estonia 45 m^2/pers. (Statistics Estonia 2005) and in Finland 38 m^2/pers. (Statistics Finland 2003). In Estonian apartments this value is 21 m^2/pers. and in overall Estonian housing stock 28 m^2/pers. The average living density in measured Estonian detached houses was about 46 m^2/pers. and 17 m^2/pers. in apartments and 43 m^2/pers. in Finnish detached houses. Thus, the studied detached houses correspond to houses with low occupancy and the studied apartments represent to slightly higher occupancy than the average.

The design loads presented in this study cannot be directly used for other types of buildings, such as commercial or educational or sports halls etc. As moisture excess is obviously dependent on moisture production and ventilation profiles.

For hygrothermal calculations, the critical moisture excess values were calculated as weekly average values over the whole year. A week was selected for the reference time period because a week is a certain living cycle and it represents more accurately indoor climate than for example a month. If we use a month for the reference time period, the averaging period will be technically too long: we do not obtain values for the whole outdoor temperature range (in particular for the cold period) and the result will be less comprehensive. If we use a shorter reference time period, the hygrothermal dynamics and different moisture production profiles may have too strong influence on the results.

The present results are compared with solutions of different standards (EN ISO 13788, prEN 15026 and ASHRAE SPC 160P) in Figure 5.1. Moisture excess was calculated according indoor climate parameters, described in the standards and was averaged for weekly average values. Moisture excess levels according to standards are close to the results of the current study during the cold period. During the warm period, the difference is larger. If the boundary conditions are given by temperature and RH, the humidity loads will have significant variation following the fluctuation of the outdoor humidity. Therefore, it would correspond to more realistic moisture production to provide humidity loads by moisture or vapour excess. Figure 5.1

shows that giving the indoor hygrothermal loads by temperature and RH will generate abnormal peaks to the moisture load curve that are not valid when calculated according to moisture production and ventilation rate profiles.

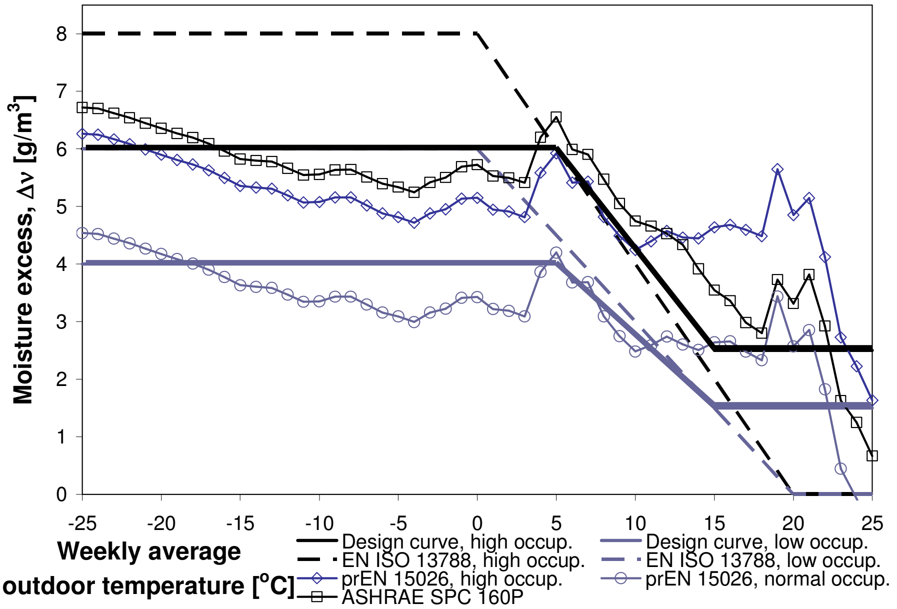

Figure 5.1 Comparison of the present results with solutions of different standards

The EN ISO 13788:2001 standard suggests using a safety margin 1.1 for moisture excess values, when the steady-state calculation method described in that standard is used. The introduction of this safety factor is intended only to allow the inaccuracies of the steady–state calculation method described in that standard. This safety factor does not include the behaviour of the occupants that can have a significant effect on ventilation or moisture production and thus on moisture excess. It should be taken into account by raising the safety factor. Commonly, safety factors are not used in hygrothermal design. The reason may be that the damage caused by hygrothermal problems is less catastrophic and dangerous compared to that of structural design. Parallels may also be drawn to the analyzes of the limiting state of service on the structural design where safety factors are not used. On the other hand, in order to determine the normative loads, the critical level is lower in hygrothermal loads. The overall consensus (Sanders, 1996) is that the return period once every 10 years seems to be appropriate in the hygrothermal analyzes, while, in the design of the bearing capacity of structures, the return period once in 50 or 100 years is used. The humidity loads are usually the most important agent, leading to the deterioration of the building envelope and limiting the service life of a building. Therefore, neglecting the safety factors in hygrothermal design deserves some criticism. In particularly, because hygrothermal loads are building use dependent. The owner, occupants, i.e. the user behaviour may change during the service life of the building, but the building envelope and servicing systems usually remain the same. In many cases, the use of safety factors in the hygrothermal design would not raise the building costs.

5.4 Critical values for the temperature factor to assess thermal bridges

Temperature factor values were calculated for two different indoor humidity and temperature conditions. The critical relative humidity RH_{si} 80 % was used for the risk of the mould growth criterion. The critical RH for mould growth depends also on many other factors. According to Hukka and Viitanen (1999), below the temperature +20 °C, a mathematical relation between the temperature and the critical RH for mould growth exists. By using this dependence, we obtain a ~3 % lower temperature factor value. Nevertheless, the constant RH value was used for safety reasons.

The determined critical temperature factor values can be directly used for thermal bridge investigations (e.g. with infrared thermography) in real buildings. Then indoor, outdoor and internal surface temperatures can all be directly measured. In the design process, to calculate the correct internal surface temperature, we should know the thermal resistance of the internal surface R_{si}. The thermal resistance of the internal surface depends on the convective and radiation heat transfer coefficients, and it may vary a lot. High values can be found in the case of significant thermal shielding by furniture and low values, for example, in a room with external walls only and a convective heating system. To calculate the correct internal surface temperature in the design process is complicated. Simplified methods and the values recommended by standards: EN ISO 10211-1:1995, prEN ISO 10077-2:2000, EN ISO 13788:2001. In most of the cases, the recommended values of the heat transfer coefficients can be considered as a safe side values. However, some inconsistency in different standards makes it unclear for designer what value should be used.

Temperature factor values are possible to use to for the building design of new buildings and infrared thermography inspections to assess the thermal performance of the existing buildings. For design of new dwellings $f_{\mathrm{Rsi}} < 0.80$ is proposed to use as design value. Temperature factor $f_{\mathrm{Rsi}} < 0.65$ may be allowed for detached houses when the lower indoor humidity conditions are clearly defined and justified. Building components that are designed for dwellings independently of their indoor hygrothermal loads (windows for example), should be expected to cope with higher values of the temperature factor without difficulty. To determine the need for repair works on the basis of thermography studies, it is suggested that building details in dwellings with the temperature factor $f_{\mathrm{Rsi}} < 0.65$ should be repaired immediately. Building details with the temperature factor $f_{\mathrm{Rsi}} > 0.80$ may be classified as satisfactory in terms of surface condensation and mould growth and have no need for corrective action. To assess the risk and to determine the need for building detail repairs between the temperature factor $0.65 < f_{Rsi} < 0.80$, different aspects should be taken into account: hygrothermal behaviour of the building envelope, parameters of indoor climate, thermal comfort, purpose of use of a building, economic aspects (repair costs, energy consumption, payback period), service life of a building, etc.

6 CONCLUSIONS

In this study, design values of indoor and outdoor climatic conditions were determined for hygrothermal design and for indoor climate and energy calculations and simulations. The design values of the temperature factor were determined to be used for the building design and building inspections.

Based on weather data from 1970 to 2000 form six meteorological station two different hygrothermally critical years were chosen with the saturation deficit method and the mould index method. These years can be used to design and to assess the hygrothermal performance of the building envelope in regard to vapour diffusion and moisture convection.

Test Reference Year (TRY) was constructed with slightly modified ISO15927-4:2005 standard method. The TRY contains months from a number of calendar years, and may be used for many applications, such as indoor climate and energy simulations, HVAC system performance, or simulation of active or passive solar energy systems. For a rough estimation of annual heating demand, the average number of heating degree-days was calculated from long-term data for six locations.

Long term measurements of indoor climate in many dwellings were used to determine average and critical temperature and humidity conditions with were used in moisture excess analysis. The average indoor temperature during measured winter seasons in Estonian detached houses was +21.3 °C and the average indoor RH 32 %. These values were +20.8 °C and 36 % in Estonian apartment +21.6 °C and 26 %and in Finnish detached houses. Despite these almost ideal winter temperatures, the variations in temperature was larger than expected to be produced by modern heating systems and well insulated envelopes. Large variations in temperature indicated that problems existed with temperature control of the heating systems. The wide band of average temperatures in houses shows that in addition to average temperature 10 % lower critical level should be taken into account in same cases. The average indoor temperature during measured summer seasons in Estonian detached houses was +23.5 °C and the average indoor RH 54 %. These values were +24.8 °C and 51 % in Finnish detached houses. Measurements showed an extensive period of high indoor temperatures during summer indicating that thermal comfort was not considered in the original design. The indoor temperature correlated with the outdoor temperature so strongly that the dependency between these parameters was determined. A need for heating during the summer period sometimes also occurred, however it can be compensated with adjustments in clothing.

The determined design curve of moisture excess curve on the 10 % critical level is +4 g/m^3 during the cold period ($T_{\text{out}} \leq +5$ °C) and +1.5 g/m^3 during the warm period ($\geq +15$ °C) for detached houses (commonly low occupancy and normal ventilation) and +6 g/m^3 during the cold period and +2.5 g/m^3 during the warm period for apartments (commonly high occupancy and/or low ventilation). Between these levels, moisture excess decreases linearly. For sensitivity analyzes and hygrothermal calculations, the levels of the moisture excess values are given with step of 1 g/m^3 during the cold period and 0.5 g/m^3 during the warm period. Current study showed approximately by 2 g/m^3 lower moisture excess levels during winter than given in EN ISO 13788 (2001) standard for both dwellings with low occupancy and for dwellings with high occupancy. Possible explanation to this difference is continuous ventilation in studied houses.

To determine and classify the thermal bridges, design values of temperature factor, f_{Rsi}, are recommended. In apartment buildings, f_{Rsi} shall be ≥ 0.80 according to mould growth criterion and $f_{\mathrm{Rsi}} \geq 0.70$ according to surface condensation criterion. In detached houses, these values are lower, 0.65 and 0.55 respectively

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Publications in peer-reviewed journals:

I Estonian Climate Analysis for Selecting Moisture Reference Years for Hygrothermal Calculations

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V Indoor climate conditions and the performance of ventilation in Estonian lightweight detached houses

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Conference publications:

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VIII Indoor hyrgothermal loads in Estonian dwellings.

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